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**TITLE OF THESIS**

ELECTRICAL ENERGY MANAGEMENT AND ITS IMPACT IN SUB-SAHARAN  
AFRICA

**By**

AFUA KHALFAN MOHAMED

**Thesis submitted in fulfilment of the requirements for the Degree of  
Doctor of Technology (D. Tech) in Electrical Engineering**

**In the Faculty of Engineering**

**At the**

**Cape Peninsula University of Technology**

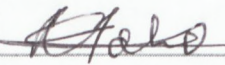
**Supervisor:** Prof. M.T.E Kahn

**Bellville**

**Date submitted:** January, 2011

## DECLARATION

I, Afua Khalfan Mohamed, declare that the contents of this thesis represent my own unaided work, and that the thesis has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

  
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## ABSTRACT

Electrical energy is an important resource for human and economic development. On the demand side, electrical energy management is needed because of the tendency of manufacturing industries to consume large amount of energy and as a result lead them to spend more money in paying bills for the consumed electrical energy. In addition, the amount of electrical energy generated in Sub-Saharan Africa is incomparable with demand requirements. The predominant sources of electrical energy generation are fossil fuels and hydro. Generation of electricity by fossil fuel needs high capital investments and high running costs. Concurrently, the process of burning fossil fuels has an adverse effect on the environment. In order to minimize these effects, electrical energy management in manufacturing industries has to be instituted and implemented.

In this research, a study has been undertaken to develop methods and strategies to be used as tools for electrical energy management in manufacturing industries and it is aimed at reducing electrical energy consumption. The research method adopted/used includes: survey of several cement industries in order to obtain current and historical electrical energy consumption, production data and to be acquainted with the methods used for energy management, measurement of electrical parameters, investigation of the use of electrical power in cement industries, analysis of power factor and power factor correction methods, analysis of energy efficiency potentials and technology used for energy saving.

From the data gathered, the following were developed: strategies for the overall electrical energy management for cement plant, strategies for energy efficiency potential and technology used for energy saving, an algorithm for assessing the potential options of DSM, an algorithm for performing industrial load scheduling, an industrial energy consumption model using regression analysis technique and a Static Synchronous Compensator (STATCOM) for industrial power factor improvement. Also, a numerical analysis and computer simulation using MATLAB/Simulink were implemented. Moreover PSIM and Excel software were used in the developed energy consumption model and for the power factor improvement method.

Numerical analysis and computer simulation showed that the developed STATCOM has the capability of improving and varying of power factor in accordance with the variation of plant loads, it improves power factor and reduces harmonics of the respective industries. Using the developed algorithm for assessing potentials of DSM options, it was found that, most of the energy management techniques used in manufacturing industries worldwide are not implemented in the visited industries.

The developed methods and strategies can be used in improving power factor, prediction of electrical energy consumption and also for development of energy consumption benchmarking in cement industries. They can be also extended and used in mining and other manufacturing industries such as paper, textiles and this can create condition for sustainable energy management program in manufacturing industries.

## ACKNOWLEDGEMENTS

### I wish to thank:

- My Supervisor, Professor M. T. E Kahn for his supervision, technical guidance and for his huge contribution in this work. During my studentship, he gave me moral support, encouragement, motivation and advice on issues related to academics and life in general.
- My employer, Dar Es Salaam Institute of Technology (DIT) for releasing me from work and hence I was able to be a full time student.
- The Department of Electrical Engineering, CPUT Bellville Campus, for providing me good learning environment, and to all staff in Electrical Engineering Department, for their technical support.
- All colleagues at the Centre for Distributed Power Electronics Systems and MTech Lab (CPUT) for their invaluable support and encouragement during my study. I will always cherish the moment we were together.
- My family, for their unconditional love, encouragement, support and prayers.
- My beloved daughter Sarah, for her warm support and encouragement.
- Management and staff of Mbeya Cement Company, Tanzania Portland Cement (TPCC), Tanga Cement, Ministry of Energy and Mineral (MEM) Tanzania and Tanzania Electricity Supply Company (TANESCO) for furnishing me with information and data that made this project to be possible.
- To the Almighty, God for his blessing, love and care.

## DEDICATION

I dedicate this thesis to my daughter Sarah for being patient and understanding for the whole period of study, my mother, Mwanahija and my sister, Riziki, for raising me to the person I am today.

# TABLE OF CONTENTS

DECLARATION .....	ii
ABSTRACT .....	iii
ACKNOWLEDGEMENTS .....	v
DEDICATION .....	vi
TABLE OF CONTENTS .....	vii
LIST OF FIGURES .....	xii
LIST OF TABLES .....	xv
LIST OF APPENDICES .....	xvi
GLOSSARY .....	xix
CHAPTER ONE: Introduction .....	1
1.1 Background .....	1
1.2 The Need for Electrical Energy Management in Sub-Saharan Africa (SSA) .....	1
1.3 Energy and Industrial Overview in Sub-Saharan Africa .....	3
1.3.1 Energy Overview .....	3
1.3.2 Comparison of Africa and Global Electricity Profile .....	7
1.3.3 SSA Industrial Profile .....	8
1.4 Statement of the Problem .....	11
1.5 Purpose of Study .....	12
1.6 Objectives of the Study .....	12
1.6.1 Specific Objectives .....	12
1.7 Significance of the Research .....	13
1.8 Motivation for the Research .....	13
1.9 Research Questions .....	14
1.10 The Scope and Limitations of the Study .....	14
1.11 Assumptions .....	16
1.12 Outline of the Chapters .....	17
1.13 Summary .....	19
CHAPTER TWO: Literature Review .....	20
2.1 Introduction .....	20
2.2 Energy Management: An Overview .....	20
2.2.1 Review of Energy Management in Cement Production Process .....	22
2.2.2 The Status of Cement Production in SSA .....	23
2.3 Electrical Energy Management Techniques in Power Supply Industries (PSI) .....	24
2.3.1 Direct Load Control .....	26
2.3.2 Load Management by Time Dependant Tariffs .....	29
2.3.3 Dispatch and Rebate Load Management Programs .....	31
2.3.4 Demand Side Management (DSM) .....	32
2.3.5 Other Energy Management Measures Taken by Utility Industries .....	34
2.4 Electrical Energy Management by Consumers Approach .....	34
2.4.1 Model Development for Industrial Load Management .....	36
2.4.2 Energy Efficiency Techniques for Energy Management .....	46
2.5 Power Factor Correction .....	47
2.5.1 Strategies Used for Correcting Power Factor .....	48
2.6 Electrical Load Management (ELM) Process .....	50
2.7 Conclusions .....	51
CHAPTER THREE: Energy Management Principle and Energy Distribution in Cement Production Processes .....	53
3.1 Introduction .....	53
3.2 Elements of Strategic Energy Management Program in Industry .....	53
3.2.1 Principles of Electrical Energy Management Program (EEMP) .....	54
3.2.2 Energy Accounting .....	55
3.2.3 Energy Auditing .....	57
3.2.4 Industrial Energy Conservation Techniques .....	58
3.2.4.1 Energy Awareness and Housekeeping Measures .....	59
3.2.4.2 Equipment Improvement .....	60
3.2.4.3 Process Improvement .....	60
3.2.4.4 Energy Efficient Standard and Labelling .....	60
3.3 Energy and Cement Production Overview .....	61
3.3.1 Cement Production Process .....	61
3.3.1.1 Raw Materials Preparation .....	62

3.3.1.2	Clinker Production .....	62
3.3.1.3	Finish Grinding .....	63
3.3.2	Energy Consumption in Cement Industries of SSA .....	64
3.4	Energy Efficiency Technologies and Consideration in Cement Industry .....	66
3.4.1	Use of Roller Mills for Raw Meal Grinding .....	66
3.4.2	Fuel Combustion Improvements in Kilns .....	67
3.4.3	Process Control, Optimization and Management Systems .....	67
3.4.4	Wet Process Conversion to Multi-Stage Pre-Heater and Pre-Calciner Kiln .....	68
3.4.5	Energy Efficient Finished Grinding .....	68
3.4.6	Product Change .....	69
3.5	Analysis of Industrial Electrical Loads and their Energy Management Potentials in Cement Industries .....	69
3.5.1	Data Collection Program .....	70
3.5.2	Energy Management Potentials in Surveyed Industries .....	71
3.5.3	Characteristics of the Surveyed Loads .....	73
3.5.3.1	Motors Principles of Operation.....	73
3.5.3.2	Analysis of Industrial Loads and its Application .....	74
3.5.4	Electrical Energy Profile for the Cement Industry; Case Study .....	75
3.6	Conclusion.....	79
CHAPTER FOUR: Demand Side Management: Development and its Role on Electrical Energy Management in Manufacturing Industries .....		80
4.1	Introduction.....	80
4.2	The Importance of DSM .....	80
4.3	Concept of Demand Side Management Program .....	81
4.3.1	DSM Planning Processes .....	82
4.3.2	Steps for the DSM Program Development.....	84
4.4	Role of DSM Programs in Utilities Industry .....	85
4.6	The Need for DSM in SSA Manufacturing Industries.....	85
4.6.1	Procedures for Development of Tools for Assessing DSM Programs Options .....	87
4.6.2	Assessment of DSM Program Options: Case Study of SSA Cement Industries .....	88
4.6.3	Barriers to the Development of DSM Programs.....	91
4.6.3.1	Market Barriers.....	91
4.6.3.2	Institutional Barriers.....	92
4.6.4	Techniques to Overcoming Barriers to DSM Programs.....	92
4.7	International Experiences of DSM Programs .....	93
4.7.1	USA .....	93
4.7.2	Thailand.....	93
4.7.3	Vietnam .....	94
4.7.4	South African Experience.....	95
4.8	Maintenance Program as a Part of DSM .....	97
4.8.1	Importance of Maintenance in Electrical Energy Management .....	97
4.8.2	Types of Maintenance System .....	98
4.8.3	Assessment and Development of the Maintenance Strategy in Cement Industries .....	98
4.8.3.1	Maintenance of Motors and Related Components.....	99
4.9	Conclusion.....	100
CHAPTER 5: Analysis of Energy Efficiency Technologies and Development of Performance Based Indicators .....		101
5.1	Introduction.....	101
5.2	Assessment of Energy Efficiency Potentials in Cement Industries.....	101
5.2.1	Energy Efficient Lighting Systems.....	102
5.2.2	Efficiency Improvements in Electric Motors and their Systems .....	106
5.2.2.1	Characteristics of Motor Loads and their Control for Energy Saving .....	110
5.2.3	Assessing Cost Effectiveness of Energy Efficient Motors .....	110
5.3	External Factors Influencing Inefficient Operation of Electric Motors .....	113
5.3.1	Unbalanced Voltage .....	113
5.3.2	Poor Maintenance .....	115
5.3.3	Voltage and Frequency Variation.....	115
5.4	Assessment of Energy Efficiency Indicators in Cement Industries.....	115
5.5	Benchmarking of Industrial Energy Consumption.....	118
5.6	Model Development and Testing – Mbeya Cement Factory.....	120
5.6.1	Cement Mill Section Energy Analysis .....	121
5.6.2	Industrial Energy Consumption Model: Development and Analysis .....	127
5.7	Energy Efficiency Improvement Barriers.....	132

5.8	Conclusion.....	133
CHAPTER SIX: Alternative Energy Management Techniques in Cement Industries .....		135
6.1	Introduction.....	135
6.2	Strategies for the Implementation of Alternative Technologies as Energy Management Techniques.....	135
6.3	Synchronous Motor vs Induction Motor Performance and Operation.....	137
6.3.1	Synchronous Motor.....	137
6.3.2	Power and Torque Characteristics of Synchronous Motors .....	138
6.3.3	Advantages of Synchronous Motors .....	140
6.3.4	Excitation System.....	141
6.4	Synchronous Motor Economic Analysis.....	142
6.4.1	Savings Calculation and Pay Back Analysis of SM vs IM Based on Efficiency.....	143
6.4.3	Analysis of Operating and Maintenance Costs of the Machines .....	145
6.4.3.1	Wound Rotor Motor with Power Factor Correction Capacitor Banks.....	145
6.4.3.2	Synchronous Motors.....	145
6.4.4	Use of Variable Speed Drive (VSD) and their Costing.....	145
6.4.5	Motor Efficiency at Low Loading .....	146
6.5	Case Study.....	147
6.5.1	Analysis of Annual Energy Cost for the Synchronous Motor .....	148
6.5.2	Induction Motor Costing .....	149
6.5.3	Influence of Operating Hours of Motor vs Payback Period.....	153
6.6	Different Electricity Tariff Structure and Metering System .....	155
6.6.1	The General Type of Tariffs .....	155
6.6.2	Real-Time Pricing.....	156
6.7	Energy Storage .....	157
6.7.1	The Principal Applications of Energy Storage Technology on Supply and Demand Side.....	158
6.7.2	Energy Storage Device .....	158
6.7.2.4	Pumped Hydro storage .....	160
6.8	Conclusion.....	160
CHAPTER SEVEN: An Overview of Industrial Power Factor Correction Methods .....		162
7.1	Introduction.....	162
7.2	Power Factor Concept .....	162
7.3	Techniques to Improve Power Factor .....	164
7.3.1	Capacitor Application .....	164
7.3.1.1	Optimal Location of Capacitor in the Circuit.....	167
7.3.1.2	Types of Correction.....	169
7.3.2	Synchronous Condensers.....	169
7.3.3	Static Var Compensator (SVC) .....	170
7.3.3.1	Thyristor-Switched Capacitors (TSC).....	170
7.3.3.2	Fixed Capacitor - Thyristor-Controlled Reactor (FC-TCR) .....	172
7.3.3.3	Combined TSC and TCR .....	174
7.3.4	Advantages of Power Factor Correction .....	175
7.3.4.1	Low Utility Charge; this is because low power factor cause the utility to over load its .....	175
7.3.5	Disadvantages of Power Factor Correction Capacitor.....	176
7.4	Selection of an Appropriate Range of Power Factor Capacitor .....	176
7.5	Influence of Harmonic Distortion in Industrial Power Factor .....	177
7.5.1	Effect of Harmonic to the Capacitor Bank Circuit.....	178
7.6	Economic Evaluation of PFC .....	178
7.6.1	Economics Analysis of Power Factor Improvement: Case Study.....	179
7.6.2	Case Study – Cement Factory.....	180
7.6.2.1	Calculation of Power Factor Penalty.....	181
7.7	Proposed Modification.....	185
7.8	Conclusion.....	185
CHAPTER EIGHT: Proposed Power Factor Correction and Control Techniques.....		187
8.1	Introduction.....	187
8.2	Power Factor Compensation Principles.....	187
8.3	Compensator Connection .....	188
8.3.1	Shunt Compensation.....	189
8.3.2	Series Compensation .....	189
8.4	Types and Problem of Power Factor Compensation Control Systems.....	190
8.4.1	Mechanical Switched Capacitors Compensation.....	190
8.4.2	Synchronous Condensers.....	190
8.4.3	Thyristor Controlled VAR Compensators.....	191

8.5	Principle of Operation of STATCOM .....	192
8.6	Voltage Source Inverter (VSI) Configuration for Reactive Power Compensation.....	197
8.6.1	Sinusoidal PWM Voltage Source Converter .....	201
8.7	Modelling and Analysis of A STATCOM .....	203
8.7.1	Modelling of part A (Transformation of Part A) .....	203
8.7.2	Transformation of Part B .....	204
8.7.3	Transformation of Part C .....	204
8.7.4	Transform of Parts D and E .....	205
8.7.5	The STATCOM Behaviour in Steady State.....	207
8.7.6	Controller Design.....	209
8.8	Designed Parameters for the Developed STATCOM .....	210
8.8.1	Total Plant Load Calculation .....	211
8.8.2	D-STATCOM Parameter Calculations .....	212
8.8.3	Compensator Rating .....	216
8.9	Results of the Developed STATCOM .....	217
8.10	Conclusion.....	221
CHAPTER 9: Proposed Energy and Demand Management Strategies.....		222
9.1	Introduction.....	222
9.2	Steps for the Strategic Energy Management Strategies.....	222
9.2.1	Methods for Demand Control .....	223
9.2.1.1	Manual Controller.....	224
9.2.1.2	Automatic Controller.....	224
9.2.1.3	Microcomputer System .....	225
9.2.1.4	Computerized Energy Management Control System.....	225
9.2.2	Determining the Potential for Demand Control .....	226
9.2.3	Operation of the Demand Control System .....	226
9.3	Algorithm for Energy and Demand Control by Load Scheduling Technique .....	227
9.3.1	Formulation of Load Model in Cement Industries .....	228
9.3.2	Load Management Method and Energy Management Model.....	233
9.3.3	Analysis of Storage System .....	239
9.3.4	Formulation of Power Factor Monitoring and Control .....	240
9.4	Strategies for Industrial Load Control.....	240
9.4.1	Use of Energy Efficient Techniques in Energy Management Strategies .....	242
9.5	Enhancing Energy Management Strategies .....	242
9.5.1	Summary of the Survey Results.....	244
9.5.2	Establishment of Energy Auditing and Accounting .....	245
9.5.3	Energy Monitoring and Control .....	246
9.6	Proposed Strategic Energy / Demand Management .....	249
9.6.1	Appointment of the Top Management Committee .....	249
9.6.1.1	Planning and Organizing.....	249
9.6.2	Policy and Planning.....	250
9.6.2.1	Planning .....	250
9.6.2.2	Developing an Energy Policy .....	251
9.6.3	Building Awareness and Motivation to Employees .....	251
9.6.4	Co-coordinating Load Management for Maximum Benefit.....	251
9.7	Conclusion.....	251
CHAPTER TEN: The Role of Electrical Energy Management in Mitigating Social, Economical and Environmental Impacts.....		253
10.1	Introduction.....	253
10.2	Environmental Effects of Electricity Generation and Consumption .....	253
10.2.1	Electricity Production by Fuel Types.....	254
10.2.1.1	Fossil Fuels.....	254
10.2.1.2	Nuclear Energy .....	255
10.2.1.3	Solar Radiation .....	256
10.2.1.4	Wind Energy .....	257
10.2.1.5	Hydropower.....	258
10.2.1.6	Tidal Energy.....	258
10.2.1.7	Geothermal .....	259
10.2.1.8	Natural Gas.....	259
10.2.2	Energy Production; Social and Economic Impact in SSA.....	261
10.2.3	Energy Consumption and Economic Activities in SSA .....	262
10.2.3.1	Environmental Impacts of Industrial Operations.....	262
10.2.3.2	The Relationship between Energy Consumption and Economic Growth in SSA.....	264

10.3	Environmental Impact Caused By Electricity Transmission and Distribution.....	266
10.3.1	Environmental Issues Associated with Transmission Lines.....	266
10.4	Energy Use and Global Climate Change .....	267
10.4.1	Global Climate Change Definition.....	267
10.4.2	Effects of Global Climate Change.....	268
10.5	Energy Efficiency Techniques.....	269
10.5.1	Lighting Systems.....	269
10.5.1.1	Impact of Large Number of Energy Efficient Lighting in Distribution System.....	269
10.5.1.2	Presence of Mercury in Energy Efficient Lighting and its Impacts .....	269
10.5.2	Energy Efficient Motors.....	270
10.6	Plant Power Factor: Environmental, Social and Economical Impact.....	271
10.7	Deregulation and Energy Trading .....	271
10.8	Conclusion.....	272
CHAPTER 11: Results and Discussion .....		274
11.1	Introduction.....	274
11.2	Simulation Using MATLAB /SIMULINK and Discussion .....	274
11.2.1	Simulation Analysis without STATCOM.....	275
11.2.1.1	Kiln Section Loads Only.....	275
11.2.1.2	Kiln and Raw Mill Loads .....	278
11.2.1.3	Kiln and Cement Mills.....	283
11.2.1.4	When All Loads Are Connected At the Same Time.....	286
11.2.1.5	When Plant Load Contain 10% of Nonlinear Load.....	290
11.2.2	Compensator is Connected to the Plant System.....	293
11.2.2.1	Kiln and Raw Mill Section Loads .....	293
11.2.2.2	Kiln and Cement Mill Loads .....	297
11.2.2.3	STATCOM with Variable System Loads (All loads have been considered).....	301
11.2.2.4	STATCOM Connected at the Initial Time .....	305
11.2.2.5	Kiln Load, Cement Mill load + 5% Nonlinear Loads .....	307
11.2.2.6	Simulation of Industrial Loads with 10% of Nonlinear Loads .....	312
11.3	Simulation Analysis with PSIM Software .....	315
11.3.1	Simulation without STATCOM .....	315
11.3.1.1	Kiln Section Loads Only.....	315
11.3.1.2	Raw Mill Connected With the Kiln Section Loads at a 200ms.....	316
11.3.1.3	Kiln and Cement Mill Load Connected at 200ms .....	318
11.3.1.4	All Loads Connected Without STATCOM.....	319
11.3.1.5	All Loads Connected at Different Period .....	320
11.3.2	Plant Loads With STATCOM Connected At 300ms .....	321
11.3.2.1	Kiln Load Connected With STATCOM.....	321
11.3.2.2	Kiln and Raw Mill Section Loads (Load 1+ Load 2) with STATCOM at 300ms.....	322
11.3.2.3	Kiln and Cement Mill Section Loads with STATCOM at 300ms.....	323
11.3.2.4	All Loads Connected with STATCOM at 300ms.....	324
11.4	Conclusion .....	326
CHAPTER 12: Conclusions and Recommendations.....		327
12.1	Conclusions.....	327
12.2	Recommendations and Future Research Work.....	334
12.3	Publications .....	335
REFERENCES .....		336
APPENDICES.....		348

## LIST OF FIGURES

Figure Title	Page
<b>Figure 1.1:</b> Elements of Electrical Energy Management	2
<b>Figure 1.2:</b> The Population and Urbanization Growth Rate in Some Sub-Saharan Africa Countries	3
<b>Figure 1.3:</b> Comparison of Electricity Generation Trend in Different Region	4
<b>Figure 1.4:</b> Rural and Urban Access to Electricity in Developing Countries, 2002	5
<b>Figure 1.5:</b> Electricity Price in SSA	6
<b>Figure 1.6:</b> A Map of Sub - Saharan African Countries	6
<b>Figure 1.7 a:</b> Correlation Between Population Increase in Developed and Developing Countries	8
<b>Figure 1.7 b:</b> Correlation Between Energy Consumption in Developed and Developing Countries	
<b>Figure 1.8:</b> Type of Energy Used in the Plant	15
<b>Figure 1.9:</b> Electrical Energy Management- A Consumer Approach	15
<b>Figure 1.10:</b> Layout of Cement Plant	17
<b>Figure 2.1:</b> General Load Duration Curve of the Power Supply Industries	25
<b>Figure 2.2:</b> Industrial Load Management Arrangement	43
<b>Figure 3.1:</b> Energy Management Design Steps	55
<b>Figure 3.2:</b> Typical Energy Management Procedure	56
<b>Figure 3.3:</b> Major Stage of Energy Awareness Development	59
<b>Figure 3.4:</b> Electrical Energy Consumption in Different Processes in Cement Plants	65
<b>Figure 3.5:</b> Electrical Energy Consumption in Various Processes	65
<b>Figure 3.6:</b> Energy Model of A Cement Industry	66
<b>Figure 3.7:</b> The Layout of Electrical Energy System (Supply And Demand)	70
<b>Figure 3.8:</b> Equivalent Circuit of an Induction Motor	74
<b>Figure 3.9:</b> Energy Production And Consumption Output	75
<b>Figure 3.10:</b> Plant Load Profile of Week Days	76
<b>Figure 3.11:</b> Plant Load Profile When Cement Mill Was Not in Operation	77
<b>Figure 3.12:</b> The Comparison of Monthly Energy Consumption and Production for Two Consecutive Years 2007-2008	78
<b>Figure 4.1:</b> Load Shape Objective	83
<b>Figure 4.2:</b> Generation Situation in SSA from 1998-2006	86
<b>Figure 4.3:</b> Algorithm for the Development of DSM Program	89
<b>Figure 4.4:</b> Overall Eskom Generation, Transmission, Distribution and Sales	95
<b>Figure 4.5:</b> Demand Saving Achieved from the Period 2005 to 2008	96
<b>Figure 4.6:</b> Overview of Maintenance Energy Management Function	98
<b>Figure 5.1:</b> Efficacy Comparison of Light Sources for General Lighting	104
<b>Figure 5.2:</b> Composition of Power Losses in a Three Phase Induction Motor	108
<b>Figure 5.3:</b> Efficiency Vs % Load	112
<b>Figure 5.4:</b> PBP as aFunction of % Change of Operating Hour and Different Energy Charge Rate	112
<b>Figure 5.5:</b> Graphical Representation of the Positive and Negative Sequence Torques of an Induction Motor	114
<b>Figure 5.6:</b> Monthly Energy Performance Indicators of Mbeya Cement Industry	121
<b>Figure 5.7:</b> Regression Analysis Linear-Fit	123
<b>Figure 5.8:</b> Residual Vs Production	124
<b>Figure 5.9:</b> Energy Consumption Vs Production Analysis	124
<b>Figure 5.10:</b> Measured and Predicted Energy Consumption	125
<b>Figure 5.11:</b> The Comparison of EPI of the Measured and Predicted Value	127
<b>Figure 5.12:</b> Residual Versus Fitted Value	129
<b>Figure 5.13:</b> Normal Probability Plot	130
<b>Figure 5.14:</b> Simulation of Energy Consumption Model	130
<b>Figure 5.15:</b> Evaluation of Energy Performance Indicator	131

<b>Figure 6.1:</b> Plant Layout of the Industry	136
<b>Figure 6.2:</b> Equivalent Circuit of 3 Phase Synchronous Motor	138
<b>Figure 6.3:</b> Phasor Diagram of Synchronous Motor At Lagging Power Factor	139
<b>Figure 6.4:</b> Excitation System of Synchronous Motor	141
<b>Figure 6.5:</b> Main Block Diagram of Synchronous Motor Control	142
<b>Figure 6.6:</b> Relationship Between Current, Power, and Power Factor with Percentage Loading	146
<b>Figure 6.7:</b> Energy Cost Versus Annual Saving	151
<b>Figure 6.8:</b> PBP Vs Energy Cost	152
<b>Figure 6.9:</b> Energy Saving Vs Percentage Change of Operating Hours of Machine	153
<b>Figure 6.10:</b> Variation of PBP Vs Operating Hours of the Machine	153
<b>Figure 6.11:</b> PBP As A Function of Percentage Change of Operating Hour and Different Rate of Energy Charge	154
<b>Figure 6.12:</b> Schematic of a Generalized Secondary Battery.	159
<b>Figure 7.1:</b> Basic Capacitor Application Flow Chart	166
<b>Figure 7.2:</b> Capacitor Evaluation System	167
<b>Figure 7.3:</b> Capacitor Placement	168
<b>Figure 7.4:</b> Arrangement of Capacitor Connection in the Main Line.	168
<b>Figure 7.5:</b> Power Factor Correction of Using Synchronous Condenser	170
<b>Figure 7.6:</b> Schematic Diagram of Thyristor Switched Capacitor	172
<b>Figure 7.7:</b> Thyristor Switched Capacitor Configuration	172
<b>Figure 7.8:</b> The Thyristor-Controlled Reactor Configuration	173
<b>Figure 7.9:</b> Combined TSC And TCR	174
<b>Figure 7.10:</b> Power Triangle	176
<b>Figure 7.11:</b> The Relationship Between the Rating of Motor with its Annual Saving	182
<b>Figure 7.12:</b> The Relationship Between Motor Size, Power Factor and Penalty	184
<b>Figure 7.13:</b> Motor Efficient Analysis	184
<b>Figure 7.14:</b> Payback Period Analysis	185
<b>Figure 8.1:</b> Principles of Shunt Compensation in a Radial Ac System. A) Without Reactive Compensation And B) Shunt Compensation	189
<b>Figure 8.2:</b> Principle of Series Compensation with Voltage Source	190
<b>Figure 8.3:</b> The Basic Structure of STATCOM	193
<b>Figure 8.4:</b> The Overall System Load Under Difference Type of Compensation.	194
<b>Figure 8.5:</b> STATCOM Schematic Representation	195
<b>Figure 8.6:</b> Voltage and Current Characteristic of Under Varying Load (Lagging, Unit And Leading).	196
<b>Figure 8.7:</b> Six-Pulse VSI With Y-Connected	198
<b>Figure 8.8:</b> Voltage Waveform of the Inverter	199
<b>Figure 8.9:</b> Two Level Sinusoidal PWM, with a Single Phase Full Bridge	202
<b>Figure 8.10:</b> Equivalent Circuit	203
<b>Figure 8.11:</b> Real and Reactive Power in Steady State	208
<b>Figure 8.12:</b> Steady-State $i_q, v_{dc}$	209
<b>Figure 8.13:</b> Plant System Representation	212
<b>Figure 8.14:</b> STATCOM Configuration	215
<b>Figure 8.15:</b> STATCOM Main L Circuit	218
<b>Figure 8.16:</b> VSI Control Circuit	219
<b>Figure 8.17:</b> PSM Simulated Model	220
<b>Figure 9.1:</b> Hierarchical Control Pyramid and Levels of Control	225
<b>Figure 9.2:</b> Cement Plant Layout	230
<b>Figure 9.3:</b> Simplified Plant Model	231
<b>Figure 9.4:</b> Cement Production Sections	232
<b>Figure 9.5:</b> The Algorithm for Solving Optimal Load Scheduling Demand Management	237
<b>Figure 9.6:</b> Solving Constraint	238
<b>Figure 9.7:</b> Power Factor Correction Control Algorithm	241
<b>Figure 9.8:</b> Plant Process with Efficiency	242

<b>Figure 9.9:</b> Evaluation of the Use of Energy Management Technology (in rank)	245
<b>Figure 9.10:</b> CUSUM analysis of the cement plant	246
<b>Figure 9.11:</b> Cyclic Action of Energy Monitoring	247
<b>Figure 9.12:</b> The Overall Energy Management	248
<b>Figure 9.13:</b> Strategy for Electrical and Demand Management	249
<b>Figure 9.14:</b> Flow Chart of Strategic Energy Management	250
<b>Figure 10.1:</b> Layout of Simplified Coal-Fired Power Plant	255
<b>Figure 10.2:</b> Contribution of GHG Emission	260
<b>Figure 10.3:</b> Human Development Index Vs SSA Country ( 2004 Data)	265
<b>Figure 10.4:</b> Per Capita Electricity Consumption for The SSA Countries	265
<b>Figure 11.1-11.89:</b> Simulation Results	275-325

## LIST OF TABLES

Title	Page
<b>Table 1.1:</b> Industrial Sector Primary Electricity Demand	8
<b>Table 3.1:</b> The Percentage Energy Consumption in Typical Dry Process Portland Cement Plant	65
<b>Table 3.2:</b> Electrical Energy Information and Characteristics of Tanzania Power Network, 2008 Survey	76
<b>Table 3.3:</b> Loads and Electrical Energy Characteristic	73
<b>Table 3.4:</b> Main Plant Loads	75
<b>Table 4.1:</b> Benefits of DSM Programs Option	83
<b>Table 4.2:</b> Screening DSM Program	91
<b>Table 4.3:</b> Market-Based Barriers to DSM	92
<b>Table 5.1:</b> Use of Different Lighting System for Different Application	104
<b>Table 5.2:</b> Performance of T5 Fluorescent Lamp's Maximum Luminous Output	106
<b>Table 5.3:</b> Comparison of Luminance Between T5 and T8 Fluorescent Tubes	106
<b>Table 5.4:</b> Calculated Model Parameters	124
<b>Table 5.5:</b> ANOVA Results	127
<b>Table 5.6:</b> Summary of Regression Output	129
<b>Table 5.7:</b> Summary of Regression Coefficient	129
<b>Table 6.1:</b> Rating of Main Motors of the Case Study	138
<b>Table 6.2:</b> Results of Energy Saving Calculations	152
<b>Table 7.1:</b> Cost Comparison of Shunt Compensator	176
<b>Table 8.1:</b> Comparison of Basic Type of Compensator	192
<b>Table 10.1:</b> Percentage Value of Emission For Different Plant	265
<b>Table 10.2:</b> Mercury Emission from Electricity Use By Using Different Type of Lighting System	271

## LIST OF APPENDICES

<b>Title</b>	<b>Page</b>
<b>APPENDIX 1.1:</b> Electricity Generation in Sub-Saharan Africa	349
<b>APPENDIX 1.2:</b> Electricity Access and Electrification Rate in Sub-Saharan Africa	351
<b>APPENDIX 1.3:</b> Per Capita Electricity Consumption in Sub-Saharan Africa	352
<b>APPENDIX 1.4:</b> Common Manufacturing (Energy Intensive) Industries Existing in Sub-Saharan Africa, Year 2001--2002	353
<b>APPENDIX 2.1:</b> Industrial Production Growth Rate for Africa, 2008	355
<b>APPENDIX 3.1:</b> Industrial Loads Estimation	356
<b>APPENDIX 5.1:</b> Share of Electricity Generation by Source	357
<b>APPENDIX 5.2:</b> Historical Data for Regression Analysis	358
<b>APPENDIX 7.1:</b> Monthly Electricity Consumption, Year 2008	359
<b>APPENDIX 7.2:</b> Monthly Production Year 2008	360
<b>APPENDIX 9.1:</b> CUSUM Parameter Calculation	361
<b>APPENDIX 9.2:</b> Survey Results	362
<b>APPENDIX 10.1:</b> Trend of Population Increase	364
<b>APPENDIX 10.2:</b> SSA Carbon Dioxide Emissions Per Capita Generated by Country Year-2004	365
<b>APPENDIX 10.3:</b> GDP of African Countries by Rank (2008 )	366

## LIST OF ABBREVIATIONS

<b>Abbreviation</b>	<b>Explanation</b>
Btu	British Thermal unit
CFL	Compact Fluorescent Lamp
CLG	Controlled Load Group
CO <sub>2</sub>	Carbon Dioxide
CUSUM	Cumulative Sum
DFP	Displacement Power Factor
DLC	Direct Load Control
DSM	Demand Side Management
EAP	East Asia and Pacific
ECA	Eastern Europe and Central Asia
EE	Energy Efficiency
EEM	Electrical Energy Management
ELM	Electrical Load Management
EM	Energy Management
EMC	Electromagnetic Compatibility
EMF	Electromagnetic Fields
EMTDC	Electromagnetic Transients including DC
EPRI	Electrical Power Research Institute
ESCO	Energy Services Company
Eskom	Electricity power Supply Company South Africa
FACTS	Flexible AC Transmission Systems
FC-TRC	Fixed Capacitor-Thyristor Controlled Reactor
GDP	Growth Domestic Product
GWh	Giga watt-Hour
GEF	Global Environmental Facility
GHG	Greenhouse Gas
GTOs	Gate Turn On
HV	High Voltage
IGBTs	Insulated Gate Bipolar Transistors
IPP	Independent Power Producer
IRP	Integrated Resource Planning
KVA	Kilovolt Ampere
kWh	Kilowatt- Hour
LAC	Latin American and Caribbean
LM	Load Management
LV	Low voltage
MD	Maximum Demand
MDT	Maximum Demand Target
NA	Not Applicable
NAMPOWER	Namibia Power Supply Company
NERSA	National Electricity Regulatory South Africa
OECD	Organization for Economic Co-operation and Development
PF	Power Factor
PFC	Power Factor Correction
PI	Proportional Integral
PSCAD	Power Systems CAD
PSI	Power Supply Industry
PWM	Pulse-width Modulation
RMS	Root Mean Square
SAPP	South African Power Pool
SAS	South Asia
SSA	Sub-Saharan Africa
STATCOM	Static Synchronous Compensator

TANESCO	Tanzania Electricity Supply Company
TEC	Total Energy Consumption
TDT	Time Dependant Tariff
TFP	Total Power Factor
TOU	Time of Use Tariff
TPCC	Tanzania Portland Cement Company
TRC	Thyristor Controlled Reactor
TSC	Thyristor Switched Capacitor
UPS	Uninterruptible Power Supply
US	United States
VSD	Variable Speed Drive
WAPP	West African Power Pool
WEC	World Energy Council
ZESCO	Zambia Electric Supply Company

## GLOSSARY

<b>Actual Peak Reduction</b>	The actual reduction in annual peak load achieved by consumers.
<b>Average Demand,</b>	The demand on an electric system over any interval of time or over a period of time and is determined by dividing the total number of kilowatt-hours by the number of units of time in the interval.
<b>Capacity</b>	The load for which a generating unit, generating plant or other electrical apparatus is rated either by the user or by the manufacturer.
<b>Customer Charge</b>	An amount to be paid periodically by a customer for electric service based upon costs incurred for metering, meter reading, billings, exclusive of demand or energy consumption.
<b>Demand</b>	The rate at which electric energy is delivered to or by a system, part of a system or a piece of equipment.
<b>Demand Charge</b>	The part of the charge for electric service based upon the electric capacity (kW) consumed and billed on the basis of billing demand under an applicable rate schedule.
<b>Demand-Side Management</b>	A term used to describe a variety of programs initiated by utility companies or regulator to encourage customers to modify their energy use. In general, DSM programs are designed to reduce demand or to modify patterns of demand as an alternative to adding new capacity.
<b>Direct Load Control</b>	A direct action by the utility to shift load to off-peak time, either by a programmed computer command or by manual implementation of remote control.
<b>Efficacy Lighting</b>	The ratio of light from a lamp to the electrical power consumed, including ballast losses, expressed as lumens per watt.
<b>Electric Utility</b>	A legal entity engaged in the generation, transmission, distribution, or sale of electric energy, primarily for use by the public; legally obligated to provide service to the public within franchised area.
<b>Electrical System Energy Losses</b>	The amount of energy lost during generation, transmission and distribution of electricity.
<b>Emission Standard</b>	The maximum amount of a pollutant legally permitted to be discharged from a single source.
<b>Emissions</b>	Releases of greenhouse gases into the atmosphere that are caused by human activity.
<b>End Use</b>	A use for which total input energy for heat, power and electricity generation is consumed at the manufacturing establishment.
<b>End-Use Sectors</b>	The residential, commercial, industrial and transportation sectors of the economy.

<b>Energy Charge</b>	The amount of money owed by an electric customer for kilowatt-hours consumed.
<b>Energy Conservation</b>	Activities that reduce end-use demand for energy by reducing the service demanded.
<b>Energy Efficiency</b>	Percentage of total energy input to a machine or equipment that is consumed in useful work and not wasted as useless heat.
<b>Energy Security</b>	The ability of the supply system to supply energy that meets demand at a price that protects economic growth.
<b>Energy Service Company (ESCO)</b>	A company that offers different techniques and support to reduce a client's electricity consumption with the cost savings being split with the client.
<b>Energy Source</b>	A substance, such as natural gas, coal or oil that is consumed in generation of heat or power.
<b>Energy, Off-Peak</b>	Energy supplied during periods of relatively low system demand as specified by the supplier
<b>Energy, On-Peak</b>	Energy supplied during periods of relatively high system demand as specified by the supplier.
<b>Flat Rates</b>	The price charged per unit is constant; it does not vary due to an increase or decrease in the number of units.
<b>Independent Power Producer (IPP)</b>	An entity, which is not a public utility, but owns facilities to generate electric power for sale to utilities and end users.
<b>Interruptible Load</b>	DSM program activities that, in accordance with contractual arrangements, can interrupt consumer load at times of seasonal peak load by direct control of the utility system operator or by action of the consumer at the direct request of the system operator.
<b>Load Curve</b>	A curve showing power (kilowatts) supplied against time of occurrence.
<b>Load Shifting</b>	Involves shifting load from on-peak to off-peak periods.
<b>Maximum Demand</b>	The greatest demand that occurred during a prescribed demand interval (15 minutes) in a calendar year.
<b>Missing voltage</b>	Is the difference between the nominal voltage and the actual voltage.
<b>Power, interruptible</b>	Power made available under agreements that permit curtailment or cessation of delivery by the supplier.
<b>Time of Use Rates</b>	Prices for electricity that vary depending upon what time of day a customer uses it.
<b>Regulated Utility</b>	Utilities distinguished as being a class of business affected with a deep public interest and therefore subject to regulation.

## **CHAPTER ONE: Introduction**

### **1.1 Background**

Electrical energy is an important resource for economic development of all regions around the world including Sub - Saharan Africa (SSA). Electrical energy is mainly consumed in industrial, commercial, agricultural, transport and household sectors. In developed countries, the industrial sector consumes more energy than any other sector. In Sub-Saharan Africa, the industrial sector consumes about 30% of the electrical energy generated.

Cement industries are considered as among energy intensive industries in SSA. Thirty percent of total input costs of the cement industries are contributed by electrical energy consumption. The raw mill and cement mill sections are the biggest electrical energy consuming sections in cement industries. The industries also consume a tremendous amount of thermal energy in its production process. The need for cement product in the commercial and individual entities causes the increase of construction of cement industries, hence energy requirements to sustain those industries also increases.

There are no clearly defined methods of electrical energy management in cement industries. The only method used to manage electricity demand is the fixed capacitor banks power factor correction technique. Therefore, it is for this reason that it is required to develop the appropriate techniques and strategies for the management of electrical energy in the cement industries in Sub-Saharan Africa.

### **1.2 The Need for Electrical Energy Management in Sub-Saharan Africa (SSA)**

The strategies for adjusting and optimizing energy using systems and procedures so as to reduce energy requirements and consumption per unit output is called energy management. The amount of electrical energy consumed in any country around the world has a close relationship to the economic development of the respective country. Moreover, reliable and affordable energy is a fundamental step towards sustainable development and poverty reduction. It is measured in terms of availability, flexibility and reliability of electricity.

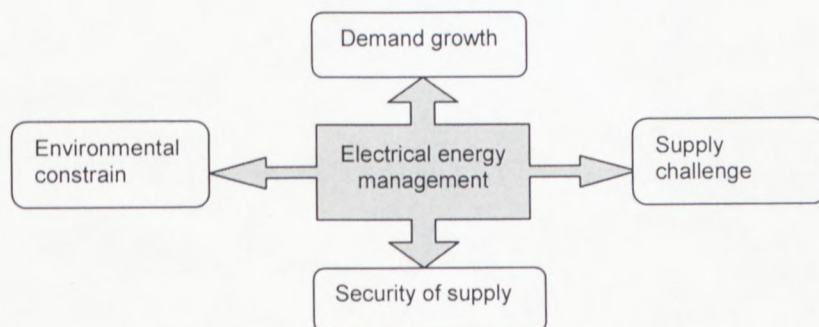
Davidson, (2002) defined a sustainable energy as the availability of affordable and accessible reliable energy that meets economic, social and environmental needs within the overall development context of the society for which the services are intended, while recognizing equitable distribution in meeting those needs. Whereas

Nkomo, (2007) emphasized that, the sustainable energy must be socio-economically viable and should meet local and global environmental standards.

There are many forms of energy, but electrical energy is a fundamental basis for the development of human activities and industries, which are associated with aspects of the social production and daily life. The economical development of many SSA countries depends mainly on agriculture, small business activities and industrial development, of which largely depends on electrical energy.

The process of electrical energy generated and consumed involves several steps of which are inefficient, for example the efficiency of fuel combustion power plant is about 40 percent (Fossil fuel power plant, 1985). The inefficient use of energy has adverse effect in social, economic activities of the country and to the local, regional and global environment. The gap between energy supply and demand in Africa has been growing and projected to grow further and make the livelihood of most Sub-Saharan Africa continue to be critically impaired by energy poverty. This slows down the social economic development of the continent (Energy for sustainable development policy, 2004). In this case, energy management can be considered as a key driver of energy future.

Energy management is a program designed and implemented on the supply side or the demand side, aimed at meeting demand growth, supply challenges, energy security and environmental standard. Figure 1.1 shows four elements of electrical energy management.



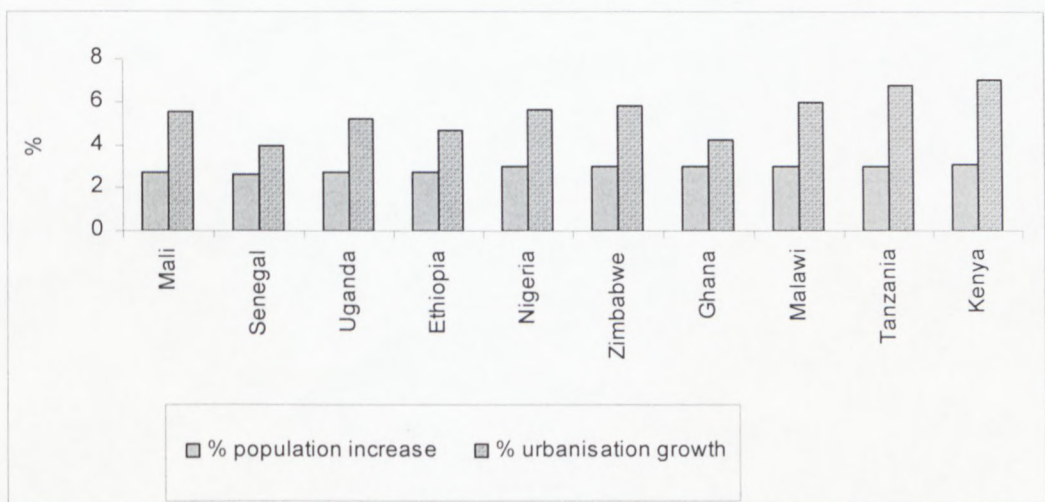
**Figure 1.1:** Elements of Electrical Energy Management

The fundamental goal of electrical energy management in industries is to consume less energy in its production processes without affecting the production quantity and quality with minimum environmental effects. This leads to the least cost of production.

### 1.3 Energy and Industrial Overview in Sub-Saharan Africa

#### 1.3.1 Energy Overview

Sub-Saharan Africa (SSA) comprises of 47 countries, with land coverage of  $24.3 \times 10^6$  Km<sup>2</sup>. It has 12% of the total world population; two- third of them live in rural areas. The region consumes 2.7% of world commercial energy (Sokona, nd). The trend of electricity generated is low compared to the population growth. This has been shown in Appendix 10.1. The urbanization growth rate in Sub-Saharan Africa also has a highest value and the number is estimated to double the national population growth rate. Figure 1.2 shows the urbanization and population growth rate of some countries. The rapid growth of population in large urban capitals/cities increases electricity demand in the system for the respective capitals or cities (Karekezi & Majoro, 2002).

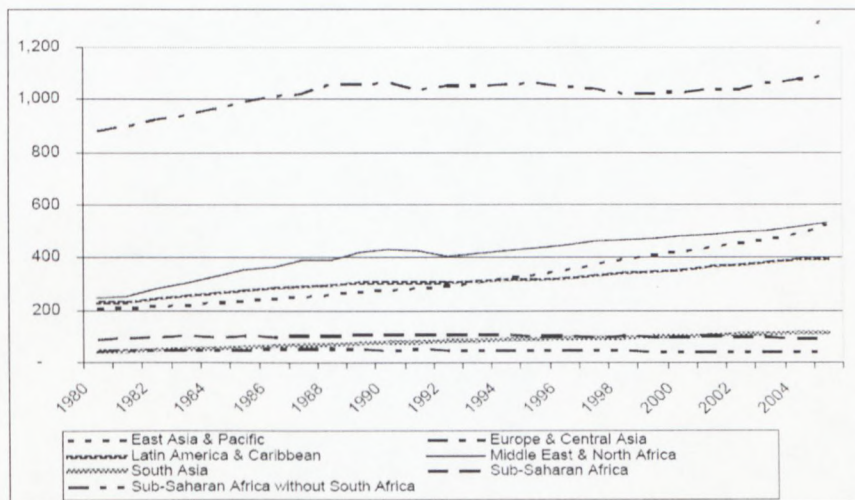


**Figure 1.2:** The Population and Urbanization Growth Rate in Some Sub-Saharan African Countries.

The Power sector of the Sub-Saharan Africa is starkly underdeveloped compared to that of other world regions. Although the region has extensive primary energy resources for power generation, it has the world's lowest levels of access to electricity consumption, Appendix 1.2. Only an average of 24% of SSA population has access to electricity (EIA, 2004). The region generates 68 GW in total. Without South Africa, the amount reduces to merely 28 GW (EIA, 2005). This capacity has remained largely stagnant during the last three decades; as a result, the energy production and consumption gap between Sub-Saharan Africa has widened (Yepes et al., 2008) as shown in Figure 1.3.

The disparities on the capacity generated among countries in the region are quite significant (EIA, 1999; Batidzirai et al., 1998), for example, in 2004 South Africa produced 227.24GWh of electricity compared to most countries in the region that generated less than 1 GWh, Appendix:1.1.

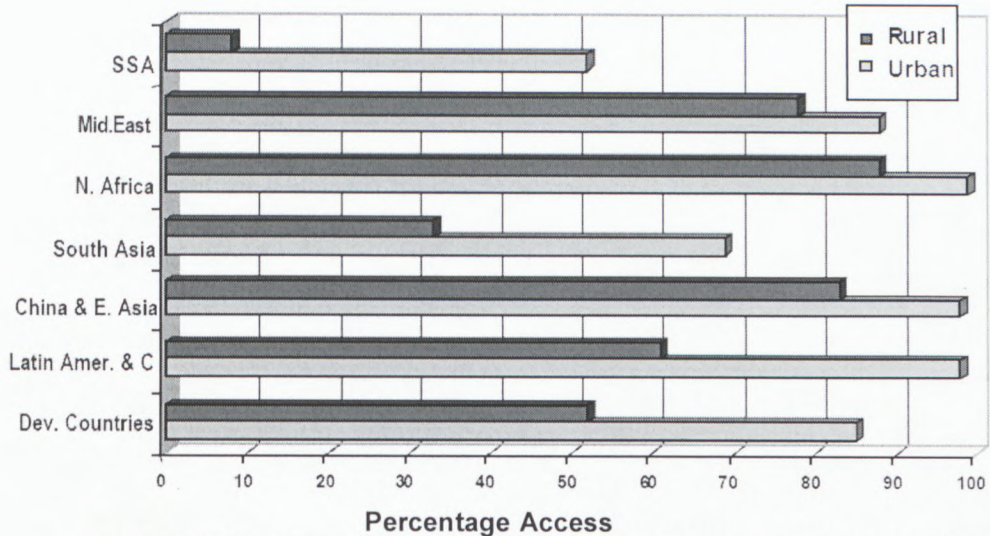
The electrical energy pattern of the region also shows that the SSA countries electrification level is low compared to many regions (International trade commission report, 2007). The overall electrical energy access levels in Sub-Saharan Africa is declining and projected to about 40 percent the population of all African countries by 2050 (Banerjee et al., 2008). The current access rate per individual country is given in Appendix 1.2.



**Figure 1.3:** Comparison of Electricity Generation Trend in Different Regions (MW per million inhabitants)

**Source:** Compiled by Authors from EIA, 2005, and World Bank, 2007a.

The average per capita electricity consumption of SSA countries is 457 kWh. If South Africa is excluded from the group, the per capita consumption reduces to 124 kWh (World Bank, 2005). In contrast, the annual average per capita consumption in the developing countries is 1,155 kWh and 10,198 kWh for developed countries. The per capita electricity energy consumption is depicted in Appendix 1.3. Appendix.1.1 shows the trend of electricity generation in SSA countries (1992-2004), (EIA, 2006). The poor electricity infrastructure in SSA countries rural areas, limit the availability of electricity grid network and hence lower electricity accessibility rate. The percentage access rate of electricity in rural and urban area is shown in Figure 1.4.

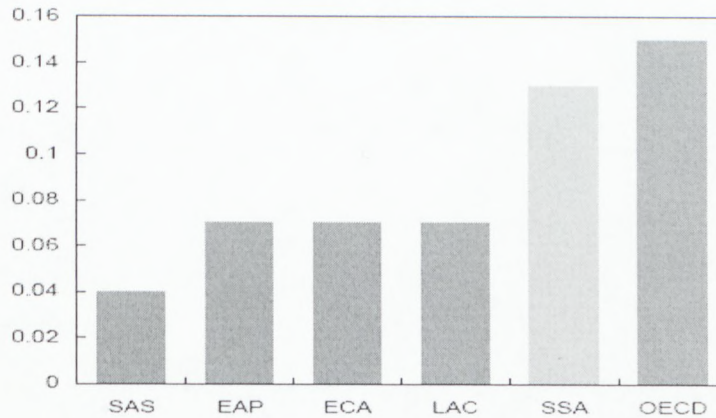


**Figure 1.4:** Rural and Urban Access to Electricity in Developing Countries, 2002  
 Source: IEA, 2004

The issue of increasing access to electrical energy to the population is very crucial. However, this is inhibited by lack of fund, poor infrastructure and limited energy resources (IEA, 2004). The small existing amount of electricity generated is therefore combined with the increased need for the electrical energy in various sectors especially industry. This calls for more electrical energy requirements in the region, and can be resolved by either increasing new generation, transmission and distribution system.

The issue of increasing generation has been facing chronic lack of funding and little interest of investors and financial institutions and has adverse environmental effect. The remaining option is to reduce energy consumption without compromising the performance of the respective services; hence the idea of construction of new power plants can be deferred by the application of electrical energy management. It is the cheapest way of improving the capacity of power supply industry (PSI). In addition, the importance of introducing electrical energy management in both industries and utilities is due to high price of electrical energy compared to international standards. The average power tariff of \$0.13 per kWh is around twice that found in other parts of the developing world as shown in Figure1.5. This comparison is presented in the World Bank's Investment Climate Assessments (World Bank, 2007).

Hence, this research recommends SSA countries to implement electrical energy management at all levels of power consumption (demand side) so as to minimize power consumed by the end user and improve the performance of power supply industries as well as mitigating the negative environmental impact caused by inefficient use of energy. Figure 1.6 shows the countries in SSA region.



**Figure 1.5:** Electricity Price in SSA  
**Source:** Ebenhard et al., 2008

The electricity demands of many SSA countries are higher than the generation capacity, this leads to reduction of the reserve margin. To cope with these shortages, some utility companies of the countries run standby power plant during peak period which is expensive and environmental threatening (Ebenhard et al. 2008). Hence the viable option is to use energy management techniques for the reduction of peak demand consumption. The peak demand period of the most utility companies of SSA countries occurs twice a day; morning and afternoon while the remaining periods are related to off peak period (Motoka, 2005).



**Figure 1.6:** A Map of Sub - Saharan African Countries

Under this circumstance demand control strategies may be used to achieve the demand or load management, while energy consumption control can be achieved by the use of energy efficient technology. Utility industries can use several techniques to influence the reduction of electric energy consumed.

Demand side management is one of the strategies proven to reduce energy stress to the system. Gelling (1992) researched implementation of demand side management (DSM) objectives in manufacturing industries and found that, there is a possibility of saving money on the demand side as well as the utility industries enjoy the stability and economical performance of the company.

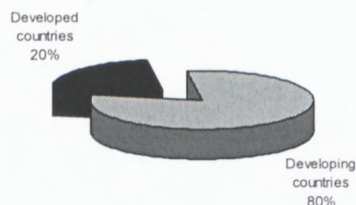
The aim of this research is to develop techniques to be used to optimize power consumed in cement manufacturing industries. Introduction of electrical energy management in manufacturing industries has the following benefits:

- Improve profits to the industries
- Enhance efficient productivity
- Protects environment
- Improve the reliability of the power supply industry and engender energy security

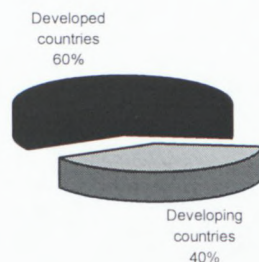
### **1.3.2 Comparison of Africa and Global Electricity Profile**

The energy sources which currently contribute to electricity generation (global) are: coal (36%); oil (9.3%); gas (14.8%); hydro (20%); nuclear (17%); biomass and other renewable sources including geothermal, wind and solar (1.4%) while the share of sources for electricity production in SSA is coal 66.6%, hydro 13%, petroleum 4.9%, and gas 4.3%, nuclear 3.5% geothermal is 0.2% and the remaining sources is 7.5% (UNDP, 2004). Coal has remained steady resource for the world's electricity generation, while hydro generation has been slightly declining during the drought period. At present, wind energy is the fastest growing generation option in terms of its share, but remains small in total power contribution. It offers the greatest short and medium term potential (Eberhard et al., 2000).

The relationship between the population growth rate and energy consumption rate between developed and developing countries is shown in Figure 1.7 a, and b. In this Figure, it is observed that, the relationship between population growth and energy consumption in the developed and developing countries does not follow similar trends. For example, the population growth in developed countries is 20% while the energy consumption rate is 60% of the world average, whereas in developing countries the population growth is 80% and the energy consumption rate is only 40%.



**Figure 1.7 a:** Correlation Between Population Increase in Developed and Developing Countries



**Figure 1.7 b:** Correlation Between Energy Consumption in Developed and Developing Countries

### 1.3.3 SSA Industrial Profile

Globally, industries consume more than 40% of the total commercial energy (Price, 2008). The large number of manufacturing industries and high energy consuming activities has been threatening cleaner and sustainable energy competitiveness. The vulnerability to the rapidly increasing electricity price, environmental concern and the issue of energy security are the drivers for improving industrial electricity efficiency (Jamashb and Pollit, 2006). The projection of electricity demand by the year 2050 is given in Table 1.1.

**Table 1.1:** Industrial Sector Primary Electricity Demand

	1971 EJ	2000 EJ	2050 EJ	Increase 1997-2000 %	Increase 2000-2050 %
Pacific OECD	2.49	4.92	7.04	2.4	0.7
North America	6.43	11.59	13.8	2.1	0.3
Western Europe	5.71	7.3	17.71	0.9	1.8
Latin America	0.773	2.89	22.37	4.9	4.2
Sub- Sahara	0.67	1.34	25.03	2.4	6.0
Middle East and North Africa	0.19	1.39	53.01	7.0	7.6
World	22	47.85	273.49	2.6	3.5

**Source:** Price et al., 2005

Industrial development needs stable and reliable electrical supply for steady production processes. The stability of electrical energy system in most Sub-Saharan African countries depends on generation plants and power system (Transmission and distribution systems) and that to large extent faces problems such as lack of funds for regular maintenance, high transmission power loss, insufficient electrical energy generation and high system voltage drop.

Energy cost accounts for a significant portion of the production cost. The high amount of energy consumption and the respective demand drawn by the loads, in combination with the high price of the electricity have a big impact in determining the price of the product due to the increase of the overhead costs. If proper management measures are not taken, there would be an increase in production cost of the plant.

Proponents of industrialization in Africa use a proposition which gives more weight to the industrial development than other sectors of development especially in the long run. Kapunda, (2005) presented the problem facing SSA countries industrial growth, such as high production costs and unstable and unreliable electrical energy supply but he also mentioned the importance and advantages of industrial growth as:

- Diversification away from the primary sector towards manufacturing reduces risks and vulnerability to the long-term deteriorating commodity terms of trade and the associated loss in real income.
- Industrial sector has more forward and backward linkages with other sectors especially agriculture and mining.
- Industrialization contributes significantly to employment creation if the right technique is chosen.
- Industrialization has relatively great possibility to technology transfer and adaptation of new technology. It also ensures economic independence.

Fred, (1999) explained the African industrial structure that, it is characterised by a dualistic structure with a large number of informal and small scale enterprises co-existing with a small number of relatively large scale modern plants and few linkages between them. Although SSA is not an industrialized region, each country has a number of industries that require attention when it comes to energy matters. The common industries existing in SSA countries are listed in Appendix 1.4.

The industrial sector can be divided into the energy intensive industries and non energy intensity industries. The energy intensive industries in Sub-Saharan Africa like cement, mining and iron manufacturing, are those industries that consume large amount of heat and electricity.

The industrial sector in SSA consumes large amount of energy in production processes. This is caused by the nature of industrial loads and inadequate energy management skills and techniques. In addition the electricity tariff structure in most SSA countries (industrial tariff) is the two part tariff that is, (\$/KVA) and (\$/kWh). The rates are fixed despite time of consumption.

The high consumption and cost of electrical energy raise the production costs; hence the price of the manufactured products is also increases, and these results into minimization of purchasing flow which influences loses of revenue to the industry and Government. This also leads to loss of employment opportunities and increases poverty among SSA people.

On account to the mentioned problems, the need for electrical energy management programs and strategies in industries is overemphasized. This reduces energy consumption; hence improve performances of industries, utility companies as well as government, due to the following reason:

- Reduction of electric bills,
- Improve revenue situation, (industry, government)
- Safeguard the power system
- Create / improve employment opportunities which contribute to poverty eradication.

In this study energy management case study was undertaken in cement industries due to the following:

- Cement plant operation process requires stable and reliable power supply. Any power interruption leads to kiln stoppage resulting in loss of production and additional fuel consumption is needed to attain requisite thermal profile. Hence, it is important to use the existing energy very efficiently so as to improve the reliability of the power supply system.
- Cement industries are among bulk users of electricity in SSA, therefore small efforts can result in huge saving.
- Cement industries are the most common industries and they exist in almost all countries in SSA, therefore management of electricity in cement industry case study will represent all SSA cement industries.
- Most industrial loads have the same types of loads and characteristics (Motors, industrial lighting). Development of the load management for one industry can be easily modified and used in another industry. The general cement plant layout is shown in Figure 1.10.

In this research, electrical energy management (EEM) in industries is presented; the main aim is to reduce electrical energy consumption in industries. By doing so, the performance and reliability of electrical energy in PSI is also improved.

## 1.4 Statement of the Problem

The industrial sector constitutes a big part of electrical load of the power system and it demands and consumes more electrical energy than the loads in other sectors. Due to the nature of industrial loads and their processes and insufficient energy management skills, industries consume large amount of electrical energy for their production process. High energy consumption causes industries to spend more money on purchasing electrical energy, consequently, increasing the running cost. In addition, high electrical energy consumption increases requirement for more electrical energy capacity, in which the most common solution focuses on the increase of new power generation which is more expensive and a threat to the environment as most of peak power plant use oil or coal fired technology.

The research intends to provide techniques which can reduce energy consumption and control the maximum demand (capacity) of the industries while maintaining the production quality and quantity.

Based on the stated main problem, the specific sub problems pertaining to industrial energy consumption include:

- **Tariffs;** the industrial tariff structure of most SSA countries does not encourage end user to participate in energy management (two part tariff). Only few countries implement the TOU or time dependant tariff.
- **Poor housekeeping;** inefficient techniques and inefficiency use of energy cause loss of electrical energy.
- **Demand controller;** inadequacy of proper system for controlling the maximum demand leads industries to pay the penalties for the maximum demand consumption.
- **Metering;** metering and accuracy of measurement and error in metering due to aging or other cause can cause industries to pay more for energy which is not utilized.
- **Maintenance;** inadequacy of maintenance strategies in many industries cause energy losses.
- **Energy efficiency standards;** lack of energy performance indicators, energy management strategies and energy policy, industries do not set a benchmark value of specific energy consumption.

Based on the mentioned problem statement, this research intends to come up with appropriate methods, tools and strategies that can be used for electrical energy management in Sub-Saharan manufacturing industries (cement industries).

Maximum demand control, use of flexible power factor correction for reactive power control, use of energy efficiency techniques and behavioural change (housekeeping) are proposed. These have an influence in strategic conservation as mentioned in DSM concept (Gelling, 1992). In addition the strategies for electrical energy management will be developed to ensure sustainability of the energy management program in industries. Numerical and computational methods using MATLAB /Smulink, Excel, Motor master and PSIM software are used in this study.

## **1.5 Purpose of Study**

The aim of this study is to investigate the use of electrical power in industries in terms of load characteristics, actual demands and production cycle in order to find out the possibilities for industries to adopt energy management techniques so as to reduce the amount of energy utilized by industries. The purpose of the study is to develop effective methods and strategies that can be used as tools for electrical energy management in Sub-Saharan Africa manufacturing industries. This initiative minimizes the power consumed by industrial consumers hence reduces the energy related cost.

## **1.6 Objectives of the Study**

Cement industries are among the important industries in SSA; this is due to the significance of cement product in commercial, industrial and household use. As the population grows the demand of cement also increases, and it dictates to increase number of industries. At present, South Africa and Nigeria alone have 11 and 8 cement industries respectively and many countries in SSA have more than 2 industries as shown Appendix 1.4.

The primary objective of this research is to devise mechanisms (tools and strategies) that can be used to minimize the amount of power consumed/ purchased by manufacturing industries (cement). This might lead to reduction of money spent on purchasing energy and improves the reliability and stability of PSI of SSA countries.

### **1.6.1 Specific Objectives**

- To analyze loads characteristics of the selected industries.
- To analyze potential options for Demand Side Management (DSM) in selected industries.
- To analyze potentials and develop strategies for the improvement of existing energy efficiency technology used in selected industry.
- To analyze the range of power factor (PF) and the correction methods used in the selected industries and introduce high efficiency PF improvement methods.
- To develop strategies for maximum demand monitoring and controller.

## 1.7 Significance of the Research

The significance of electrical energy management in the industrial sector is its ability to manage the consumption of electrical energy in industries via demand and energy management. The importance of the proposed demand control method is its possibility to reduce the cost caused by maximum demand and high energy consumption. It also minimizes the need for industries or utility industry to install new demand meters for supporting EEM like Eskom Megaflux by which its implementation need legislation process and replacement of all metering system which is costly.

Unlike other types of load control practiced in many industries, the proposed load management technique is more efficient, since production characteristics are the governing factors which must be observed in the development of the energy management program. Therefore, through the proposed method, industries are likely to benefit on efficient consumption of electrical energy and spend less money for purchasing electrical energy, thereby improve production. In addition, the utility industries benefit from reduction of peak demand cost by industrial load management program instead of creating or developing their own programs.

At Regional level, electrical energy management is a key driver for clean environmental initiative. This is because it minimizes carbon dioxide emission generated during the power plant operation, hence reduce global warming impact.

## 1.8 Motivation for the Research

- The amount of electrical energy generated and consumed in developed countries is higher than that generated and consumed in developing countries. The generation situation is even worse in SSA, where 800 million people live. This small amount of electrical energy generated should be used efficiently.
- Cement industries consume high amount of electrical energy for the production of cement compared with best practice standards. This contributes to the increase in production cost.
- Methods used for controlling the demand are traditional, despite change of technologies mostly in the control system. For example converters for varying speed of the motors, this make the composition of loads to have none linear loads characteristics, but the methods for power factor correction remains mechanical switched capacitor bank. Therefore, alternative and effective methods are needed.

- Many methods used for EEM are utility based initiatives and mainly manually controlled. These either depend on influence of tariff structure or direct load control.
- There is neither a specific tool for LM or LM strategies in many SSA countries.
- DSM programmes are not yet developed in many SSA utility industries.

The implementation of energy management techniques will enhance a considerable amount of energy saving which might be supplied to other customers.

### 1.9 Research Questions

- Does the use of electrical energy management techniques, tools and strategies in industries minimize electrical energy consumption and reduce the level of electricity demand in the industry?
- Can the flexible power factor correction (STATCOM) connected in the industry play a role in managing reactive power under variable plant load?
- Can the implementation of electrical energy management in the industrial sector improve the reliability of electrical energy supplied by the utility industry?
- How does inefficient consumption of electrical energy play a role in environmental degradation?

### 1.10 The Scope and Limitations of the Study

Thermal and electricity are the common forms of energy that are used in the industrial sector. This research focused only on the electrical energy side as shown in Figure 1.8. Energy management in industries was introduced in order to ensure sustainability of energy in industrial sector. In this study, energy management focuses on electrical energy management in industries. Figure 1.9 shows different forms of energy management.

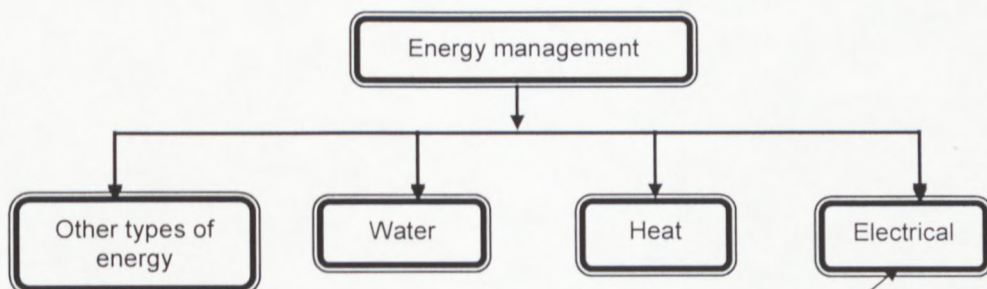


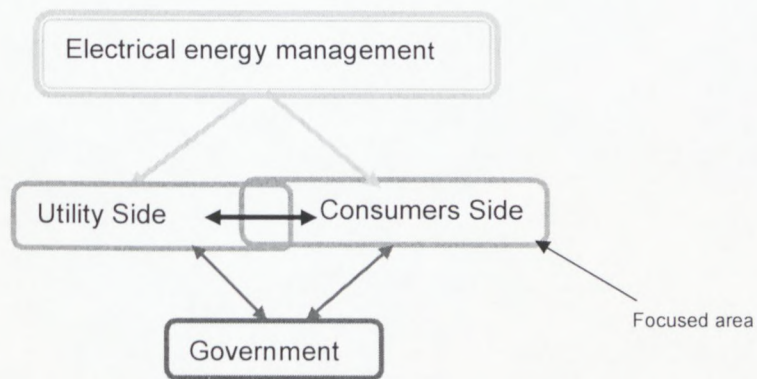
Figure 1.8: Types of Energy Used in the Plant

Focused area

The term electrical energy management in both consumer and demand side is seen as the management of kWh only. In this research this term is referred to the management of energy (kWh) and demand (KW or KVA). In other words the term energy refers to different forms of energy (heat, mechanical, thermal and electrical). In this research, whenever the word energy management is used it means “Electrical energy management” (EEM).

In general, in many countries, the initiative of electrical energy management planning, development and implementations is motivated by three main areas:

- The utilities interest ,
- Consumers interest, such as industrial, commercial, residential and
- Government interest



**Figure 1.9:** Electrical Energy Management Correlations

The energy management in this research is based on the consumers, specifically, the industrial sector as shown in Figure 1.9. The benefit of introducing energy management in this sector can be realized by the utility industries as well as satisfy the government interest.

Electricity utilities have many reasons that cause them to participate in energy management programs including reduction of peak demand, insufficient power generation and environmental pressure. In general, utilities have significant resources (financial, human capital) to easily establish energy management programmes, but most of SSA countries; utility industries (with the exception of South Africa) have not developed any EEM program such as the DSM program despite the scarcity of electrical energy generated in these countries. This might be due to lack of resources or inadequate studies which show the importance of EEM including DSM. On the consumer's side, industries have been participating on energy management

programs because of their tendency to consume high amount of electrical energy and its relative high cost resulting in increase of running cost.

### 1.11 Assumptions

Energy management initiatives are done on the demand side. The developed energy management system is adequate for both vertical integrated or deregulated energy system. In many Sub-Saharan African countries, the industrial tariff structures are of the two part tariff. The rates for energy and demand are fixed at all time. In some utility companies, the rate varies according to the amount of consumption. In this study, two part tariff based structure is used (industrial rate).

Most of the plants have fixed capacitor banks for power factor correction. The research covers SSA countries but most of the data and information is taken from Tanzania, South Africa, SAPP and WAPP as case study.

The reason for considering these countries in a case study is: Tanzania is among the countries characterised by low energy pattern in terms of electrification, capacity and low per capital electricity consumption. Electricity supply industry is a vertical integration and has not yet developed a DSM programme for energy management programme. Tanzania represents the countries that generate less than 3 GW.

South African electricity industry is amongst the prominent utility industry worldwide. It has many programs for electrical energy management including the DSM program. It generates about 40GW. Its generation capacity is comparatively high and serves the country with high per capita energy consumption. SAPP and WAPP are regional power pool for Southern Africa and Western Africa respectively. Considering their importance or relevance, these two countries and regional power pools give an approximate information and data that is used in the organization of this research and the energy management over view for all Sub-Saharan African countries.

Over 70% of energy consumed in industries is utilized in motor system. The size and rating of motors differ depending on the driven loads. One of the big concerns of the motors is the inrush current developed at the instant of starting. Although, the starting action takes a short period, the current drawn has impact in raising the maximum demand. If many big motors are started at the same period, the maximum demand rises to a high value. To overcome this problem, motors are either started in a proper sequential order and or by the use of current limiter. This research assumes that, the starting methodology has already been taken care of.

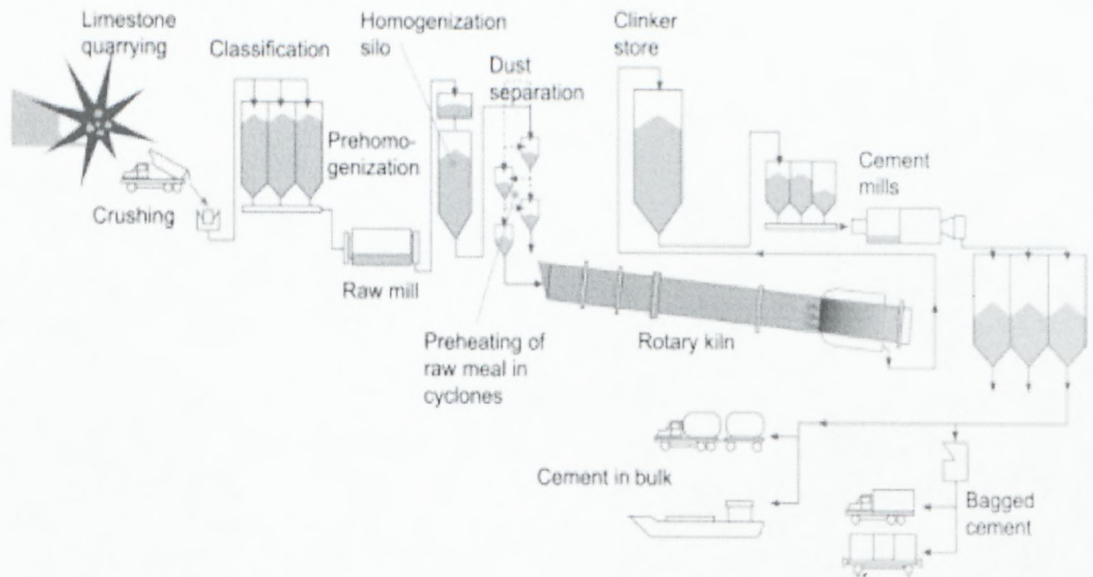


Figure 1.10: Layout of a Cement Plant

## 1.12 Outline of the Chapters

Chapter one presents the introduction of the whole thesis. The background, statement of problem, objective and significant of this research has been presented.

Chapter two presents the brief overview of the electrical energy management (EEM) techniques carried out on the power supply side and demand side. The result of the review showed that, many methods of load management developed in the utility industries worldwide have not been practiced in SSA, for example, DSM has been developed in few countries. Load shedding is the most commonly used method of load management for peak demand reduction; it is used in case power crises in the supply system. In the industrial sector, the use of capacitor banks for power factor correction is a commonly used load management technique.

Chapter three presents energy management principles and study of energy consumption in different sections in cement industries. It involves the element required for achieving strategic energy management. It also incorporates energy accounting and auditing in order to get a clear picture on how electricity is consumed in the different section. Energy conservation and good housekeeping measures are mentioned as initial and important energy management methods in cement industries. Finally, the Chapter shows data collection results which involve high energy consuming loads, total plant energy consumption and production data.

Chapter Four presents the DSM program, its role and the possibilities that can influence electrical energy management in the manufacturing industries. As it was

introduced, many utility industries in SSA do not have such kind of program. This chapter introduce how the DSM program is formulated and how it may be integrated to the manufacturing industry. The objectives and component of DSM, tool for assessing and implementing DSM options in industries is presented in the case study. The experience of other developing and developed countries DSM program is also elaborated in order to get the strong argument on how DSM programs are interlinked with electrical management.

Chapter Five analyses the potentials of energy efficiency technologies existing in cement industries. Energy consumption model was developed and techniques for the development of performance based indicators were also demonstrated. The possibility of adopting energy efficient technologies in different sections in the cement industries was highlighted. Energy efficient indicator is compared with best practice value in order to know how much electrical energy can be saved. A technique for the development of energy consumption benchmarking was developed.

There are many mechanisms that can be used for energy management; however, this study concentrates on a few of them. Other methods and techniques depending on the area and situation of utilization can be analysed in depth as a future research. The methods and techniques are presented in chapter Six and they include; the use of brushless synchronous motors instead of slip ring induction motors, performance and economic evaluation is presented. The influence of electricity tariff, the use of energy storage element and renewable energy for energy management has been analysed and presented in this chapter.

Chapter Seven presents the commonly used method for energy management in the industrial sector, that is, power factor correction. Analysis of the existing methods for power factor correction was made. The algorithm for capacitor application was analysed and developed. Economic evaluation for its implementation is presented.

Chapter Eight proposes the flexible power factor correction method. Due to the shortcomings of the existing techniques of PFC, they do not provide much benefit especially if plant loads are varying. The proposed STATCOM provides variable power factor correction as in the case of synchronous condensers. MATLAB/SIMULINK and PSIM results are shown in this chapter.

Chapter Nine, proposes demand management techniques and develops strategies for load management. The algorithms for developing demand management and strategies were presented.

Chapter Ten, presents the role of electrical energy management in mitigating energy related social, economical and environmental impacts. The environmental, social and economical impacts caused by power generation by using different energy resource were presented in this chapter. The impact caused by the transmission and distribution line was also presented. The chapter also considered how other energy efficient and energy management techniques have influenced global warming. Finally, the chapter considered the role of deregulation and energy trading in mitigating the energy based impacts. And Chapter Eleven presents results and discussions on the power factor correction STATCOM developed in MATLAB /SIMULINK.

### **1.13 Summary**

Electrical energy management (EEM) is a significant element in manufacturing industries. The importance of EEM in the industrial sector is its ability to manage the consumption of electrical energy in industries by the introduction of various techniques and application of tools developed for those activities. The importance of the proposed energy and demand control methods is the reduction of the cost bearing caused by maximum demand and high energy consumption. It also minimizes the need for industries or utility industry to install new energy/ demand meter for supporting EEM which its implementation need legislation process and replacement of all metering system.

The research has implemented a set of strategies, several techniques and approaches to achieve the intended results.

The variable power factor correction STATCOM was proposed and developed in this study. This technique is capable of varying power factor by variation of reactive power generation from lagging to leading according to the variation of loads. MATLAB/ SIMULINK and PSIM software were used to verify the flexibility of the power factor correction method. An energy consumption model was developed, this provide the possibility of doing energy efficient analysis and development of energy benchmarking. An algorithm for performing load scheduling for assessing potential DSM options and power factor monitoring was developed. The expected outcomes include reduction of power consumed in the industry, improvement of power supply reliability and mitigation of negative environmental impacts. To ensure sustainability of the energy management system the strategy for load management was also proposed. Finally, conclusions and recommendations were made.

## **CHAPTER TWO: Literature Review**

### **2.1 Introduction**

Industrial activities around the world consume large portions of the total electricity generated. The amount and magnitude of consumption varies depending on the level of industrialization of a particular country. The higher the degree of industrialization, the greater the industrial energy consumption

There is a linkage between energy management in supply and demand sides, these facts were seen when EM action was taken in the demand side where the outcome of the reduction and benefits could be observed in the supply side. When energy management was initiated by the supply side, most of the controlled loads were in the demand side, again, both energy sides were involved. Most of the EM techniques bore the same characteristic, but they only depend on which side of energy management was implemented. Therefore, when energy management techniques were reviewed, it was worth to consider both demand and supply side.

The aim of this chapter is to review the types of energy management techniques and methods carried by the PSI industry as well as the demand side (industries) in order to analyse and understand the methods used in terms of reliability, adoptability and viability and also analyse the cost implication and find the existing gaps among them.

### **2.2 Energy Management: An Overview**

Energy management, energy efficiency technology and energy savings are integral to ethos of the twenty-first century. The primary reason for emphasising energy conservation and management in industries is to attain systematic reduction of energy use and hence lower the money spent on purchasing energy. Reduction of energy consumption and energy costs for a unit product is encouraged by many factors such as, political, social and environmental. Energy management becomes a responsible route and attractive action in many industrial and commercial entities.

The founder of management philosophy "Fayol,1916" specified the main management tasks or processes that are still around today on the operational level aimed at optimizing and controlling the organization's resources. The main management tasks considered are planning, co-ordinating, organizing, staffing, controlling, budgeting and reporting (Zoran and Dusan, 2008).

In many cases, most of the electrical energy used in industries is provided by the power supply industries. Depending on the Utility restructuring type (vertical integrated monopolies or horizontal structure), the main purpose of the power supply industries is the production and delivery of electric power. The power supply industry (PSI) of a vertical integrated monopoly is commonly split into four processes, these are generation, transmission, distribution and retailing of electric power which are working as one business, while horizontal structure is having generating, transmission and distribution company as a separate business facilities (Glover et al., 2008).

Electric utilities are responsible for the provision of the power supply to customers, at any time and at the most economical cost, at acceptable standards and at high level of reliability. However, in many SSA countries this mission is not realistic due to the reasons include high population growth; which tremendously increases the demand of electric power and causes many PSI not to fulfil their responsibilities as stipulated. Hence, it appeals to the need for increasing the capacity of power generation, transmission and distribution infrastructure. This needs proper planning and funds to support that investment. On top of that, the rapid rise of the cost of construction of new generation plant, high price of fuel, unexpected load growth and other environmental constraints make utilities load management (LM) programs to be very important concerns around the world.

The development of an electrical energy management program in PSI was proposed by AL-Shakarchi and ABU-Zeid, (2002), aimed at decreasing the rapidly raised need for the capacity additions as well as reducing the cost involved by the raised fuel costs. The proposed programs include a direct load control (DLC), that, power supply industries (PSI) implemented to reduce the system peak demands. In this case, PSI can increase the off-peak valley-hours load demand to improve the utilization facilities and reduce the overall cost of electricity. In their work, they demonstrated the potential and cost effectiveness of implementing DLC in the Jordan's electrical power system. The load management focused on cycling consumer's appliance to reduce load during peak hours. This was done through remote switching control.

Channele (1997) contend that, many PSIs worldwide were providing incentives to the end-users so as to modify electricity usage patterns; this provided benefits to the supply and demand side as well. Other techniques used to manage the raised need of electricity demand by the end- user are given by Finamore et al. (2003).

Kissock and Eger, (2008) presented energy management by the use of energy efficiency techniques and practices. They emphasized the importance of energy

efficiency improvement as a means of improving energy consumption, reduction of costs and increase productivity across a large industrial entity.

Common load management methods undertaken by manufacturing industries and PSIs include load shedding and restoring, load shifting, power wheeling, installing energy efficient processes and equipment, use of energy storage devices, co-generation, renewable energy and reactive power control. All these activities have found base in the Demand side management (DSM) programmes (Yang, 2006; Gelling and Chamberlin, 1993).

The demand side is the part of energy system which is associated with the final energy users. Whereby, energy consumption in this side is normally controlled by the end user. In power system, the demand side starts after the electric meter. This research intends to facilitate electrical energy management in manufacturing industries so as to reduce energy consumption and limit peak demand.

### **2.2.1 Review of Energy Management in Cement Production Process**

Cement is produced by burning limestone to make clinker. The clinker is blended with additives and finely grounded to produce different cement types. Cement production involves raw material preparation, clinker production, and finishes with grinding. Cement industries are among large consumers of electrical energy in Sub-Saharan African industrial sector.

A significant number of studies have been published in this field, which shows some potentials and means of improving energy consumption in cement industries. Schuer et al. (1992) analysed energy consumption values and presented energy saving methods and potentials for German cement industries. The study consists of two parts, namely electrical energy and thermal energy saving methods. The results were presented in the form of energy flow diagrams.

Saxena et al. (1995) studied various means of improving the energy efficiency of cement industries in India and presented energy consumption figures and the means of conservation together with estimated savings. The study considered the parts of the cement production process only.

Worell et al. (2000) performed energy analysis for the US cement industries for the years 1970 and 1997. They reported an in-depth analysis of the US cement industry, identified carbon dioxide saving, cost-effective energy efficiency measures and potentials between 1970 and 1997. They discovered that, the use of blended

cements is a key cost-effective strategy for energy efficiency improvement and carbon dioxide emission reductions in the US cement industry.

Feng et al. (1995) presented the analysis of energy efficiency techniques used in Chinese cement Industries. The raw material grinding facilities including automatic load control and retrofitting efficiency of grinder was used. Energy efficiency motors were also studied and suggested to be used in place of standard efficiency motor, while Hasanbeigi et al. (2010) presented the use of conservation supply curves model to estimate the cost effective and technical electricity efficiency potentials for the cement industries. The cost-effective electricity-efficiency potential for Thai cement industry in 2008 was estimated to be about 265GWh, accounting for 8% of the total electricity use in the cement industry in 2005. The total technical electricity saving potential was 1697GWh accounting for 51% of total electricity use in the cement industry in 2005. The model also used economic analysis that can be used to calculate the annual net cost saving.

### **2.2.2 The Status of Cement Production in SSA**

The performance improvement of Africa's economies has led to a strong growth in cement demand in the region. New investments and construction of residential and commercial properties and infrastructure projects, such as roads have increased the demand of cement. Construction expansion occurring in other regions around the world makes some countries in Sub-Saharan Africa (SSA) to enjoy the increase of export of cement product. The sector also attracts the interest of overseas investors because the product may be supplied to the local market or exported to other markets where demand is high. These factors combined with economic reforms, have led to strong growth in real GDP in the Sub-Saharan African region. Real GDP for the region rose by 6.2% in 2005; this represents the highest growth since 1996 (Africa Building Foundation, 2006).

Prospects for the regional cement sector are also favourable, generally positive outlook for real GDP growth in SSA, suggests rising demand for cement. The per capita consumption of cement in Sub-Saharan African countries is considerably lower than the world average that is, 65 tonnes and 340 tonnes respectively. At country level, economic growth has close relationship to the increase in cement consumption due to increase in infrastructure development and construction of modern buildings and shelters.

Cement industries have been considered as one of the energy intensive industries. This means that, more cement plant in the region, means more electrical energy is

required and consumed for the production of cement. Therefore electrical energy management in cement industry is essential. Appendix 2.1 shows an estimate of industrial production growth rate for SSA countries.

### 2.3 Electrical Energy Management Techniques in Power Supply Industries (PSI)

Industrial energy consumption in the developing countries was nearly 40 percent of the total worldwide industrial sector in 2001 and their share is projected to increase to almost one-half of all industrial sector energy consumption by 2025 (EIA, 2004). This is due to the projected economic growth in the region (developing countries).

The power system of any country comprises of three distinct levels, that is; generation system, transmission system and distribution system. The variation of the system depends on their structures, power transmission capabilities, voltage levels and interconnectivity. The generated electric power is characterized as a non-storable product and is a periodically fluctuating quantity.

The loads on a PSI are the devices or bunch of devices that draw energy from the power system. Therefore the total loads of the system are the sum of the group of loads such as residential, commercial and industrial loads. Industrial loads are composite loads and induction motors form a big portion of these loads. These loads form a major part of the system load. Commercial and residential loads consist largely of lighting, heating, and cooking loads. These loads are independent of frequency and consume a negligibly small reactive power (Mohamed, 2000).

The load characteristics of the plant are analyzed by the load curve which is defined as a curve depicting the consumer's load demand against time. The daily-load curve of a utility is a composite of demands made by various classes of users in 24 hours. The greatest value of load during a 24-hrs period is called the peak or maximum demand. To assess the usefulness of the generating plant, load factor is considered. Load factor (LF) is the ratio of average load over a designated period of time to the peak load occurring in that period. The annual load factor is the most useful since a year represents a full cycle of time. The daily load factor is calculated as:

$$\text{Daily LF} = \frac{\text{average load} \times 24\text{hr}}{\text{peak load} \times 24\text{hr}} \dots\dots\dots 2.1$$

And the annual load factor is calculated as:

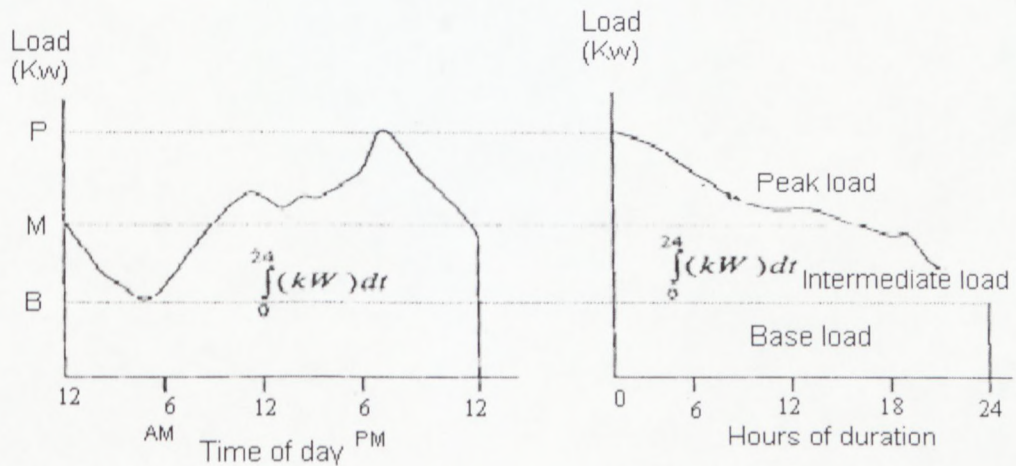
$$\text{Annual L.F} = \frac{\text{total annual energy}}{\text{peak load} \times 8760\text{hr}} \dots\dots\dots 2.2$$

A typical example of system load curve (daily load curve and load duration curve) of many power supply industries (plot of load, in kW, against the time at which it occurs) is given in Figure 2. 1.

The load duration curve (LDC) is generated from the aggregation of all daily load curves and is used for planning purposes. Daily load curves are plotted using the load against the number of hours during the day for which it occurs. The area under a (daily) chronological load curve measures the total energy consumption during the day, which is evaluated by:

$$W_T = \int_0^{24} (kW) dt \dots\dots\dots 2.3$$

Where  $(kW) dt$  is expressed in kilowatt-hour (kWh) terms.



**Figure 2.1:** General Load Duration and Daily Load Curve of the Power Supply Industries

The costs of supplying electricity to the consumers is categorised into demand and energy costs. Demand (load or capacity) costs are the capacity related costs for generation, transmission and distribution. The energy costs are those, which vary directly with the quantity of units (kilowatt-hours) generated and they are largely made-up of the costs of fuel, fuel handling and labour. The energy and demand charges are regulated by tariffs.

As explained in chapter One, the electricity generation in SSA is low even compared to other developing countries. This electricity generated should be utilized efficiently so as to meet the system demand of the power supply system. In this regard electrical energy management (EEM) is an important activity and low cost action for conserving electrical energy in the PSI.

In electrical power system, large part of the electricity generated is consumed by the aggregate loads of the system. Load management (LM) in the power supply industries is an indispensable action for the provision of better performance and stability of the system. Load management in the utility industry includes planning and implementation of such utility activities that are designed to influence customer's use of electricity in a way that produce a desired change in the utility load shape.

The common techniques used for electrical energy management on the utility industries include; direct load control, tariff structure (Time of Use tariff) and special program that involve the use of different methods and technologies so as to manage the electricity demand (Demand Side Management program) (Benergee,1998). As per (Benergee, 1998), load management involve the analysis of variations of loads, identification of controllable and non controllable loads, selection of control option and implementation of energy management strategies. The nature of control options includes:

- Direct load control where utility can directly switch off the customers loads.
- Interruptible load control; utility provides advance notice to the customer for switching off their loads.
- Time of use (TOU) tariffs; where utility provide incentives to the customers to shift their load from peak to off - peak period for provision of an appropriate tariff.

These methods of load management are initiated by PSI due to the specific EM requirement, for example when the energy generated is less than the demand requirement or when generation of electric power is very expensive due to the raise up of fuel price and if there is inadequate fund for construction of new power station.

### **2.3.1 Direct Load Control**

Direct Load Control (DLC) refers to a program of activities that can interrupt the consumer's load at the time of peak load by direct control of the utility system operator and by interrupting power supply to individual appliances or equipment in a consumer's premises. These usually involve residential consumers. The cost effectiveness of direct load control includes:

- Power system production cost savings.
- Power system generating capacity cost savings.

- Power system loss reduction.
- Load management equipment reduction expenses.

Bhatnagar & Rahman (1985) defined load management as a means of reducing peak load growth and slow down the race of increasing capacity addition. They further explained that, LM could defer the capacity addition or an increase of the off peak energy utilization duration, hence an increase of system load factor as well as boosting up the revenue of the company. They analysed the effectiveness of DLC and concluded that, LM depends on various indicators including; generating mix, load curve shape, planned capacity addition, types of load to be controlled and metrological characteristics.

The indicator used for monitoring the effectiveness of LM was the amount of the reduced load, reduction of production cost and fuel saving, increase of deferral load, increase of load factor and attaining system stability. Finally, generating mix in summer season had shown the potential of DLC. The direct benefits of LM programmes to the utilities and consumers have been mentioned as:

- Better use of existing generation, transmission and distribution equipment through control of loads.
- Deferment of capital investments for new equipment.
- Reduce spinning- reserve requirements.
- Lower operating costs and increase system load factors.

Backer (1986) performed direct load control in the Pacific gas and Electric Company. He proposed five ways of controlling the loads of the customers and he classified them according to the size of load. Telephone, radio signal and power line were used to produce signal that interrupted large industrial consumers. Before the action, the customers were informed to reduce their electric demand to emergency service load for only 10 min upon request. There was also an agreement to some consumers that interruption should not exceed 320 hours in a year. Some customer's loads were directly installed with under frequency relay, which operated, and responded very fast when frequency was below 59.75 HZ (American system).

Implementation of Duty cycle approaches and demand side design as a DLC was analysed by Ryan et al. (1989). Duty cycle model (DCM) was developed and offer several advantages compared to other available DLC method. DCM presents an integrated approach to DLC impact analysis because it explicitly takes into account the casual mechanism through which cycling alters appliances energy use. It employs a convenient transformation standard (kWh) and gives the size of an appliance in KW. Its energy use may be expressed as an average duty cycle per unit time. Average duty cycle (t) was calculated by statistical approach as:

$$t = \frac{\text{Average load}}{\text{Connected load}} \dots\dots\dots 2.4$$

Where appliance load average was computed over the time interval “t”, for example, half hour and considered as the percentage of time that the appliances were “on” during the measurement period. It has been concluded that, duty cycle distribution is a useful means for characterising and analysing customer’s user patterns over a course of the day and different day types. Computer based workstation had proven to have a viable, cost-effective means for analysing the value of data used in the program evaluation.

A DLC with a profit based load management was introduced by Kah-Hoe & Sheble (1998). They examined the generic direct load control scheduling and the profit margin on the electrical system that was obtained when the controllable load is scheduled. The algorithm, that determined the number of customers to be controlled was developed and considered in all possible control durations. Successive approximation technique was employed. The developed model concentrated on total load, which is a sum of controllable and non controllable load, hence DLC was categorised into two different customers load group as:

$$CL_j = \sum_{\forall i} \left( x_{ij} P_{ij} + PS_{ij} \right) \dots\dots\dots 2.5$$

Where:

- $P_{ij}$  Variable Load for DCL<sub>j</sub> at period *j*, provided by each customer within the customer load group
- $x_{ij}$  Number of customers within *i* at period *j*
- $PS_{ij}$  Schedule controllable load within each control load group

From equation 2.5 it is seen that, at any period, profit can also be determined by:

$$PRFT = \sum_{\forall i} R_{ij} \left( x_{ij} P_{ij} + PS_{ij} \right) + r_j N L_j - S_j (T L_j) \dots\dots\dots 2.6$$

Where:

- $R_{ij} \left( x_{ij} P_{ij} + PS_{ij} \right)$  The revenue collected from CLG, *i*

$r_j^{NLj}$	Revenue collected from none controlled load
$s_j(TL_j)$	Monotonically increasing system cost and
$R_{ij}$	Rate charge after joining DLC

Ahsan (1990) analyzed the load management process and impacts on the reliability and production cost of interconnected systems. The aim of the study was to evaluate the impacts of load management strategies on the reliability as well as production cost of two interconnected systems. The investigation has been made to find the equivalence in terms of reliability improvement and production cost benefit between the tie line capacity and the percentage reduction of peak demand. The segmentation method was utilized and the numerical simulation was performed. A model of basic approach of load management applicable to two interconnected systems was developed. The basic approaches considered were the direct load control which involves interruptive and non interruptive loads, indirect load control and energy storage. In this study, it has been observed that, instead of increasing tie line capacity, a load management scheme could be applied to the system as an alternative solution.

### 2.3.2 Load Management by Time Dependant Tariffs

The total costs of generating and delivering electricity to the consumers may be categorized into the fixed and variable costs. The fixed costs are independent of units (kWh) of energy produced or day to day operation of the system. They depend on the installed capacity of the system. They are the capital costs of many activities and services such as; the costs of land, building, equipments, lines and substation. While variable costs are the part of cost that depends on the energy units (kWh) produced. This includes cost of fuel, lubricating oil, cost of water, maintenance and repair of equipment and wages and salaries of operational/maintenance staff (Subir, 2007).

These costs may be viewed as the costs for the customers, distribution, and transmission and generation services. Hence the tariff structure is then designed in such a way that the annual fixed and variable costs and the profit are accrued annually from the revenue collected. Hence integrated utilities in regulated states must set rates to cover their costs for all of the above services (Steven et al., 2007).

In states with restructured retail markets, distribution utilities set tariff rates to cover their customer and distribution services costs. Competitive energy providers set a

price that covers the cost of providing generation services which they believe will be attractive to consumers. The ways that, electric consumers are charged include:

- Flat rate and two- part tariffs
- TOU
- Spot price

**2.3.2.1 The Flat Rate Tariff;** an electric utility that charges a flat rate does not charge different rates based upon the demand that the customer place on the system. A customer pays the same amount of electricity for any time of day. However it is simple, it suffers from serious drawback of charging consumer even if he/she does not spend energy at all for a period of time. It also does not discriminate different categories of consumers such as, different power factor, load factor and diversity factor.

**2.3.2.2 Two- Part Tariff;** an electricity utility set the fixed cost \$/kWh for energy consumed and charge for maximum demand \$/KW of maximum demand reached during billing period. The running cost, on the other hand, is recovered on the basis of units (kWh) consumed according to a rate per kWh. The maximum demand is assessed by the company on the basis of connected load or is measured by a maximum demand meter.

The implemented industrial tariff structure in most SSA countries is two- part tariffs (TANESCO, ZESCO, NAMPOWER). The mentioned tariff structure does not have direct connection to energy or load management in turn, time dependant tariffs (TOU) has been developed for the purposes. Only few countries in SSA have been implementing TOU tariff.

**2.3.2.3 Time of Use Tariff (TOU);** the TOU rate plays a direct role to promote load management (Chamberlin & Herman, 1996), in that, the utility give transparency signal to the customers to increase off peak electricity consumption and decrease peak period consumption by varying the price of electricity depending on the cost of generation at a particular time. In time of use rates, the price of electricity varies depending on season or time of day. Rates are higher during periods of peak demand and lower during off-peak periods. Some utilities have made time of use rates mandatory for large customers. Savings from time of use rates vary depending on the size of the peak/off-peak price differential and the length of the peak period.

Babu (1995) presented reduction of maximum demand by using tariff setting. He designed discriminatory time of use tariffs in which the price correspond to the marginal cost of supply. A utility provided signal to customers about consumption and price of electricity during peak hours. In his study, he identified that, the price of electricity have significant factor in energy management, which can be used for load management scheme. He developed an econometric model for the demand of electricity in the domestic sector. He presented the following methods that can be used for the electricity tariffs design:

- Linear programming; load profile was used along with consumer class and target revenue for the particular class and;
- Total surplus; tariff established by maximizing the total joint surplus of consumers and producer in the electrical energy sector.

For DLC, the message was sent to customers to indicate when electricity is cheap and at what time the price is high. He further cautioned that, consumer may not respond to this method if the cost of response is greater than the potential savings and if no information about present and expected price to enable him/her to make decision on his /her consumption. Under this circumstance, implementation of spot price scheme is very important, if electricity price fluctuation is large and if the consumer can anticipate price behaviour and be able to respond quickly.

**2.3.2.4 Spot Price;** Spot price is a pricing mechanism of which electrical utility deal with concepts such as block rate, demand charges, back-up charges, and capacity credits. The spot price for buying and selling electrical energy is determined by the supply and demand conditions at the instant. This scheme is desirable because it improves the efficiency of the electric power system and provides higher profits for both utility and customers.

### **2.3.3 Dispatch and Rebate Load Management Programs**

In the dispatch load management method, customers agree to reduce their demand during peak periods when requested by the utility. In exchange, customers receive a discount on their electric bills. The size of the discount depends on the demand reduction. These programs are primarily oriented towards large commercial and industrial (C&I) customers. The number of participants is generally low, but load reductions per customer can be significant (up to several megawatts) and overall load savings is substantial. For example, one study of 50 industrial programs found an average contracted reduction per customer of 1.5 MW and an average contracted reduction per program of 105 MW (Blevins & Miller, 1991).

The rebates program is the financial incentive offered by electric utilities over the past decade. In the residential sector, rebates have been commonly offered for the purchase of efficient appliances and compact fluorescent bulbs, In the C&I sectors, lighting rebate programs and multiple end-use rebate programs were common program followed by air conditioning and motor efficiency rebate programs. Rebate levels vary widely, from approximately 20-100% of the cost of appliance (Nadel, 1992). Results of rebate programs have been uneven, with some having low participation, low savings and high cost per kilowatt hour saved and others having just the opposite impact.

In residential sector, the results vary widely from one program to another depending on how efficient an appliance must be to qualify and how effectively the utility markets the Program (Nadel & Geller, 1991). Some PSI in SSA countries like Eskom, through its DSM programs planning and energy efficient companies (ESCO) have started implementing this system and attest potentials in energy saving (Mthombeni, 2007).

#### **2.3.4 Demand Side Management (DSM)**

The process of managing the consumption of energy to optimize available and planned generation resources is known as DSM. This can be achieved by demand response and or load management. Demand Response (DR) is a set of activities aimed to reduce or shift electricity use to improve electric grid reliability, manage electricity costs, and ensure that customers are involved in the program and receive signals that encourage load reduction when the electric grid is stressed.

The increase of the widespread demand responsiveness is the prevention of future electricity crises and the reduction of electricity prices. The objectives of most developed utilities' DSM programs are aimed to achieve the following goals:

- Planning goals
- Load shape objectives

The planning goals of many power supply industries including South African (Eskom) are as presented in NER (2000) include:

- Minimize future revenue requirements.
- Reduce future utility capital expenditures.
- Increase opportunities for all customers to reduce their bills.
- Improve the means of financial performance.
- Minimize investor's risk.
- Maximize planning flexibility.
- Minimize customer capital costs.

These planning goals are established as guides for long term activities which make them to be strategic goals (Thompson & Strickland, 1999; Hitt et al., 1999; De Bryn, 2001). Other goal-setting objectives of the DSM programs are the identification of a specific set of load shape. The planning goals may then be seen as the evaluation criteria for the load shape objectives and as such guide the whole process. The load shape goals are distinguished as:

- Peak clipping
- Valley filling
- Load shifting
- Strategic conservation
- Strategic load growth as given in Gelling and Chamberlin, (1998)

DSM development and implementation in the demand side was presented in several industries. Jyoti et al. (1995) presented the result of a survey on DSM programs for the high-tension industries of Maharashtra. Technical potentials, costs, savings and the need for financial mechanism were covered. The essential steps in analyzing the DSM programmes were the understanding of the behavior of firms in the techno-economic environment in which they operate. The barriers to implementation of DSM were also discussed. Several options were listed and analyzed for the DSM option.

Mathews and den Boef (2005) described the implementation of the Demand Side Management (DSM) strategies at Anglo-Gold's Kopanang Mine, for a period of three months in 2001. Since the unit price of electricity was very high during certain hours of the day, it endeavoured to save costs by scheduling the operation of specific high power drawing equipment (clear water pumps and bulk air coolers), to operate mainly outside of peak hours. This objective was achieved by modelling and calculating a daily optimum operation schedule, which was daily used to the mine. As a result, an amount of R335 000 in electricity costs was saved during this period.

Fawkes, (2005) introduced the use of energy efficiency in South African Industries. This study showed that strong incentives exist for energy efficiency improvement in South African Industries, in particular, the potential for increasing profit, the need to reduce greenhouse gas (GHG) emissions, to maintain economic competitiveness and to delay the cost of new peak-load electricity generation facilities. Finally the study showed how the organization structure, financial controls and culture can be barriers to the implementation of energy efficiency projects. By ensuring the support of top management, and by early initiation of an energy management program, these barriers can be avoided.

### **2.3.5 Other Energy Management Measures Taken by Utility Industries**

National energy strategies are striving towards achieving sustainable and reliable sources of energy to meet the demands of their citizens. Traditionally, much of this demand has been met by burning fossil fuels such as oil, coal and natural gas, but in recent years, concerns have risen on the environmental impacts caused by burning oil or coal (the most predominant source of energy for electricity generation) thus leading to the exploration for alternative sources of energy.

Nuclear energy has been put forth as a cleaner alternative and used successfully in a few places, but this source is not feasible without its own set of environmental concerns. Other alternatives to fossil fuels are now emerging, including renewable energy technologies (RETs) like solar energy and wind power and biomass fuels such as corn-based ethanol and other species under development. These alternative fuel sources can help reduce humankind's dependence on fossil fuels.

Renewable energy technologies (RETs) provide attractive environmentally sound technology options for Africa's Electricity Industries. RETs could offset a significant proportion of foreign exchange that is used for importing oil for electricity generation in most countries. In addition, renewable energy is modular and is well suited for meeting decentralized rural energy demand. The modular nature of most renewable energy technologies and the low investment levels makes them particularly suitable for capital-constrained African countries. Most renewable energy technologies utilize locally available resources and expertise therefore they would provide employment opportunities for the locals. The final product can improve the system electrical energy by providing some surplus to the grid system.

### **2.4 Electrical Energy Management by Consumers Approach**

The term energy management refers to the management of electrical energy consumption; on the demand side, this notably means reducing consumption of electrical energy by improving efficiency of powered devices such as electrical equipments and use of other techniques to reduce peak demand.

The peak demand or peak load is a term used in energy demand management describing the electrical power /demand expected to be provided for a sustained period at a significantly higher value than average supply. The peak demand fluctuations in any industry may occur at any instant of energy usage for example on daily, monthly, seasonal and yearly cycles. For an electric utility company, the actual

period of peak demand is half hour or hourly period, which represents the highest point of customer consumption of electricity.

Load management can be implemented in the main part of the plant, in the sections or departments or individual machine. For example, in the cement mill, a crusher department can be operated on weekends and holidays when cement mills are not working.

EEM by consumers approach was initially established due to the reason that, most of EM programmes were initiated by the utility industries. Few works have shown electrical energy management studies directly initiated by the demand side (Faiza, 2007; Ashok, 2001; Bjorke, 1985). Gellings (1985) developed the DSM concepts, which highlighted that, utility industries were involved in load management action aimed at reducing the total system peak load for the benefit of their own side (supply side). Hence, consumers are not directly benefiting from the PSI load management program. Therefore the idea of EEM in industries can bring direct profit as highlighted by (Antonio et al., 1991) that is, production industries can reduce the cost and reduction of specific energy consumption and PSI can improve its reliability.

Kah-hoe & sheble (1999) proposed a load management program, which recognizes two economic objectives namely:

- Reduction of operational costs including energy costs, and
- Reduction of peak demand so as to improve the reliability of the transmission system.

The concept of electrical energy management in industries is to manage the total load by controlling the energy and maximum demand use in industries; this action is called load management (LM).

In this research, the word electrical load management (ELM) or load management (LM) refers to the approach undertaken by the consumer side (demand side) to reduce industrial load which consequently results in reduction in electric energy cost as well as improve the reliability of the PSI. Generally, ELM is categorized into a number of subdivisions; example, domestic, commercial and industrial ELM. The focus of this study is the electrical energy management in the industrial sector specifically manufacturing industries (cement). Various methods for load management especially in PSIs, have been developed since the electrical energy management era started.

Bjorke (1985) highlighted the possibilities of achieving good load management results including implementation of load management in industries. In this sector, unlike the

residential sector, it is possible to control a large amount of load demanded by one consumer. In addition, some of the loads in plants have similar characteristics, which enable to share base data among industries.

He proposed an inventory study to be undertaken to identify the viable techniques used for industrial LM implementation. This study endeavoured to determine the types of load (controllable load and none controllable load) existing in the industries and which load provides a big potential for demand reduction. The proposed LM actions were:

- Bivalent systems; for heating of premises as well as process heating and process media heating. This system uses least electricity by shifting electric heating load from peak to off peak.
- Load priority systems, these are the systems of which depending on every loads priority for the production, keep the peak demand below the preset limit,
- Energy storage in industrial process and other feasible application, and
- Cycling group of load (On and off)

Finally, he concluded that, load priority system has a big potential for industrial load management. The method used to develop Load priority system incorporated differential rate tariffs. Loads were allowed to vary as per rate schedule and a software was developed to monitor the operation of the system.

Jong- Ching (2005) proposed energy management in the telecom industry aimed at reduction of cost of electrical energy and relieving the electricity shortage crises during summer period. Power consumption data was gathered to identify the actual load and potentials of power saving. High-energy consumption as well as reducing energy resource is the key factor in developing the philosophy of optimization of energy consumption. In using different energy optimization methods it was realized that, it is possible to reduce energy consumption in the demand side. Finally, for simplicity of attaining the solution, a load model was proposed for the optimization of the energy system.

#### **2.4.1 Model Development for Industrial Load Management**

Since the portion of this work involve modelling of industrial loads and of energy consumption, the previously model developed was studied. There are two types of models used for electrical energy management. A model used to build up load curves from data on process, production, production schemes, labour, for example model for rescheduling process. Another type of model is the one used by electricity utilities to forecast the electric load growth and how the load growth may be influenced by load management. The second model is not the focus of this study.

Manichaikul et al. (1979) proposed the physical based modelling for industrial electric load demand. In their model the demand of an industrial firm was analysed in detailed from two basic physical aspects: the stochastic aspects of the use of individual pieces of equipment and the product flow and the storage structure of the individual process. The modelling methodology was tested and verified with data from seven industrial customers. This model hold the promise to answer question concerning the effect of various types of change could have on load such as change in production schedule and introduction of new technology or introduction of new inverted charge rate. Hence they found that, modelling of each industrial firm consists of the following general steps:

- i) Development of physical load model and
- ii) Combine the developed physical model with various types of economic analysis depending on the issues of interest.

The developed model may also be used for modelling residential and commercial load. The modelling perspective under taken considered load of any individual  $j^{\text{th}}$  machine as  $P_j(t)$  and the total plant load  $P_T(t)$  of an industrial customers can be modelled as follows:

$$P_j(t) = X_j r_j U_j(t) \dots\dots\dots 2.7$$

$$P_T(t) = \sum_j P_j(t) \dots\dots\dots 2.8$$

Where:

- $X_j$  represents the installed capacity rating,
- $r_j$  represent the fraction of loading for the  $j^{\text{th}}$  machine.
- $U_j(t)$  The utilization factor, is a random process and is bound by 0 or 1.
- $U_j(t), P_j(t)$  and  $P_T(t)$  are continuous time random process.

Let  $P(n)$  be the time average sample load of  $P(t)$ , averaging time step is  $\Delta$ , then ;

$$P(n) = \frac{1}{\Delta} \int_x^{n\Delta} (n-1)\Delta P(t) dt \dots\dots\dots 2.9$$

The typical values for  $\Delta$  are 15 minutes, 30 minutes or 1 hour. Two state Markova was widely used. Random process used to model a group of tightly coupled machines behaving as one single block. The operation of a machine was random therefore the entire plant was random. The load of machine can be modelled as a stochastic process to account for their random nature load, this was defined as:

$m_j(t)$ : Mean value of  $j^{\text{th}}$  machine demand

$$m_j(t) = E\{P_j(t)\} \dots\dots\dots 2.10$$

If,  $\varepsilon_j(t)$  is residual, therefore

$$\varepsilon_j(t) = P_j(t) - m_j(t) \dots\dots\dots 2.11$$

The autocorrelation of residual is:

$$R_j(t_1, t_2) = E\{\varepsilon_j(t_1)\varepsilon_j(t_2)\} \dots\dots\dots 2.12$$

Load scheduling is a term used to describe the practice of trimming peak power demand to reduce high demand penalties. The goal of load shedding is to schedule the operation of non-essential equipment to provide a uniform power to the utility company. It is one of the DSM objectives that are used in peak shaving.

On demand side, load scheduling is used for demand control. A controller can be designed to analyze the energy management possibility available and switch loads as needed to maintain a relative constant power demand drawn from the utility company. The system may be programmed to recognize which loads have priority and which ones are not essential.

Ashok & Banerjee (2000) introduced load management applications for the industrial sector. Load shifting was considered as a best method for reducing customer demand during the peak period. The load shifting techniques was used to select the load or processes, which can be shifted/ rescheduled. The method used in their study was the use of economic incentives and disincentives offered through the electric rate structure to encourage voluntary changes in customer consumption patterns.

They analysed common energy intensive loads in industries and found that, these loads have different operational characteristics; finally, they studied the energy consumption characteristics of the individual load so as to identify the potential saving of energy for high-energy consumption equipment. The method for the optimization of the process load was developed to improve the system load factor. The proposed method involve shifting load in such a way that loads are diverted from peak period to off peak period, in this manner shaving the peak and filling the valley of the load curve. This method was easily implemented and did not affect the production output when industrial loads were rescheduled to operate in cheap period.

The energy management concepts proposed by Ashok, explained the importance of the selection of the appropriate load to be rescheduled. Interlock and storage limitations were studied and considered in load shifting process; the constraints of the processing plant in conjunction with scheduling of the load by TOU tariffs have been worked out. There was no procedure for monitoring Load or process flow.

Ashok & Benerjee (2001) developed the mathematical model for energy optimization in the processed industry. The model was formulated using integer linear programming for minimizing electricity cost by scheduling the loads satisfying the process storage and production constrains. The model was also used to analyze industrial response to different tariffs. In this literature, the objective function was only to reduce energy cost.

Industrial load can be classified into controllable loads and fixed time load. Fixed time loads occur at specific time and cannot be subjected to load management action. The controllable load can be grouped in to process independent loads, process interlocked loads storage constraints and sequential loads.

In cement industries most of the energy intensive electric loads are classified as controllable loads have, they are subjected to load management and some few loads like lighting loads, kiln are uncontrollable load. Kah-Hoe & Sheble (1998) modelled the total system load at any period as, the total load  $TI$  which is a combination of controllable ( $CI$ ) and non controllable load ( $NI$ ), hence the total load is given by:

$$TI = CI + NI \dots\dots\dots 2.13$$

The modelling method of the controllable loads can be performed based on the type of processes which are grouped into:

- Process independent loads,
- Process interlocked loads, and
- Sequential loads.

The mathematical formulation presented by Ashok (2001) based on discrete time representation of the entire time horizon, "H" of interval. For example one day was calculated by:

$$\sum_{i=1}^N t_i = H, \text{ for the total intervals } N, \text{ in the time horizon } \dots\dots\dots 2.14$$

Decision variable: The decision variable,

$I_{mi} = 1 \Rightarrow$  the machine  $m$  is on interval  $i$

$= 0 \Rightarrow$  the machine  $m$  is off interval  $i$

$t_{im}$  – Time interval i.e start and end of the process

The constraints of the industrial process were given as:

- Production constraints; in the development of the control system, it is required to specify minimum production output ( $Q$ ) of the final product in the time Horizon, then:

$$\sum_{i=1}^N \sum_{m=1}^M P_{mi} \times t_{mi} \times I_{mi} \geq Q \dots\dots\dots 2.15$$

Where:

$M$  The total number of machines processing or producing the final output.

$P_{mi}$  Production rate of machine  $m$ , in the interval  $i$

Using the variable  $P_{mi}$  it is possible to incorporate the change in production rate of machines at different intervals considering the variation of utilization and efficient parameters.

- Storage constraint; the process loads with storage facility and maximum capacity limitations were modelled as follows:

$$\sum_{i=1}^T \left[ \sum_{m=1}^M P_{mi} \times t_{im} \times I_{mi} - \sum_{r=1}^R q_{ri} \times t_{ri} \times I_{ri} \right] \leq S_m$$

for  $T = 1$  to  $N$  ..... 2.16

$S_m$  is maximum storage capacity

This model shows the comparison between the sum of the production input and output so as to identify the consumption rate. In this system the storage capacity has greater importance to the LM program.

- Process flow constraint; in the production process, material flow need to be monitored so as to ensure the continuous production and is given as:

$$\sum_i^T \left[ \sum_{m=1}^M P_{mi} \times t_{mi} \times I_{mi} + \sum_{l=1}^L S_l \right] \geq \sum_i^T \left[ \sum_{r=1}^R q_{ri} \times t_{ri} \times I_{ri} \right] \dots\dots\dots 2.17$$

for  $T = 1$  to  $N$

- Sequential constraint; some of the processes necessary to operate in sequence for example the condition for the start of machine are to be observed.
- Maximum demand constraint; in order to achieve demand reduction, peak demand of the plant should be limited to the economical value. This is an important factor for load scheduling since many industries are subjected to maximum demand restriction.

$$\sum_{m=1}^M \left( \frac{K_{mi}}{pf_{mi}} \right) \times I_{mi} \leq KVA_i \dots\dots\dots 2.18$$

Where  $KVA_i$  is the maximum demand limit,  
 $K_{mi}$  is electrical power input and  $pf_{mi}$  power factor of the machine  $m$

- Electrical load estimation; the predetermined load of the industries was modelled as:

$$K_{mi} = \left( \frac{R_m \times U_{mi}}{\eta_{mi}} \right) \times I_{mi} \dots\dots\dots 2.19$$

Where:  $R_m$ , is the rated capacity of device  $m$  in kW and  $U_{mi}$  utilization factor of the device  $m$  at the interval  $i$  and  $\eta_{mi}$  is the efficiency of the machine. This can be considered as a percentage loading of the device, which can be obtained from the input measurement and device manufacturing data or characteristic.

- Objective function; the objective function of the research was to minimize the cost of electrical energy by minimizing energy consumption in the industries.

When  $C_i$  is the cost of energy for the interval  $i$  the governing equation for the objective function is:

$$Min. \sum_{i=1}^N \sum_{m=1}^M \left( K_{mi} \times I_{mi} \times t_{mi} \right) \times C_i \dots\dots\dots 2.20$$

For the LM schemes, the additional cost of load management action should be included in the objective function as follows:

$$\text{Min. } \sum_{i=1}^N \sum_{m=1}^M (K_{mi} \times I_{mi} \times t_{mi}) \times C_i + (C_{ai} \times I_a) t_i \dots\dots\dots 2.21$$

Ashok (2006) presented the load model, which incorporates the characteristics of batch type loads related to any type of process industry. The developed model was coupled with an optimization formulation solved by integer linear programming for minimizing the total electricity cost and satisfying production, process flow and storage constraints for different tariff structures.

Mathematical formulation based on discrete time representation similar to that proposed for continuous loads. The proposed model can be extended for any type of process industry, like cement industries and incorporated the following characteristics of batch-process loads.

Batch time and batch capacity, material input (charging) – time periods and quantity, material output (discharging) – time periods and quantity and power demand variations with time and quantity, type or quality of material for the batch. The operating parameters and sequences of the batch process were described. The electrical power input in kW to the equipment  $m$  at any interval  $k$  when it is processing  $j$ th product was modelled in equation 2.19. Hence the energy consumed by equipment when processing the product  $j$  for the batch started in the  $d^{\text{th}}$  interval is:

$$E_{mjk} = \sum_{d=k-(z+c)+1}^{k-z+1} P_{mjk} \times I_{mjd} \times t \dots\dots\dots 2.22$$

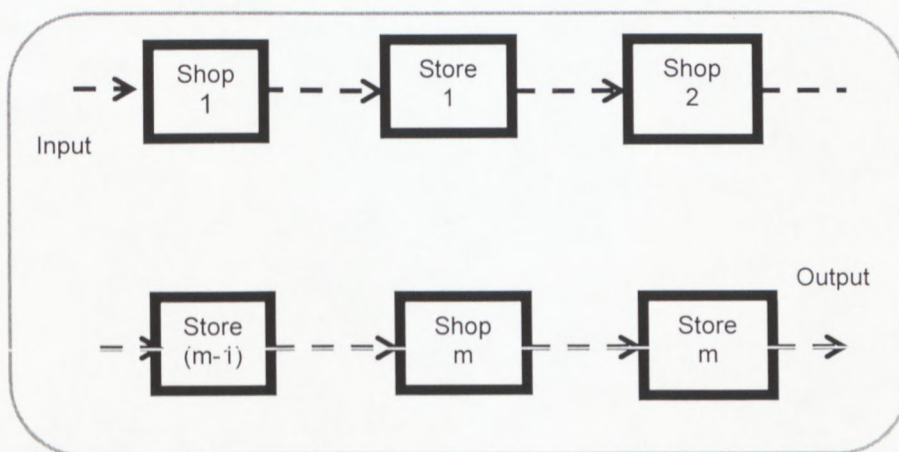
The objective function is the same as stated by Ashok, (2001) but here maximum demand charge was considered. The production, storage and process constraints were modelled as in equation, 2.15 and 2.16.

In this thesis, the presented model was adopted with some improvements like objective functions by which, demand /energy consumption constraints should be considered. It was used in the development of the algorithm for performing load scheduling. Hence reduction of energy cost as well as cost caused by maximum demand can be achieved. The LM application intends to follow DSM programs objectives developed in many countries worldwide, which involve the use of energy efficient technology and reactive power control.

Mathematical model for load-controlled consumer (LCC) for active load management was reported by Savely (1998). The model considered that, each system has some

load management facility that can reduce energy consumption and prevent system shut down during power shortage. Active load management is defined as a means, through which consumers create the possibility to meet short power limitation without any malfunction. The considered area for the load management was the energy consumption devices and energy management plan. The model was developed and analyzed in order to determine the technical potentials and cost of the active load management for industrial consumers.

The developed model has a sequence of the production section where technological processes occur. It was assumed that, LCC had a storage unit between each production section as given in Figure 2.2. Power limitation of some shops lead to the decrease of the product output, however, it didn't affect the normal work of the adjacent section because it used the production from the previous section. It was assumed that, the plant output product was proportional to the plant energy consumption.



**Figure 2.2:** Industrial Load Management Arrangement

The model parameter was nominal power load of the  $i^{\text{th}}$  section is  $q_i$  (kW) and its maximum reduction is  $Q^0$  (kW), this reduction was determined on the base of minimal power consumption that allow the section to perform its basic operation. It was assumed that, the full capacity of the  $i^{\text{th}}$  store is reached at  $h_i$  (hours) and the instantaneous capacity was assumed as  $\delta_i h_i$  (hours). Instantaneous capacity of the store is the discharge time, when the  $(i+1)^{\text{th}}$  section consume its nominal load, but the  $i^{\text{th}}$  section does not work at all. When load regulation is applied to LCC, its total power consumption reduces.

The total limitation of the plant was  $Q$  (kW), for time  $T$ -hours and  $i^{\text{th}}$  shop, the limitation of individual load becomes  $Q_i$  (kW). Therefore the balance of regulation was given by:

$$\sum_{i=1}^m Q_i = Q \dots\dots\dots 2.23$$

The main constraint of the LCC was achieving constant output from the last shop in the production line. That is:

$$Q_i^o \geq Q_i \quad i=1 \text{ to } m \dots\dots\dots 2.24$$

In addition, it is assumed that, nominal work does not affect store units. It means that the nominal operating point was the whole product that  $i^{\text{th}}$  shop produces and consumed in the  $(i+1)^{\text{th}}$  shop.

The regulation of power becomes:

$$r_i = \frac{Q_i}{q_i} - \frac{Q_{i+1}}{q_{i+1}}, \quad i=1 \text{ to } (m-1) \dots\dots\dots 2.25$$

The developed mathematical model was working under power reduction. This model was designed to solve problems of optimal distribution of power limitations between LCC's and shops and maximum time of power limitation when LLC reduced power demand by  $Q$ .

Real-time energy management in the cement industry was presented by Mathews et al. (2008). The procedures for identifying viable DSM opportunities were developed. These procedures include data gathering and refining, simulation of silo levels and material flows, as well as optimization of simulation predictions to result in a load shift schedule for different plant systems. During the investigations, an actual cement factory was used as a case study. The researchers presented DSM solutions for the cement industry. The factory management highlighted certain constraints. These are the following:

- There must be enough storage capacity for production materials.
- The equipment constraints must be taken into account.
- The quality of the products and production must be maintained.
- The downtime of the plant must not be increased.

The most energy intensive electrical energy users in the cement factory are raw mills, kilns and finishing/cement mills. The DSM solution was implemented on the raw milling section only.

A control philosophy was developed to realize the DSM potential found in the raw mill circuit. This philosophy considered electricity pricing structure, material flow, storage silo levels, availability of the mill/equipment, and equipment start up procedures. Control software was developed in order to control the raw mill system according to DSM control philosophy. The software made use of the existing supervisory control and data acquisition (SCADA) system in the factory. Automatic dynamic simulation of the raw mill system was conducted in a real-time environment. The simulation results were used to optimize the schedule of the raw mill circuit for DSM purposes.

The storage potential also was established as one of the requirements for successful load shift. Storage of product during downtimes, the sizes of the storage silos at the factory were determined. The control system is equipped with a computerized logging system that logs the hourly material flow from limestone bins to the raw mills.

This provided an effective way to calculate the actual running hours of the raw mill systems on both lines.

Process flow information includes values like the material flow out of the raw mills to the silos as well as the material flow from the silos to the kilns. The relevant material flow values were given and the baselines were established. The baselines are average daily electrical energy (kW) load profiles for a specific piece of equipment or section of equipment. Simulation of the milling schedule had to comply with the constraints for optimization of the raw mill systems. The constraints considered for the simulation were:

- The Eskom Mega Flex tariffs must be used for the savings calculation.
- The electricity cost must be minimized during the peak times
- The maximum electrical load cannot exceed the installed capacity.
- If possible, the maximum demand must be kept at, or below the current value.
- The correct material flows and silo capacities should be known.
- The simulation must be energy neutral (the areas under the baseline and the simulated schedule must be the same).

This simulation software allows the user to simulate a process or system by choosing to minimize or maximize results by changing process values subject to user-defined constraints. The results obtained from the simulation provided more accurate description of the actual material flow through the raw mill systems than the energy simulation alone. The respective results were plotted to provide graphic representation of the simulation. The goal was to switch off the mill during the Eskom evening peak period.

Finally, the study showed that the milling systems can be large contributors to demand side management initiatives. Using this concept it is possible to perform optimal load shedding that can allow the reduction of the demand at any instant. This action may reduce cost associated with energy and demand drawn from the power supply and improve stability of the power supply industry.

#### **2.4.2 Energy Efficiency Techniques for Energy Management**

Energy efficiency refers to the ratio of energy outputs and energy input. Application of energy efficiency techniques and measures are important and encouraged in an energy management program. The use of energy efficiency products, equipments or techniques results in reduction of energy consumption. There are many studies that analysed the importance and contributions of energy efficient techniques for energy management in industries.

The contribution of energy efficient motors to demand and energy savings in the petrochemical industry was presented by Pillay & Fendley (1995) aimed at examining the potential for energy savings. In-depth survey of motors in a chemical plant and refinery was conducted. MotorMaster software was used for the analysis, results of which showed that payback period was within acceptable range.

McKane et al. (2005) presented the current status of developing international energy management standards, including analysis of the shared features and differences in terms of implementation. The purpose was to describe the current state of best practice for emerging area of energy efficient policy making and suggested the creation of international energy management standards consistent with ISO. The purpose of the standards is to provide guidance for industrial facilities to integrate Energy Efficiency (EE) techniques into their management practices. Step by step energy management procedures were also presented. The features of energy management standards in various countries were presented whereby similarities were indicated.

Thollander et al. (2005) studied the effect of rising electricity prices on the Swedish iron and steel foundry industries and quantified energy efficiency potential for those industries. In this study it was found that, energy costs at industrial plants can be reduced by three principal ways: reduction of energy use, load-management measures, and changing energy carriers.

Energy audit was conducted for about 6 months in 2003 in order to investigate the potentials and opportunities for the implementation of energy efficiency techniques in

industries. On the basis of the results from the industrial energy-audit, computer calculations were made to study the consequences of energy-efficiency measures and electricity-price fluctuations in terms of energy costs. The energy audit in the Swedish iron-foundry resulted to a number of potential energy-efficiency measures targeting energy costs reduction. The largest energy-saving potential was realized in melting and holding processes, in delivery and waste heat to the local district-heating system and in strategic production planning. Furthermore, large energy savings could be found in the compressed-air system through the elimination of leaks, lower idling energy demand during weekends and holidays, investment in a new sand preparation process, and more efficient ladle heating.

Finally, the result of the energy audit resulted in seven major energy-efficiency measures to include: new melting furnaces, district heating supplied to municipality, compressed-air leak elimination, new sand preparation, different ladle heating, lowering idling losses, load management. Implementing the measures could reduce the use of energy at the foundry by about 33%, and more specifically the use of electricity by 23%. By far the most economically advantageous energy-efficiency measure at the foundry is to aggregate load-management practices with the foundry's strategic production planning.

Energy efficiency projects can save a significant portion of energy costs. This is achieved by creating a receptive management system by ensuring the support and participation of top management in creating an energy management program (Fawkes, 2005). He highlighted the need for strong incentives for energy efficiency improvement in South African industries are, the potential for increasing profit, the need to reduce greenhouse gas (GHG) emissions, the need to maintain economic competitiveness and to delay the cost of new peak-load electricity generation facilities. He also proposed measures that can be used to eliminate barriers including ensuring a high level of trust between consultant and management, ensuring the support of top management, and by the initiation of an energy management program.

## **2.5 Power Factor Correction**

Power factor is the ratio between the kW and the KVA drawn by an electrical load. It is a measure of how effectively the current is being converted into useful work output and more particularly it is a good indicator of the effect of the load current on the efficiency of the supply system. Instruments and analysis techniques for evaluating power factor were devised only to consider the phase shift component of power factor. Phase shift is measured in degrees. Today this component of power factor is

called the displacement power factor (DPF), to distinguish it from the true power factor (TPF) that accounts for distortion as well as phase shift. Utilities that impose low power factor penalties measure only DPF. Many utility companies charge additional fee when power factor is below their limit. Low power factor reduces electrical system's distribution capacity and increase voltage drop.

### 2.5.1 Strategies Used for Correcting Power Factor

In many cement industries, capacitor power factor improvement is used to correct power factor of the whole plant or of a specific section. Capacitor banks are connected in parallel to the load so as to compensate the reactive power loads. At present, in most industries, attention is drawn to the power factor known as DPF. The research intends to correct both DPF and TPF as they might be generated due to the presence of nonlinear loads.

Conventional power factor correction techniques were mostly done by using capacitors as presented by (Richard, 1989). The reactive power compensation technology state of the art was presented by (Dixon et al., 2005). They presented different methods used for the compensation of reactive power including the traditional one (capacitor). The reactive power compensation principle was explained. The traditional technique used to control capacitor banks' for reactive power compensation was fixed or mechanical switched capacitor bank. The next generation of reactive power compensation techniques was thyristorized Var compensators used in the late 1960s whereby thyristors were used to switch on/off the compensator. In these techniques, the compensator is either thyristor switched capacitor (TSC), thyristor switched reactor (TSR) or fixed capacitor thyristor switched reactor (FCTSR). The compensator characteristics were also presented.

El- Sadek (1991) presented static var compensator for reducing energy loss in large industrial loads. He presented the control of voltage regulation and reactive power in large industrial installations by using var compensators (SVC), that control start up time and inrush current and maintain consumed and reactive power at minimum levels, resulting in energy loss reduction and kW generation savings. In this work, the fixed capacitor thyristor controlled reactor was used. The SVC model used was variable controlled current source which is given by:

$$I_c = \left( B_c + \frac{1}{X_{TCR}} \right) V_2 \dots\dots\dots 2.26$$

The system was connected in shunt with inductive reactance  $X_{TCR}$ . Filter capacitors were used as shunt capacitors for SVC at fundamental frequency. The control system improved the performance of SVC and reduces energy loss.

Multi level converters and compensation techniques were presented by Draou et al (2001). They presented three objectives of reactive power compensation which include: power factor correction, improvement of voltage regulation and load balancing. The advanced static Var compensator (ASVC) used a voltage source inverter with capacitor at the DC side as an energy storage element. The PWM was used to control the compensator. Dynamic behavior of the system in the open loop condition was identified. The ASVC system was modeled using d-q transform. Two levels voltage source inverter was used as a var generator. The governing equations for steady state behavior were obtained through the following models:

$$i_q = \frac{V_s \sin \alpha}{R_s} \quad \text{and} \quad i_d = 0 \dots\dots\dots 2.27$$

$$v_{dc} = \frac{V_s}{m} \left( \cos \alpha + \frac{\omega L_s}{R_s} \sin \alpha \right) \dots\dots\dots 2.28$$

Hence

$$P_c = \frac{V_s^2 \sin^2 \alpha}{R_s} \dots\dots\dots 2.29$$

$$q_c = \frac{V_s^2 \sin \alpha \cos \alpha}{R_s} \dots\dots\dots 2.30$$

Where:

- $V_s$                     Source voltage
- $i_q$                     Current in the quadrature axis
- $R_s$                     Resistance of the source
- $L_s$                     Source inductance
- $v_{dc}$                    DC Voltage
- $P_c$                     Active power of compensator
- $Q_c$                     Reactive power of compensator

From the equations it is observed that, active and reactive power depends on the square of supply voltage and the coupling resistor of the ASVC to the mains. According to the control system the ASVC can operate at any power factor. MATLAB

software was used for the simulation and showed good dynamic performance in generating or consuming the reactive power.

3rhkTheory, design and simulation of a 12-pulse, 11KV distribution STATCOM was presented by (Noor Izzri et al., 2002). The designed D-STATCOM used an advanced power electronic based voltage source inverter, to provide voltage stabilization, flicker suppression, power factor correction and harmonic control. The aim was the mitigation of voltage sag on the 11KVdistribution system. PI controller was used to control the flow of reactive power. PWM switching control was used to switch on or off GTOs. Simulation software used was PSCAD/EMTDC

The construction of a prototype D-STATCOM for voltage sag Mitigation was presented by (Masdi et al., 2009). The STATCOM was replacing the static var compensator (SVC). In this work 12 pulse D-STATCOM configuration with IGBT was designed and the graphic based models of the D- STATCOM was developed by using PSCAD/EMTDC simulation program. SPWM controller was used to achieve excellent performance. The simulation was carried out to illustrate the use of D-STATCOM in mitigating voltage sag in distribution systems.

## **2.6 Electrical Load Management (ELM) Process**

Electrical Load Management is a process designed by either the end user or supply side to support perfectly load management in the plant. The load management process should follow the following process:

### **2.6.1 Load Character Assessment**

In this step the load's character is to be defined by measurement, analysis of the data and then by characterization. Statistical parameters, load duration curves, duty cycles and load-profiles are all the means used to define the character of the load. Techniques such as statistical regression may then be used to develop energy consumption model. A statistical regression model gives the energy consumption of a particular load as a function of various variables (Nobel, 1995). The regression model is important in the DSM as it attempts to establish the relationship between the consumer's behaviour via behavioural parameters and the consumer's energy consumption. Large number of loads under DSM programs is generally behaviour driven (Kempton, 1988).

### **2.6.2 Load Control Impact Assessment**

In this step, a load model can be created and can be used to predict the load behaviour with or without the effect of control. It can therefore, model the load and the load's response under all possible load control initiatives. It can also be used to identify control strategies which maximize total benefits.

### **2.6.3 Load Control Implementation**

Depending on types and environment of control, load control can be implemented by various techniques. Communication and information network have direct impacts on load control and other demand-side management programs.

### **2.6.4 Verification**

Post implementation measurements of production, demand and energy consumption information are required to verify the ELM program. This is required in order to avoid a large impact on the energy bill and also lower production.

## **2.7 Conclusions**

In this chapter, a review of electrical energy management has been presented. The review of electrical energy management on the PSI and on the production industry is presented. In the power supply industry, the review found that, there are mainly three methods used for load management, namely direct load control, interruptible load control and time of use (TOU). These methods were developed by the PSI but implemented on the customer's side.

Most LM implemented on the supply side was based on DSM objectives. Various methods of DSM objectives have been reviewed. Load management initiated by customers on the demand side was also reviewed in this chapter. The common load management techniques used were load scheduling, valley filling, peak clipping and strategic conservation. It was observed that, there is a similarity in the methods used to manage load on the demand and supply side.

This research is intended to develop a load management strategy in the demand side in order to minimize the energy cost bearing (demand side), improve the reliability of the supply side, and reduce environmental degradation. Many utility industries in SSA countries have not yet developed or implemented DSM (South Africa is among the SSA countries which have strong DSM) (NER, 2006). Among the results of this research were the identification of the opportunities, possibilities and importance of

developing and using DSM programs for energy consumption reduction that can be adopted by SSA countries

The research also intends to develop an energy consumption model which will be used for the development of an energy performance indicator. Reactive power control is one of the DSM options, which this study will work with. It has been observed that, most of the developed load management activities, did not combine the effect of power factor of the industry and energy efficiency. In this research, DSM program activities adopted include energy efficient program and variable power factor correction. Most of the load scheduling method performed in industries does not involve variable power factor correction. Therefore, the developed STATCOM will ensure variable power factor correction at any variation of load. Finally, using the feedback obtained from the industrial survey, the energy management strategies will be developed

## **CHAPTER THREE: Energy Management Principle and Energy Distribution in Cement Production Processes**

### **3.1 Introduction**

Energy developments are one of the essential activities for sustaining human life and industries. At present, most of the electrical energy generated in SSA countries depends on fossil fuels and renewable energy resources. Generation of electricity by fossil fuels needs high capital investments for construction of the power plant. The process of burning fuels also has an adverse effect on the environment. Renewable energy technologies are considered as green energy but it needs more time and high capital investment for its development. In this regard electrical energy management (EEM) is an essential program for the reduction of electrical energy consumed in many countries around the world.

Electrical energy management is a logically planned method employed by the supply or demand side aimed at the reduction of energy consumption in the system through various initiatives without causing disturbances and inconvenience to the system and users respectively. For the development of strategic energy management programs, energy management principles should be followed. Through industrial survey it has been noticed that, most of the visited industries do not have energy management programs.

This chapter presents energy management principles that can be used in the development of an EM program in any organization including cement industries. The aim of energy management is to enhance reduction of energy consumption in any system whilst maintaining the standard of the production output. The chapter also presents the techniques used to analyse loads in cement industries and analyse the industrial loads using information obtained during the industrial survey. In addition the energy distribution in different sections in cement industries is analysed so as to get an essential basis for the establishment electrical energy management.

### **3.2 Elements of Strategic Energy Management Program in Industry**

An energy management program (EMP) is made up of planning, monitoring, controlling and conserving energy in the industry. It is one of the successful and cost-effective ways of providing the opportunities for energy saving improvement. EMP provides guidance on which steps should be followed for the execution of energy management actions in industries.

It has been observed that, there are few initiatives regarding energy management programs in many SSA industries, resulting in high energy consumption. Some studies mentioned the capacitor bank power factor correction as the most widely used energy management technique to manage electrical energy in industries (Boak et al., 2003).

A successful energy management program begins with a strong commitment and a continuous improvement of the energy system and efficiency. Such commitment involves the appointment of an energy coordinator/ manager, assigning oversight and management duties to energy directors and coordinators, establishing an energy policy and creating an energy team that establishes procedures to assess the performance by regular reviews of energy data, technical assessments and benchmarking (Barney et al., 2005).

In order to acquire broad energy management techniques, industries are required to develop energy use baseline and set improvement goals so that production processes can be tuned to produce greater energy savings (chapter 5). The necessity of energy management in industries is due to the nature of the industrial loads of having big potentials for saving large amounts of energy with little EM initiative. It is also influenced by aspects of industrial operation and activities such as:

- Energy costs which affect the company profitability
- Energy costs which affect the competitiveness of the products in the broad market
- National energy supply/demand balance
- National trade and financial balance
- Local and global environments
- Occupational safety and health
- Loss prevention and waste disposal reduction
- Improved product quality

### **3.2.1 Principles of Electrical Energy Management Program (EEMP)**

As mentioned in section 3.2, the initial stage of designing EEMP is the commitment of the top management to energy management initiatives (Barney et al., 2005). The responsibilities of top managers are to commit to energy management program so as to ensure energy management of the industry or organization is involved to the organization's main program. In the initial process of EEMP, industrial management has to understand the necessity of energy management and they must have a desire for the program to be implemented.

The next step is to appoint an energy management coordinator who can coordinate all energy matters in the industry. The general energy management chart as shown in Figure 3.1 is represented by six steps namely:

- Step 1: make commitment
- Step 2: assess performance and set goals
- Step 3: create action plan
- Step 4: implement action plan
- Step 5: evaluate progress
- Step 6: recognize achievements ( Energy Star, 2007)

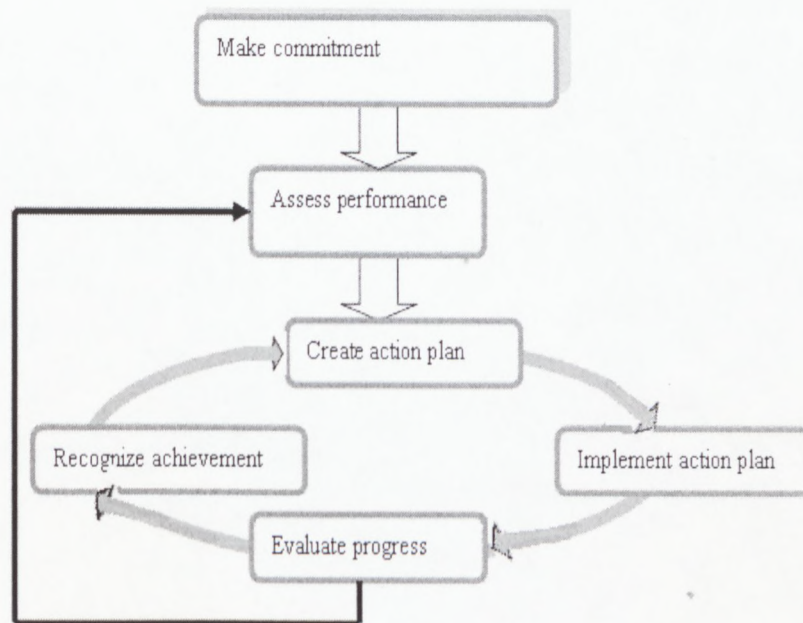


Figure 3.1: Energy Management Design Steps

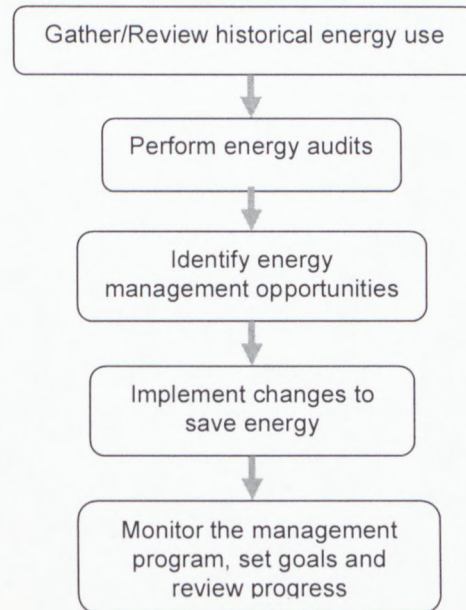
The general procedure for the implementation of an energy management program in industries involves five steps as depicted in Figure 3.2.

### 3.2.2 Energy Accounting

Energy accounting is a system used to track energy consumption and cost on a regular basis. Energy accounting is a critical tool for energy management. It is one of the cost-effective tools that an organization can use to minimize energy costs. With regard to this thesis, energy accounting is the initial stage to be taken for electrical energy management. In industries, energy accounting is carried out by undertaking the following three steps namely:

- Energy use monitoring,
- Energy use record and,
- Performance measures.

The tools used in energy accounting process are as presented by (Barney et al., 2005). These include measuring instruments, computers and related software programs.



**Figure 3.2:** Typical Energy Management Procedure

Energy accounting is also an essential process for evaluating and controlling energy conservation programs. The industrial energy accounting process starts with measurements of data followed by the analysis of those data. The importance of energy accounting includes:

#### **3.2.2.1 Record and Attribute Energy Consumption and Costs.**

Energy costs depend on the amount of energy consumption and the price. In an organisation with many departments, energy accounting compares energy and cost consumed in each section/department and monitor how the use of energy changes over the period.

#### **3.2.2.2 Troubleshoot Energy Problems, Billing Errors and Evaluate Energy Program Success and Communicate Results.**

By consistently tracking energy use, it is possible to identify the problems that may occur throughout the system such as a sudden increase in energy consumption. It also helps to find out whether the expected savings were met or not. This step gives the basic information on the past performance and allows for further actions to achieve the target savings. The information obtained from the evaluation exercise is

communicated to the decision-makers and implementers who are responsible for the energy accounting activities.

### **3.2.2.3 Provide a Basis for Prioritising Energy Capital Investments.**

Facilities or processes which have the highest energy costs are identified and prioritised for energy efficient retrofits or other energy management efforts. Energy accounting by itself is not saving energy but when used as a tool for energy management, it can produce saving. Energy accounting can also help in budgeting, allocating resources for capital investment, and verifying the results of all energy management activities (Gray, 2000).

### **3.2.3 Energy Auditing**

Energy audit in energy management is defined as the monitoring, analysis and verification of the energy consumed in a particular industry or organization or in particular section of the plant. It includes submission of a technical report containing recommendations for improving energy efficiency with cost benefit analysis and an action plan to reduce energy consumption.

The significance of carrying out energy auditing in industries is due to the fact that, the top industrial operating expenses are energy, labour and raw materials. The relationship to the potential cost savings in each of the operating expenses, energy would invariably emerge as a top ranker and thus strategic energy management function is a key player for cost reduction.

Energy audit helps to understand the ways electricity and fuel are consumed in industries and assist to identify areas where energy waste can occur and where the opportunity for the improvement exists. It quantifies energy usage according to its discrete functions.

Industrial energy audit is an effective tool in defining and pursuing a comprehensive energy management programme as it would give a positive orientation to the energy cost reduction. Such a programme helps to keep focus on variations which occur in the energy costs, availability and reliability of energy supply, decide on appropriate energy mix and identify energy conservation technologies. In general, energy audit is the translation of conservation ideas into realities by lending technically feasible solutions with economic and other organizational considerations within a specified time frame. Energy audit is performed based on the type of industry and depth of which final audit is needed and is categorized in to two types:

**3.2.3.1 Preliminary Energy Audit;** is a relatively initial step of energy audit. It establishes energy consumption in the organization, estimates the scope for saving, identifies the most likely and the easiest areas for attention, identifies immediate (especially no/ low cost) improvements, sets a reference point, identifies areas for more detailed study/measurement. Preliminary energy audit uses existing or easily obtained data.

**3.2.3.2 Detailed Energy Audit;** provides a detailed implementation plan for a facility since it evaluates all major energy using systems. This type of audit offers the most accurate estimate of energy savings and cost. It considers the interactive effects of all projects accounts for the energy use of all major equipment and includes detailed energy cost saving calculations and project cost.

### **3.2.4 Industrial Energy Conservation Techniques**

The electricity consumption trend in SSA has been shown to increase rapidly as the population grow (EIA, 2006). This growth of population is incomparable to the increase of generation capacity, transmission and distribution system. This is attributable to the high investment required for the construction of new power plant, transmission and distribution infrastructure. In this situation, the cost effective action is to conserve the existing energy so that it can be used by many consumers while the plan for securing sources of funding for new generation are made.

There are many energy conservation techniques that are practiced by different industries. But most of them are not implemented because of their economical nature (Rajan, 2006). Such techniques and technologies need critical re-examination and re-evaluation. Generally, energy conservation techniques fall into the following categories:

- Efficiency improvement of equipment and specific systems
- Heat recovery
- Power recovery
- Recovery and reuse/recycling of waste materials/waste minimization
- Utilization of renewable energy technology
- Good housekeeping
- equipment improvement and process modification

The adoption of these methods is supported by the establishment of an energy policy and planning to guide and monitor the energy performance. In this manner a strong energy conservation policy is needed to overcome all types of barriers that impede energy management development. Hence the responsibility of energy planning

division includes; setting objectives and targets; preparing detailed action plans and allocating management resources.

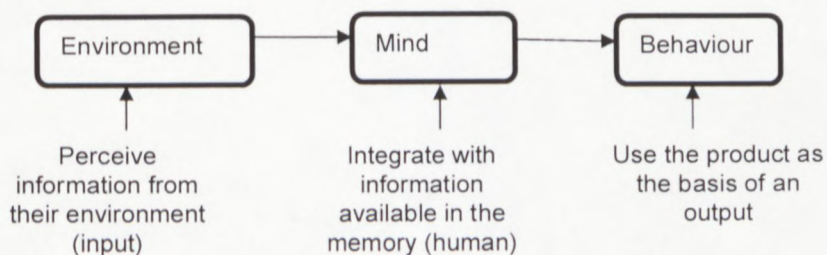
### 3.2.4.1 Energy Awareness and Housekeeping Measures

Awareness is defined as knowing or having knowledge of something as a result of an observation, hearing, noticing or realization of a particular fact. In connection to energy management, energy awareness offers tremendous opportunities to save energy by engaging with issues like attitudes, knowledge, awareness and skills (Vesma, 2002). In any energy management process, awareness is the first step of the behaviour change. Without awareness, there is no further action to conserve energy.

Wogalter and Laughery (1996) explained the important stages that lead to behaviour change as complying with warning or attention, comprehension, beliefs and attitudes, and motivation. A critical determinant of motivation is the cost of compliance. The social influence is another motivational factor affecting compliance.

Figure 3.3 shows the important stages of development of energy management awareness that can be used in industries. The first stage is the environment stage where an external stimulus (information) is the primary input. It is a theory of learning which states that a person will change behaviour because of the experience with the environment. The second stage is the mind, perception and cognition plays important roles in handling, selecting and interpreting information that is acquired. The third stage is behaviour where the information received reflects in the receiver's behaviour.

Energy awareness should be an ongoing process and it can start with top management. There are few energy management initiatives in SSA countries with regards to energy management awareness and housekeeping in industry. For sustaining energy awareness program, energy policy development is of a great importance.



**Figure 3.3:** Major Stages of Energy Awareness Development

During data collection, it was realized that, cement industries do not have energy policy. Energy housekeeping measure is the system and behaviour that can be established in industries with the aim of achieving preliminary energy saving. This can only happen by changing people's habits and promoting day to day energy savings awareness of which it includes:

- Shutting down of unused equipment during idle or unoccupied periods
- Shutting off lights, computers, photocopiers and other heat-producing equipment when not required; upgrade lighting technology
- An increased use of day lighting, where possible
- Checking and recalibrating control components such as room thermostats, air and water temperature controllers, set them properly and verify setting of time clocks
- Checking and adjusting motor drives on fans and pumps for belt tension and coupling alignment

#### **3.2.4.2 Equipment Improvement**

This can be made by improving energy efficiency of the equipment by minor modification of existing production line to provide waste heat recovery and gas pressure recovery or by introducing efficient energy conservation including replacement with advanced equipment.

#### **3.2.4.3 Process Improvement**

This intends to reduce energy consumption by substantial modification of the production process itself by technological development. This is accompanied by a large capital investment. It is linked to the modernization of process aimed at energy conservation, high quality, high added value, improved product yield and man power saving.

#### **3.2.4.4 Energy Efficient Standard and Labelling**

There is an increase of the use of electrical energy dependent appliances and equipment worldwide which results in rapid rises of energy consumption. One of the most cost-effective used methods to curb rising energy/electricity demand from electrical appliances and equipment is to establish energy efficiency standards and labels. Such standards and labels are designed to improve energy efficiency without degrading performance, quality, safety and feature of the appliance.

Energy efficiency standards is the procedure and regulations of the efficient performance of manufactured products or prohibiting the sale of products with less energy-efficient than the minimum allowable standard, often called minimum energy

performance standards (MEPS). The energy efficiency labels are informative tags affixed to manufactured products indicating a product's energy performance (usually in terms of energy use, efficiency, and/or cost) to provide consumers with data necessary for making informed purchases.

Energy labels complement energy standards to provide consumers with information that enables the selection of more efficient models. The rationale and benefits of energy efficiency standards and labelling programs include provision of enormous energy savings potential that can directly lead countries towards sustainable energy use, reduce need for new power plants, reduce greenhouse gas emissions and improve competitiveness for local manufacturers.

### **3.3 Energy and Cement Production Overview**

Cement industries are amongst the energy-intensive industries in SSA countries and found in many countries in the region. Due to the importance of cement products in SSA, a number of new industries has been constructed in many countries as depicted in Appendix 1.4. For example South African has 11, Tanzania has 4, and Nigeria has 7 cement industries.

The increase of these industries leads the direct increase of energy consumers. Therefore, utility industries must have a surplus of energy generation capacity to supply the increased demand, however energy management can be implemented to limit new generation. In addition, the importance of energy management in these industries is due to the context of both local and global energy and environmental discussions because the process of cement production involves the use of high energy resulting in carbon dioxide emission (Worrell et al., 2000).

#### **3.3.1 Cement Production Process.**

Cement production involves the chemical combination of calcium carbonate (limestone), silica, alumina, iron ore and small amounts of other materials. It is produced by burning limestone to make clinker; the clinker is blended with additives and then finely ground to produce different cement types. This process is highly energy intensive. The desired physical and chemical properties of cement can be obtained by changing the percentages of the basic chemical components ( $\text{CaO}$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{Fe}_2\text{O}_3$ ,  $\text{MgO}$ , and  $\text{SO}_3$ ) (World Energy Council, 1995). The cement production process is categorised as shown in Figure 1.10.

### **3.3.1.1 Raw Materials Preparation**

The common raw materials used for cement production are limestone, chalk and clay (Greer et al., 1992). The raw materials are crushed and ground so that the resulting mixture has the desired fineness and chemical composition for delivery to the pyro-processing system. Raw material preparation is an electricity-intensive process. The materials processing differ depending on the pyro-processing process used for example, wet or dry processing.

In dry processing, the materials are ground into a powder using ball mills or roller mills. In a ball mill, steel balls are responsible for decreasing the size of the raw material pieces in a rotating tube. The raw materials may be further dried by waste heat from the kiln exhaust before pyro-processing.

The moisture content in the feed of the dry kiln is typically around 0.5%. When raw materials contain more than 20% moisture, wet processing is preferable. In the wet process, raw materials are ground with the addition of water in a ball mill to produce slurry typically containing 36% moisture.

The energy consumption in raw materials preparation accounts for a small fraction of overall primary energy consumption (about 5% of the total energy). It consumes a large part of electrical energy than other forms of energy. Electricity used in the raw mill and finished grinding mill, strongly depends on the hardness of the material (limestone, clinker, pozzolan extenders) and the desired fineness of the cement as well as the amount of additives.

### **3.3.1.2 Clinker Production**

Clinker production is the most energy-intensive stage in cement production, accounting for over 90% of primary energy use. Clinker is produced by pyro-processing in large kilns. Kiln systems evaporate the free water in the mill, calcine the carbonate constituents and form cement minerals.

The common kiln type used is rotary kiln. The ground raw material, fed into the top of the kiln, moves down the tube toward the flame. In the sintering (or clinkering) zone, the combustion fuel reaches a temperature of 1800–2000°C. Once the materials are ground, they are fed into a kiln for burning. In modern kilns, the raw material is preheated using the waste heat of the kiln. During the burning or pyro-processing, the water is first evaporated after which the chemical composition is

changed and a partial melt is produced. The solid material and partial melt combine into small marble sized pellets called clinker (Worrell et al., 2000).

The raw meal processed in wet rotary kilns, typically contains approximately 36% moisture. These kilns were developed as an upgrade of the original long dry kiln to improve the fineness control in the raw mill. Fuel use in a wet kiln can vary between 5.3 and 7.1 GJ/t clinker (COWIconsult, 1992 & Van der Vleuten, 1994).

The choice of processes is dictated by the characteristics of available raw materials, cost of fuel, and conditions of the location. The main advantages of the wet process are lower plant construction costs, higher feedstock flexibility and easier manufacture of high-quality products.

The feed material in a dry kiln has much lower moisture content (0.5%). The first development of the dry process was long dry kiln without preheating or with one stage suspension preheating. Later developments have added multi-stage suspension pre-heaters (a cyclone) or shaft pre-heater. Additionally, pre-calciner technology was more recently developed in which a second combustion chamber has been added to a conventional pre-heater that allows for further reduction of kiln energy requirements. The dry process is the most modern and energy-efficient configuration.

The typical fuel consumption of a dry kiln with 4-5 stage preheating can vary between 3.2 and 3.5 GJ/t of clinker (Van der Vleuten, 1994). The dry kiln is used in the case study consume fuel amounting to 3.52 GJ/t while most efficient pre-heater pre-calciner kilns use approximately 2.9 GJ/t of clinker. A kiln dust (KD) bypass system is required to remove alkalis, sulphates, and chlorides. Such systems lead to additional energy losses. The clinker is cooled using a grate cooler or the tube or planetary cooler in order to ensure maximum yield of alite (tricalcium silicate), an important component for the hardening properties of cement.

### **3.3.1.3 Finish Grinding**

The clinker nodules are stored in the clinker silo. The equipment and process are used to transport clinker from the clinker coolers to storage and then to the finished mills including belt conveyors and bucket elevators (Greer et al, 1992).

The nodules of cement clinker are ground in this section to produce cement powder. Grinding of cement clinker, together with additives (3–5%) to control the properties of the cement (gypsum and anhydrite) can be done by using ball mills, roller mills, or

roller presses or combinations of these milling techniques. In ball and tube mills, the clinker and gypsum are fed into one end of a horizontal cylinder and partially ground. Coarse material is separated in a classifier to be returned for additional grinding. Modern ball mills uses 32 to 37 kWh/t (Seebach et al., 1996).

Finished cement is stored in silos, tested and filled into bags, or shipped in bulk on bulk cement trucks or railcars. Additional power is consumed for conveyor belts and packing of cement. The energy used in this section is electricity and the total consumption is about 5% of the total power consumption.

### 3.3.2 Energy Consumption in Cement Industries of SSA

The energy consumption pattern of the process is very important for a result-oriented energy management of the organization. Cement industries consume two basic forms of energy in its production process, that is, fuel such as coal, oil and gas for thermal generation and electricity. Energy consumption constitutes of fuel input for clinker burning and electricity used for raw material processing, clinker grinding and packing.

The major thermal energy consuming process is clinker burning, it consumes up to 99 percent of the total thermal energy of the industries (WEC, 1995) while electricity is more consumed in the remaining processes. Figure 3.4 shows the energy breakdown for the major processes in a typical cement plant of dry process kiln while Figure 3.5 shows the breakdown of electricity consumption in most of the cement plants.

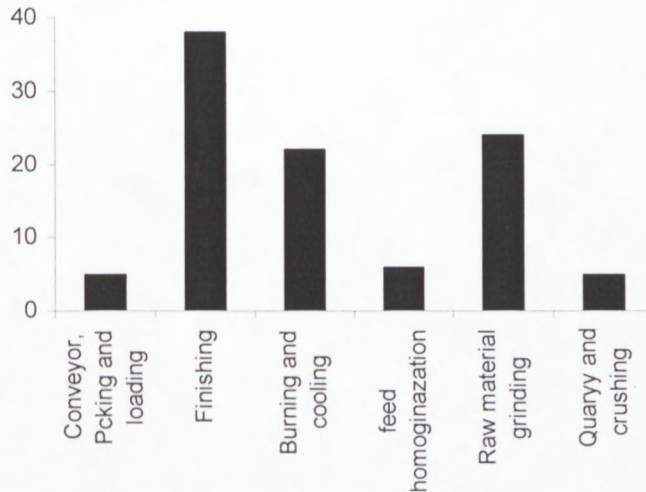
Table 3.1 shows the energy consumption of cement industry sections for a typical dry kiln. It is observed that, only two of the sections directly use fuel energy for the production process, while electricity is consumed in each section. Therefore this study focuses on the management of electrical energy only.

**Table3.1:** The Percentage Energy Consumption in a Typical Dry Process Portland Cement Plant

Process	Fuel %	Electricity %	Total primary energy %
Raw material collection	1	5	2
Raw material processing	-	33	8
Clinker burning	99	19	79
Clinker grinding	-	38	10
Conveying, packing	-	5	1

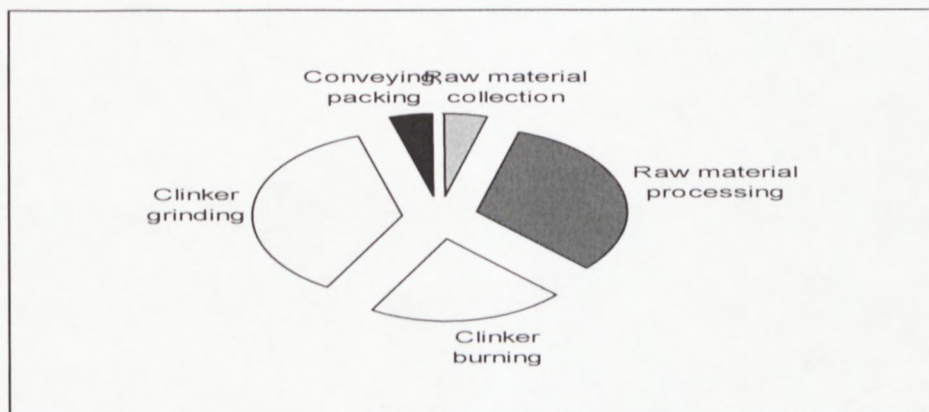
**Source:** WEC, 1995

One of the techniques used to reduce high energy consumption in cement production is the use of different energy types within the process (electricity, coal, gas and others). This is called energy mix and has been practiced in several countries to minimize the need for heavy dependence on oil in cement industries (ECCJ, 1994). Currently, waste products (tires and municipal solid waste) and low-grade fuels are used extensively as energy sources for clinker burning. In 1992, in Japan, nearly 20 per cent of the waste tires were used for clinker burning. Figure 3.6 show an energy model for a cement industry.



**Figure 3.4:** Electrical Energy Consumption in Different Process of Cement Plants

Many cement producers around the world have been realizing that, electrical energy contributes more than 30% of the total cement production cost and 50% of the total energy costs (Fujimoto, 1994) while the LAFRAGE report (2007) shows that, electrical energy cost contribute 31% to the total production cost.



**Figure 3.5:** Electrical Energy Consumption in Various Processes

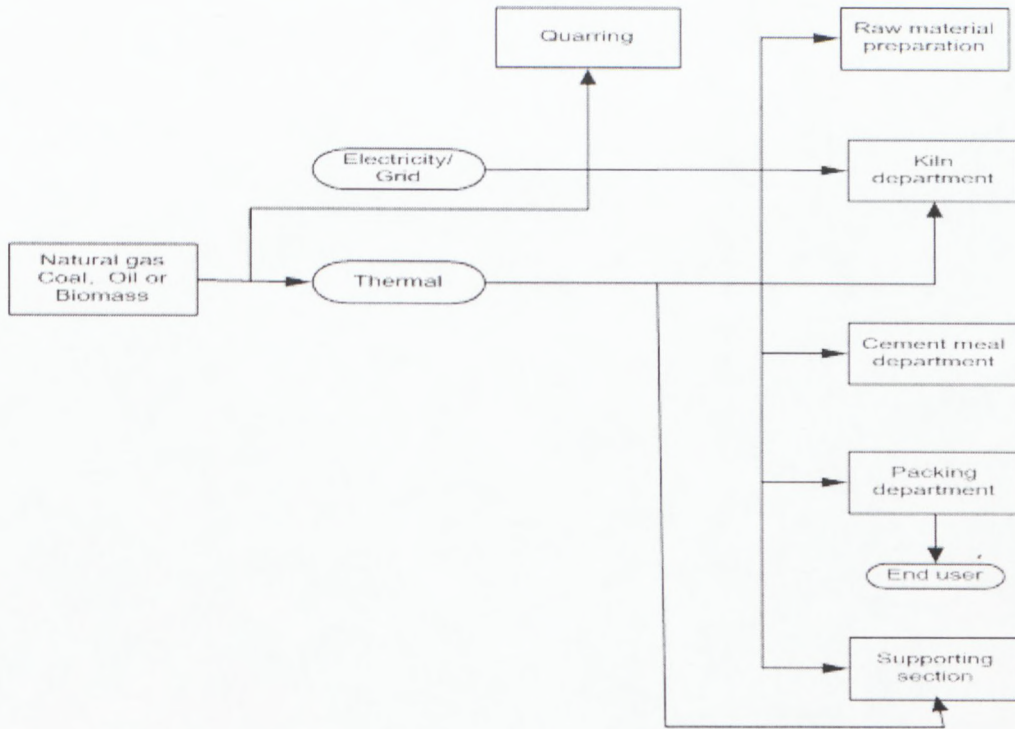


Figure 3.6: Energy Model for a Cement Industry

### 3.4 Energy Efficiency Technologies and Consideration in Cement Industry.

There are a number of technologies and measures that can reduce the energy consumption (the electricity or fuel consumption per unit of output) in cement production processes. Martin et al. (1999) provided measures used to estimate the average potential energy savings and costs of each measure, and they are considered according to the process as outlined below:

#### 3.4.1 Use of Roller Mills for Raw Meal Grinding

The traditional ball mills used for grinding raw materials is either replaced by a high-efficiency roller mills, ball mills combined with high pressure roller presses, or by horizontal roller mills. The use of these advanced mills saves energy without compromising product quality. The estimated energy savings was 7 kWh/t of raw materials, by the installation of a vertical or horizontal roller mill (Best Available Techniques for Cement Industry, 1997). An additional advantage of these mills is that they can combine raw material drying with the roller process by using large quantities of low grade waste heat from the kilns or clinker coolers (Venkateswaran & Lowitt, 1988; Holderbank Consulting, 1993).

The energy-efficient practices and technologies in raw materials preparation are essential and can be adopted from the following sections:

- Efficient transport systems
- Raw meal blending systems (dry process)
- Conversion to closed circuit wash mill
- High-efficiency roller mills (dry cement)
- High-efficiency classifiers (dry cement)

#### **3.4.2 Fuel Combustion Improvements in Kilns**

Fuel combustion systems in kilns can contribute to kiln inefficiencies if firing is poorly adjusted, incomplete fuel burn-out with high carbon monoxide (CO) formation and combustion with excess air. Techniques of flame control resulted in fuel savings of 2-10% depending on the kiln type (Venkateswaran and Lowitt, 1988). A recent technology that has been demonstrated in several locations is the Gyro-therm technology that improves gas flame quality while reducing NO<sub>x</sub> emissions. A demonstration project at an Adelaide Brighton plant in Australia found average fuel savings of between 5 -10% as well as an increase in output of 10% (Centre for the Analysis and Dissemination, 1997).

The energy-efficient practices and technologies in this section can be considered in the following:

- Fuel combustion system improvements
- Kiln shell heat loss reduction and use of waste fuels
- Conversion to modern grate cooler
- Optimize grate coolers
- Heat recovery for power generation
- Conversion to pre-heater, pre-calciner kilns
- Conversion to semi-wet kilns
- Long dry kiln conversion to multi-stage pre-heater kiln
- Addition of pre-calciner to pre-heater kiln

#### **3.4.3 Process Control, Optimization and Management Systems**

Optimization, load management and operational improvement are the process that involve financial investment but are found to have encouraged energy saving results. Heat from the kiln may be lost through non-optimal process conditions or process management. Use of automated computer control systems may help to optimize the combustion process and conditions. Improved process control can also help to improve the product quality, for example reactivity and hardness of the produced clinker, which leads to a more efficient clinker grinding.

Most modern systems use fuzzy logic or expert control, while some use rule-based control strategies. Expert control systems do not use a modelled process to control

process conditions, but it tries to simulate the best controller using information from various stages in the process. Energy savings from such process control systems may vary between 2.5 - 10% and the typical savings are estimated at 2.5–5% (Energy Technology Support Unit, 1988 and Ruby, 1997). Savings of 4% of fuel intensity and 3% savings of electricity intensity or 4 kWh/t cement is estimated.

#### **3.4.4 Wet Process Conversion to Multi-Stage Pre-Heater and Pre-Calciner Kiln**

In some cases, it may be feasible to convert a wet process facility to a state-of-the-art dry process production facility that includes both pre-heater and pre-calciner technology. Average fuel consumption in wet kilns is estimated at 6.0 GJ/t. Studies of several kiln conversions showed the possibility of fuel savings of 3.4 GJ/t, but the baseline of wet kiln energy use was higher than current levels (6.8 GJ/t) (Venkateswaran & Lowitt, 1988). For example, In Hranice, the Czech Republic a 1050 tones wet process plant was converted to a dry kiln plant, thus the energy consumption was 3.13 GJ/t clinker (Cement Plant Modernization in Central Europe, 1994). Therefore, a fuel savings of 2.9 GJ/t and an increase in power use of about 10 kWh/t clinker was realized.

#### **3.4.5 Energy Efficient Finished Grinding**

The energy efficiency of ball mills used in finished grinding is relatively low, it consumes up to 33–45 kWh/t cement, depending on the fineness of the cement (Marchal, 1997).

The designed new mills have significantly reduced power consumption in the finished mill to 22–33 kWh/t cement (Seebach et al., 1996). Today, high-pressure roller presses are most often used to expand the capacity of existing grinding mills and are found in the countries with high electricity costs or with poor power supply (Seebach et al., 1996). The electricity savings obtained when the ball mill was replaced with new finish grinding mill was estimated to be 27kWh/t. An estimate of the additional savings of 8 kWh/t was realized for a pre-grinding system to a ball mill (Scheuer & Sprung, 1990; Holland et al., 1997). Capital cost estimates for installing a new roller press vary widely in the literature, ranging from \$3.6/t to \$8/t cement capacity. The capital costs of roller press systems are lower than those for other systems (Kreisberg, 1993).

The common area to be considered for energy efficient improvement in the cement industries are as highlighted:

- Use of slip power recovery system
- Use of variable voltage & frequency drive
- Use of soft starter for motors
- Use of high efficiency fans
- Use of high efficiency separators
- Use of high efficiency motors
- Use of bucket elevator in place of pneumatic conveying
- Introduction of pre crusher in raw and cement mill

#### **3.4.6 Product Change**

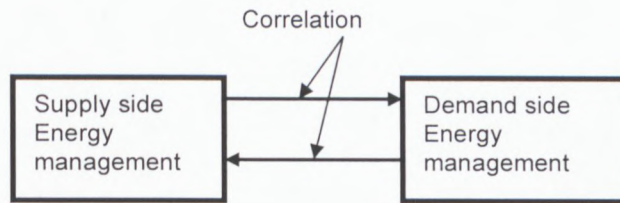
The production of blended cements involves the inter-grinding of clinker with one or more additives (fly ash, pozzolans, blast furnace slag, silica fume, volcanic ash) in various proportions. The use of blended cements is particularly attractive efficiency option since the inter-grinding of clinker with other additives not only allows for a reduction in the energy used in clinker production, but also corresponds to a reduction of carbon dioxide emissions in calcination as well. Blended cements are very common in Europe and blast furnace and pozzolanic cements account for about 12% of total cement production with Portland composite cement accounting for an additional 44%. Electricity consumption however, is expected to increase due to the added electricity consumption associated with grinding the blending materials. The increase in electricity consumption is estimated at 17 kWh/t. Hence the efficiency improvement of the grinding machine is very important.

### **3.5 Analysis of Industrial Electrical Loads and their Energy Management Potentials in Cement Industries**

Industrial electrical energy management program is an essential tool for the reduction of electrical energy consumed in the plant. This can also reduce the overall energy consumption in the system. Figure 3.7 shows the block diagram of two energy systems (demand and supply), where correlation between them is analysed. The representation of the two electrical energy systems explained as; generation, transmission and distribution belong to the supply side block, whereas the demand side block (consumers) can be residential, commercial or industrial. In this thesis the demand side is the cement industry.

The importance of industrial energy management is stimulated by the tendency of industries to consume large amount of energy than in other sectors. Industrial sector loads are aggregate loads such as motors with capacity ranging from a fractional watt to several thousand Mega watts. The second reason for the analysis of EM in industry is that, many industrial loads in many industries have similar characteristics of which the development of load management programs for one industry can be

used in other industries having loads of the same characteristics. In addition, it seems that, a small energy management initiative can result in enormous energy saving.



**Figure 3.7:** The Layout of Electrical Energy System (Supply and Demand)

An industrial survey and preliminary energy audit have been undertaken so as to identify types of industrial loads which have opportunities and can be subjected to energy management. Through industrial survey in some cement industries in SSA, it has been found out that, electric motors, lightings and electronic equipment have a great energy saving potentials. The presented survey results are for cement industries in Tanzania.

According to the nature of the cement production, all cement industries have almost the same types of load in their production section. The main difference is that, some industries have more than one production line which leads to higher loads than the one that have single production line and they might have different control system.

### 3.5.1 Data Collection Program

Table 3.2 and Table 3.3 present electrical energy information and characteristics of Tanzania supply network and loads of a single line cements production industry (Mbeya Cement). The presented loads are those that have an influence in high energy consumption.

It has been observed that, the term electrical energy management is not a new terminology to industries; it has been implemented for the reduction of electricity energy costs. Power factor improvement is a widely used method for the load management. The aim of electrical energy management in industrial authority is to reduce the plant's electric bill so as to reduce production costs. Bjorke (1985) defined energy management as the activities that can minimize running costs for the industry and improve the reliability of the power supply system.

**Table 3.2:** Electrical Energy Information and Characteristics of Tanzania Power Network

Important information from TANESCO (Power Utility Company)				
S/N		Thermal (MW)	Hydro (MW)	Others source
1	Available capacity	562	561	No database
2	Number of customers	Industrial (T3)	Domestic (T1)	
		189	560,173	
3	Annual consumption status (kWh)	1,447,878,745 (2007)		
4	Peak demand (MW)	615 with peak time 18:30-20:30		
5	Load factor	65% ( 2002)		
6	Type of heavy industrial consumers	Those belongs to Tariffs T3 and T5		
7	Any energy consumption standards and labelling	NA		
8	Per capita energy consumption (kWh)	100		
9	Developed DSM programs	Not developed		
10	Heard about DSM programs	Yes		
11	Any energy management arrangement	Load shedding during the energy crises		
12	Pf	0.85 (2001)		
13	Type of Tariff applicable	Two part tariff and fixed rate tariff		
14	Tariffs allocation for industrial consumer	Two part tariff		
15	Demand forecast	Yes		
16	Energy efficiency program	No energy efficient program		
17	Load duration characteristics	Given in appendix 2 (2002)		
18	Strategy for loss reduction	NA		
19	Number of current and forecast industrial customers (T3)	377-(2010)	417- (2011)	
20	Forecasted percentage increase of industrial consumer , from 2008	99.4%	120.6%	

**Source:** TANESCO, From 2002-2011

T1 Electricity tariff for domestic category

T3 Electricity Tariffs for Industrial category

In the process of energy consumption in different activities some energy is wasted. This requires analysis of the existing loads and system so as to identify the extent of wastage and propose concrete measures. The proposed methods to be used for LM in industries include:

- Flexible power factor improvement and power quality improvement
- Optimal load scheduling
- Use of energy efficient techniques (motor)
- Good house keeping

### 3.5.2 Energy Management Potentials in Surveyed Industries

**3.5.2.1 Power Factor Correction;** capacitor banks are used in many industries. Most of the switching mechanism is mechanical and do not vary when the plant load is varying. The presence of nonlinear load also has not been considered.

**3.5.2.2 Load Scheduling;** manual load scheduling is rarely applied in the industry. Authors of many literatures have presented load scheduling as an energy management

technique in the supply side, but there are some studies which show that, this method is being used in some industries worldwide including SSA (Ashok, 2006). The way it is implemented depends on various factors including the use of time dependant tariff, use of price signal like spot price signal. In some cases automatic load scheduling is used but in this case the authors concentrated more on energy saving without considering production output. Many of the users of this method intend to reduce maximum demand.

**Table 3.3:** Loads and Electrical Energy Characteristic

<b>Mbeya Cement Industry ; Energy Information</b>				
1	Production line	1		
2	Plant capacity MVA	6		
3	Types of industrial loads	Motors, lightings, Fans, air-condition, computers and other miscellaneous loads		
4	Power /tone of cement	125kWh/t		
5	Plants/section which consume large amount of Electrical energy	1. Cement mills	2. Raw material preparation (RM)	3. Kiln
6	Average Electrical energy Consumption/ month kWh (2008)	1041717	729804	602918
7	% consumption of electricity	38%	32%	27%
8	Load curve characteristics	Given in Figure 3.11,3.12,3.13		
9	Average site power kWh (2008)	2,603,400		
10	Types of motor control system used in the plant	Resistance control and few VSD		
11	Areas contributing to energy losses	Motors, lightings, electronics equipments		
12	Type of kiln,	Dry rotary kiln ( efficient drive)		
13	Production characteristic	Refer Figure 3.10 and Figure 3.13		
14	Any energy efficiency measure/ technology existing.	Maintenance but it is not done intentionally for loss reduction it is intended to minimize the plant breakdown		
15	Demand side management option implemented in industries	NA		
16	Energy management program existing in industry	Power factor improvement (fixed capacitor bank)		
17	Relationship between energy consumption and production capacity	kWh/tonne Refer Figure 5.7		
18	Operating power factor of the industry (improved)	Before correction is 0.79, after correction is 0.93 capacitor banks is used		
19	Any electrical energy conservation measure taken by industry	None		
20	Any use of product change	Pozolana		
21	Average industrial consumption of electrical energy	Attached in <b>Appendix 6.1</b>		
22	Energy efficient motors and ratings	NA		
23	Summary of the plant load	See <b>Appendix 3.1</b>		

**Source:** Mbeya Cement Industry (2008)

### 3.5.2.3 Use of Technology Innovation or Advancement Process and Energy Efficient

**Motors:** In this method, energy efficient motor is compared with the standard motor, payback period is analyzed due to the saving achieved from the energy efficacy technology and the replacement is undertaken (In many cases, influence of under or overload is not much studied) although many theories and literatures show how these factors relate with energy losses.

**3.5.2.4 Good Housekeeping;** the survey results show that, many workers and technical personnel's are not aware of EEM.

**3.5.2.5 Load Mix;** The common types and composition of cement industrial loads constitutes; 70% induction motors, 13% lighting loads and 17% other loads.

### 3.5.3 Characteristics of the Surveyed Loads

Motors are the predominant load of the studied industry, because most of the power consumed is used by motor drives to convert electrical energy into mechanical energy. Depending on the size and types of motor, a three phases or single phase voltage is applied (Boldea & Nasar, 2001). When energy is converted from electrical to mechanical form, losses are generated, the type of losses and margin of the losses are elaborated in chapter 5. Other factors causing energy losses include motor working under or over voltage and an unbalanced load. For this reasons, this research also analysed the three phase induction motors principles and operation.

#### 3.5.3.1 Motors Principles of Operation

Electrical energy consumption is dynamic and its variation depends on many factors including size of loads and percentage loading.

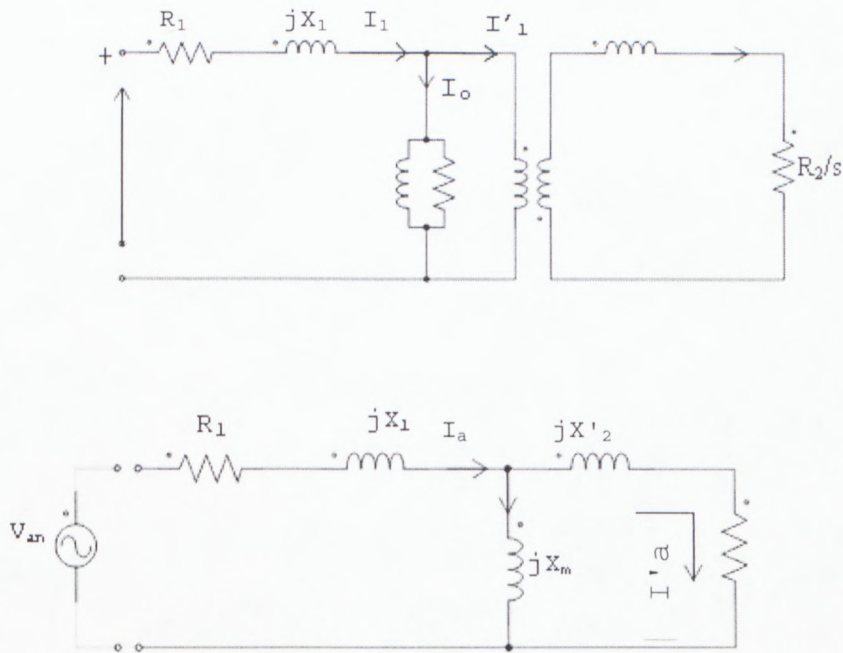
Three phase system power is given in the equation below.

$$P = \sqrt{3} \times \frac{I \times V \times \cos\theta}{1000} \text{ (kW)} \dots\dots\dots 3.1$$

Where:  $I$  is the phase current  
 $V$  is line voltage and  
 $\cos\theta$  is the power factor of the system and it is a phase difference between voltage and current.

Globally the motor system is disaggregated in its consumption as shown in Figure 3.8. Figure 3.8 is the equivalent circuit of the motor which is mostly useful for the motors analysis.

$jX_2$



**Figure 3.8:** Equivalent Circuits of Induction Motor

In cement industries, motors are used to drive most loads including crushers, blenders, raw mill, kiln drive, cement mills and many small loads in the plant. The big motors are mostly found in raw mill, kiln and cement mills sections and they are of slip ring. The rating of the most influential motors is shown in Table 3.4. Analysis is made to find out how these equipment and machines consume energy and how this consumption can be reduced.

### 3.5.3.2 Analysis of Industrial Loads and its Application

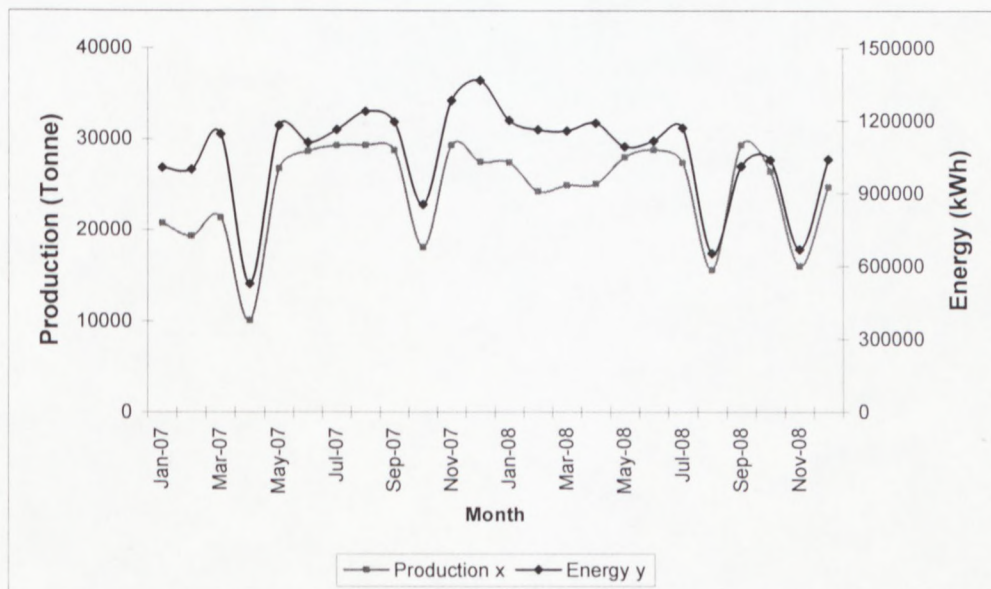
Table 3.4 shows, the predominant load in cement industries, they are three phase induction motors. These loads are considered as main energy consumer of the cement industry. Apart from normal load consumption loss there are areas which have not yet been given much consideration in electrical energy management concern, namely, Voltage and frequency distortion. Control of starting current by establishing the starting sequence has not been considered in the energy management in many literatures. In this study the impact of unbalanced voltage to the motor energy saving is studied and compared with numerical analysis. The visited industries are taken as a case study but the findings from the study can be used in other industries in Sub-Saharan Africa. The total load composition calculation is given in Appendix 3.1

**Table 3.4:** Main Plant Loads

Section	Types of load	Quantity	Rating (kW)
Crushing department	motors		30
	Auxiliary motors		
	Hammer mills motors	2	90
	Crane and auxiliaries		90
Raw mill department	Raw mill motor	1	1250
	Mill fan motor	1	584
	Auxiliary motor		158
Kiln and kiln feeding department	ID fan motor	1	670
	Compressor motors	3	132
	Auxiliary		350
Cement mill and packing department	Mill motor	1	1820
	Compressor	1	132
Other supporting services (estimated)	Lighting, fans, A/C, computers and printing, and other miscellaneous load		60

### 3.5.4 Electrical Energy Profile for the Cement Industry; Case Study

The industry is located in the South-western part of Tanzania. The capacity of the industry is 6 MVA and has one production line. The industry uses coal and heavy fuel oil for its thermal energy and electricity for other forms of energy. Figure 3.9 shows the comparison of monthly energy consumption and production output. From this Figure it is evident that energy management is not practiced.

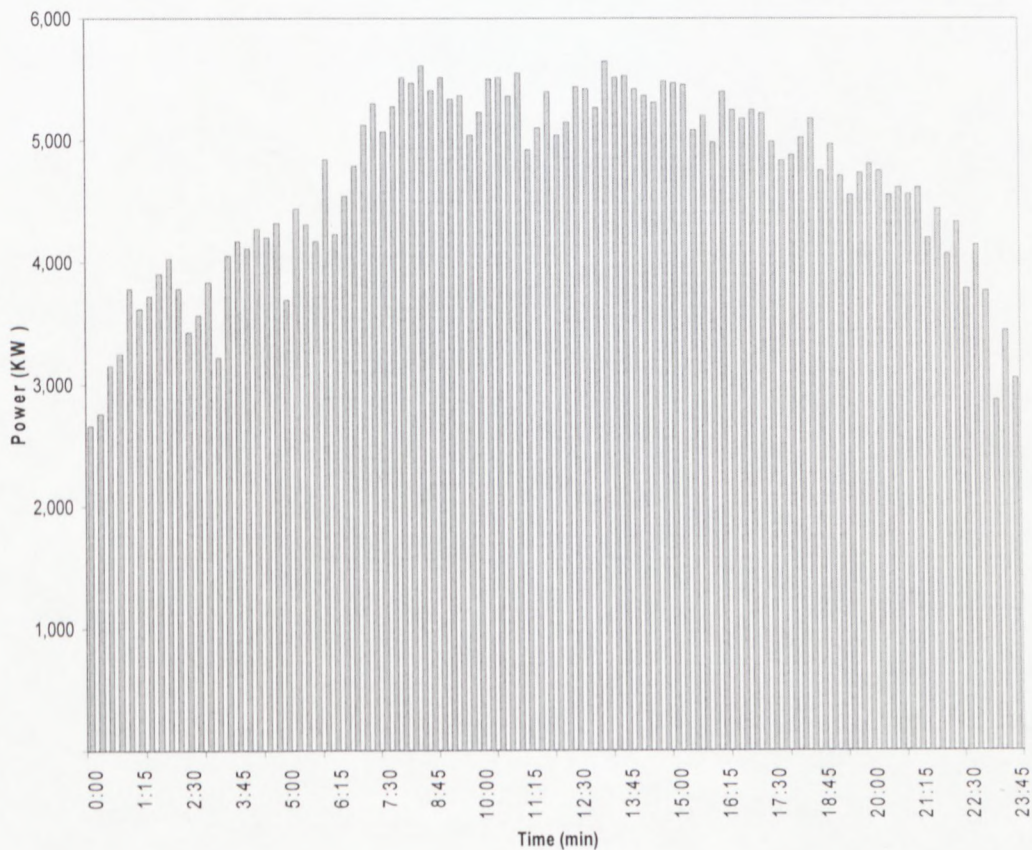


**Figure 3.9:** Energy Consumption and Production Output

The production characteristic for the 24 months is steady, that is almost constant but there is a big deviation on energy consumption for the same production period. In the

month of October, energy consumption was very low for the same amount of production output. In this case, energy management program is required so as to find the optimal value of energy needed for the production output.

The plant load profile of one day is given in Figure 3.10. The data presented is the plant demand for 24 hours as the plant operates continuously. It is assumed that at this particular day, all influential or main machines were in operation. The data was taken at every 15 minute interval of time in the day of 18<sup>th</sup> of September 2008. The data was measured by KW meter installed in the plant. There is an over shoot of energy at around 8 o'clock AM after about 30 min. The over shoot went down and the next one was at around 11:30. This is assumed that, it was caused by an injection of load into the system.

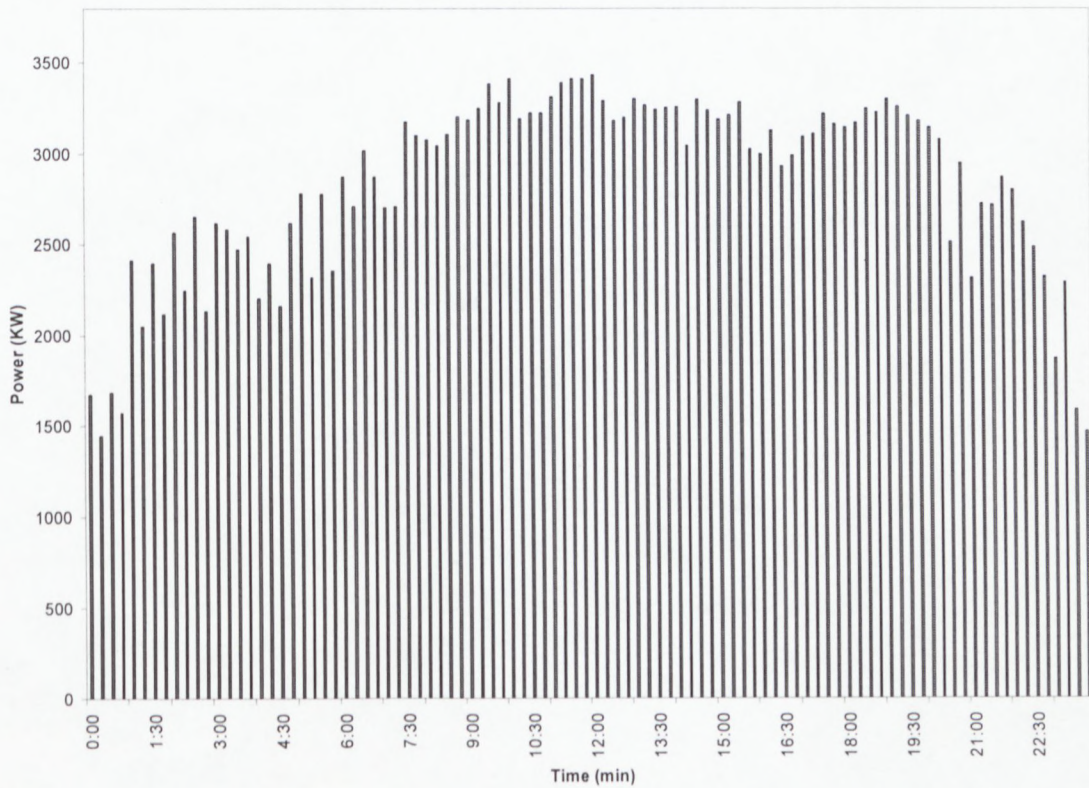


**Figure 3.10:** Plant Load Profile of Weekday

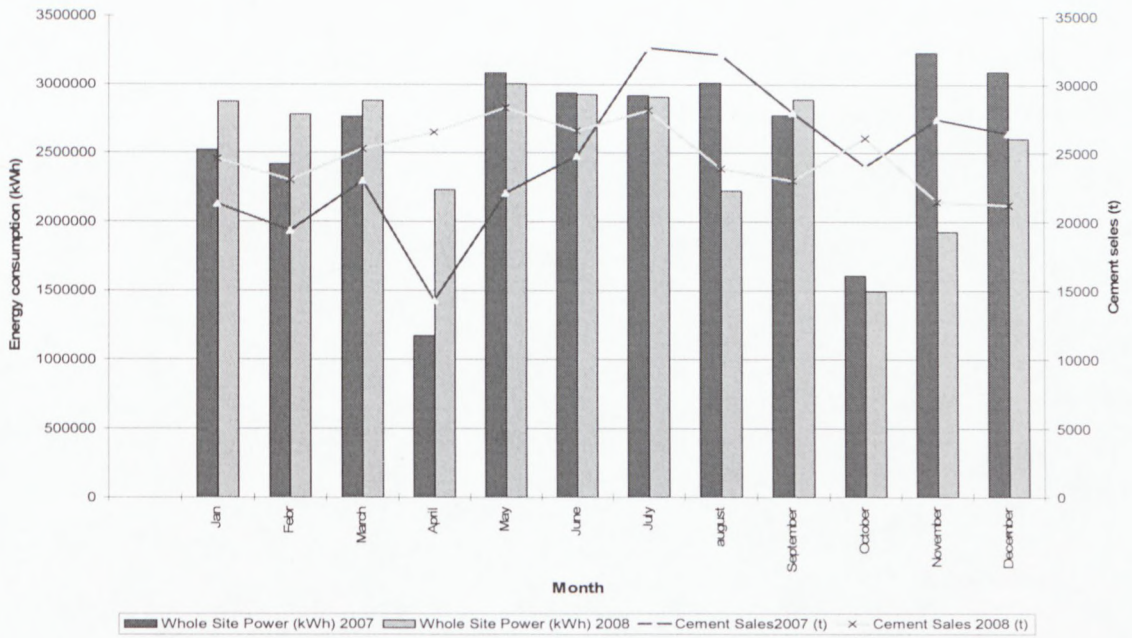
Figure 3.11 shows the plant load profile of one day for 15 min interval when the cement mills machine and most of load in that section were off. In general, from load patterns of the two cases (Figure 3.10 and Figure 3.11), it is evident that, if proper load shedding design is implemented, it can lead to the plant demand management

which would enhance the reduction of demand charge. The demand at the 15 min interval in Figure 3.10 is 5.6MW while for the Figure 3.11 is 3.45MW. Hence, if the plant is designed to operate with one of the big machines at a time (Raw mills or cement mills), a considerable amount of demand might be controlled thus leading to the saving of money for purchasing energy.

Figure 3.12 shows the comparison on monthly energy consumption and cement sales for the year 2007 and 2008. This information shows that, there is an improvement in energy consumption in year 2008 compared to the year 2007 for approximately the same production sales.

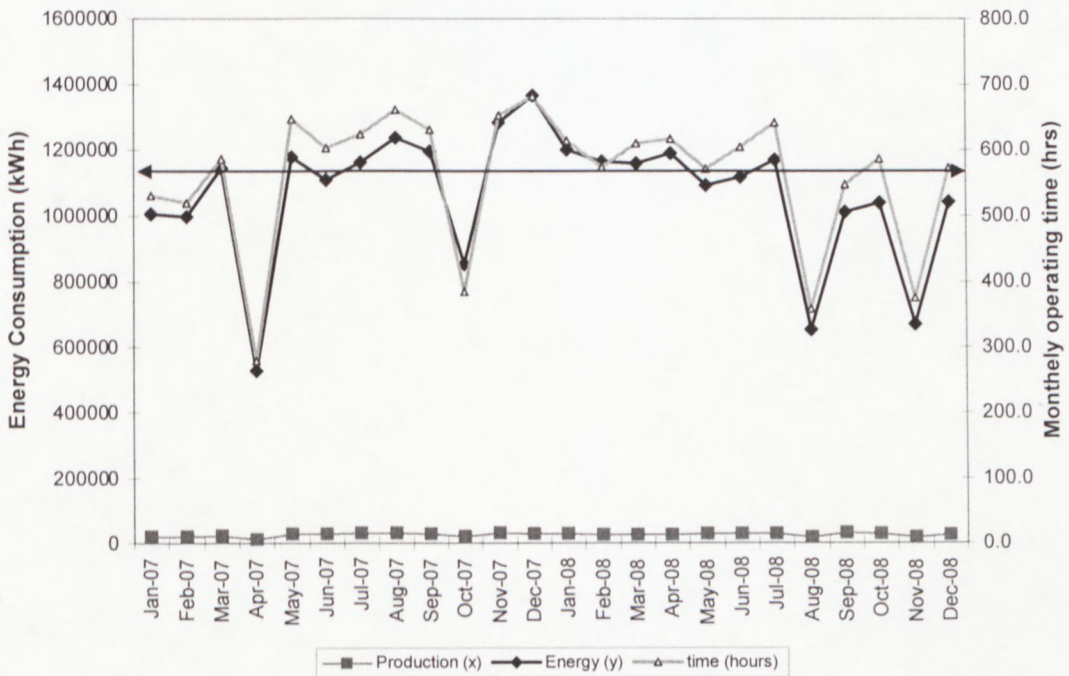


**Figure 3.11:** Plant Load Profile when Cement Mill was not in Operation



**Figure 3.12:** The Comparison of Monthly Energy Consumption and Production for Two Consecutive Years 2007-2008.

The relationship between monthly electrical energy consumption and hours of operation within a month is given in Figure 3.13. In this figure, the straight line drawn indicates the average energy consumption that can be targeted without affecting the production



**Figure 3.13:** Relationship between Energy Consumption, Operating Hours and Production

### 3.6 Conclusion

This chapter presented energy management principles that can be applied in organizations/ industries and enhance reduction of electrical energy consumption. Energy accounting and auditing are mentioned to be the most important process in energy management. Energy distribution in cement industry was highlighted. It has been revealed that, energy conservation is mainly influenced by target setting, operational control and improvement and process optimization. The potential areas for energy conservation in cement industries have been also analysed. The monthly energy profile of the case study industry showed that, there is a deviation of monthly energy consumption in some months. Large amounts of energy was used in some months while in other months moderate electrical energy was used for the same quantity of production. This reveals that the industry is not implementing enough measures for the reduction of electrical energy.

In addition, this variation of consumption shows that, energy housekeeping and, energy conservation measure and awareness are not implemented in this industry, hence it is proposed that, an energy policy be developed so as to build an energy management program.

It has been observed that, many cement industries in SSA use some form of energy management methods while some other forms are not yet implemented. Generally the area to be considered for energy saving includes energy efficient equipment, reactive energy control and peak load reduction. The plant load profile data shows that, scheduling of sections or big machines can have an influence on demand management and can lead to money saving (industry).

## **CHAPTER FOUR: Demand Side Management: Development and its Role on Electrical Energy Management in Manufacturing Industries**

### **4.1 Introduction**

Demand-Side Management (DSM) program is an electric utilities' planning, implementing and monitoring of activities designed to encourage customers to modify their levels and patterns of electricity consumption. These activities are aimed at reducing future demand or demand growth through the use of energy efficiency techniques or and load management programs. DSM program is either developed by the supply side or other regulatory unit associated with the supply side but the actions are mostly implemented on the demand side. The DSM program comprises number of programs depending on the focused sector such as industrial/ commercial or residential.

This chapter presents the concept of DSM, its effectiveness and role to electrical energy management in industries. The process needed for the development and effectiveness of operation is also highlighted. It also assesses the potentials for electricity load management techniques and analyses barriers behind the development of DSM in other countries within SSA. In this chapter, a tool for assessing DSM options is also developed and used on the cement industry as a case study to help identify the ELM opportunities in industries.

### **4.2 The Importance of DSM**

Historically, DSM was first developed to avoid the construction of new electricity power plants and for grid strengthening. Recently DSM programs are used to reduce the need for additional peak or base load generating capacity and/or distribution facilities. Many SSA countries have neither developed nor adopted DSM. South Africa is amongst the countries enjoying the advantage of the DSM programs (Eskom, 2005; DSM South Africa, 2002). Through different load management actions, Eskom has been reducing peak demand especially during evening peak.

There is a strong relationship between DSM and industrial load/ energy management. Looking on how they relate, DSM is interested in the effects from an aggregate number of loads in the system whilst electrical load management (ELM) is only interested in the effect of control interactions of one specific consumer's electric load such as an industry.

For the customer's side, DSM offers the opportunity to reduce their energy bill through efficiency and conservation measures. In case of industrial customers, this would translate into lower production costs and more competitive product. Utilities can therefore be one of the key driving forces behind DSM programs implementation by encouraging and motivating consumers on the effective and efficient use of energy subsequently reduce the energy demand and thus energy costs.

In addition, consumers may benefit on special incentives offered by DSM program. Organizations with energy-dependent activities such as industries are participating in DSM to reduce their own energy consumption and costs. Industries may reduce overall energy demand by adopting ELM programs. Depending on the ELM techniques, many customers see the flexibility to reschedule their periods of highest demand to reduce their peak demand over a longer or different time period. Hence it is seen that, DSM program focuses on three main categories:

- Cost reduction motives; -- for demand and supply side
- Environmental motives; -- supply authority and state/ government and
- Reliability and network motives; -- supply authority and government

#### **4.3 Concept of Demand Side Management Program**

The concept of DSM was derived in response to the prospective problems of energy security, global warming and the need for sustainable energy development. This was triggered by the oil embargo of the 1970's that resulted in high cost of energy services. It was designed to respond to the logical process that helps utilities optimize the required demand. DSM activities involve actions taken on the demand side of the electric meter. These activities include load management, strategic load conservation (energy efficiency), electrification and strategic load growth (Gelling & Chamberlin, 1993).

In this study DSM concentrate on voluntarily customer's control of maximum demand and energy consumption by adopting DSM objectives namely strategic load conservation, load scheduling and peak clipping. (Eskom DSM, 2005) defined DSM as the planning, implementation and monitoring of end-user's activities designed to encourage consumers to modify patterns of electricity usage by altering the time of consumption and reduction of electricity demand level.

Many Utilities that run DSM programs achieve major energy savings at low costs (Reddy, 1996). For example, in the US electrical appliances efficiency standards have saved consumers over \$100 billion in energy costs and displaced the need for

over 15,000MW of new power plant capacity (Geller, 1997; Turiel, 1997). The benefit of DSM are categorised into 3 major classes as given in Table 4.1 and the specific benefits include:

- Reduces customers peak and overall energy demand
- Improves the electric grid's reliability
- Balances the electric grid through increased efficiency
- Enhances the use of energy efficiency
- Manages electricity costs in both supply and demand side
- Conservation through both behavioural and operational changes
- Distributed energy, and
- Provide systems that encourage load shifting or load shedding during times when the electric grid is near its capacity or electric power prices are high

Analyzing these measures, it is seen that, there is a direct connection between the DSM program and load management program.

**Table 4.1:** Benefits of DSM Programs

<b>DSM benefits</b>		
<b>Customer</b>	<b>Society</b>	<b>Utility</b>
Lower bills	Capital freed for other projects	Lower cost of service
Improved service	Reduce foreign debt	Less generation and transmission capacity required
Non-energy business benefits	Lower business costs	Improved operating efficiency
	Reduced pollution	Improved customer service
	Conservation of indigenous energy resources	More available resources for use in future

#### **4.3.1 DSM Planning Processes**

The important step in DSM planning processes is the identification of suitable and practicable DSM options. It is obtained by studying electricity user's profile or it may be obtained through the observation of energy consumption or measurement. In most cases, energy auditing process is used to understand end-uses electricity consumption and identify end-use options that can offer maximum DSM potentials.

The need for more specific options for DSM implementation would require the identification of many alternative techniques. In other words, it is required to list many available options for the DSM screening. In order to approve the selected DSM options, the techniques are compared in the screening criteria that form the basis of estimating DSM potential. Hence the following steps are required in order to enhance DSM:

#### 4.3.1.1 Load Research

It is mostly done on the supply side and is assessed by considering the customer base, tariff, load profiles and identify the sectors contributing to the load shape.

#### 4.3.1.2 Define Load-Shape Objectives

Based on the results of the load research, load shape objectives for the current situation should be defined. The possible load-shape objective includes:

**4.3.1.2.1 Peak Clipping;** the reduction of utility load primarily during periods of peak demand

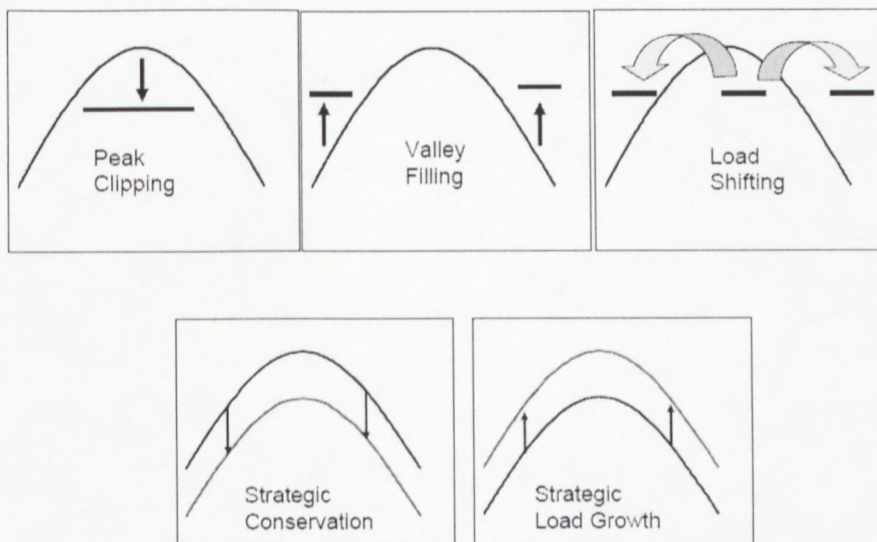
**4.3.1.2.2 Valley Filling;** the improvement of system load factor by building load in off-peak periods.

**4.3.1.2.3 Load Shifting;** the reduction of utility loads during periods of peak demand, while at the same time building load in off-peak periods. Load shifting typically does not substantially alter total electricity sales.

**4.3.1.2.4 Load Building;** the increase of utility loads, more or less equally, during all or most hours of the day.

**4.3.1.2.5 Conservation;** the reduction of utility loads, more or less equally, during all or most hours of the day.

**4.3.1.2.6 Flexible Utility Load Shape;** refers to programs that set up utility options to alter customer energy consumption such as an interruptible agreements. These are represented in Figure 4. 1



**Figure 4.1:** Load Shape Objective  
**Source:** Gelling, 1995

#### **4.3.1.3 Assess Program Implementation Strategies**

This stage designs the program for specific end use applications that promote the program to the target audience through marketing approaches such as advertising and focused group meetings. The end-users that are potentially targeted to reduce peak demand with higher subsidies are identified. Detailed end use and utility benefit-cost analysis is carried out for the end-users and the utilities including analysis on societal as well as environmental benefits.

#### **4.3.1.4 Monitoring and Evaluation**

At this step, the designed DSM program and implementation is traced and compared with the proposed goal set by the utility. It also identifies the benefits that participants achieve from the program such as reduced bills or incentives given to the industrial end users. The DSM processes are used in industries to identify the options for the proposition of the measures that can improve the energy situation.

#### **4.3.2 Steps for the DSM Program Development**

The first step in development of the DSM program is to decide on the basic features of the program. DSM programs target area where they can have largest saving impacts. For example the industrial sector and consumer's that account for the largest power consumption and peak loads. In the case of cement industries, big electric motors such as cement and raw mills motors can be considered. The hierarchy followed for DSM development involve:

##### **4.3.2.1 Demand Forecasting**

The demand forecast is an important process as it can help to justify the need for the DSM. This approach is carried out to identify future demand requirement or energy consumption growth. Indeed demand forecast, estimates of current electricity consumption and peak demand is disaggregated by sectors and end users such as industrial power and lighting, the load curves are derived for each sector or end user.

##### **4.3.2.2 Load and Market Research**

The knowledge on how, when and what amount of electricity used is important in designing a DSM program. Load research should be undertaken to estimate load curves for each sector, using local sub-metering, and customer bill analysis and customer surveys. Market research is needed to understand the targeted market, identify barriers and evaluate possible solutions.

#### **4.3.2.3 Financing**

Finance is a critical item in many DSM development activities. It is needed in every step of DSM development. It is also needed for individual projects undertaken by participants.

#### **4.4 Role of DSM Programs in Utilities Industry**

The reasons for the utilities to be involved in DSM programs are related to the optimal resource allocation, cost competitiveness, good customer service considerations and government guiding principles. The involvement of electric utilities in DSM programs can be categorized based on three principal motivating factors namely policy, regulation, and business. For example, utilities are either owned or regulated by government are convenient vehicles for implementing government policies such as energy efficiency policy. Utilities are in a position to understand how a group of customers use their electricity.

The on-going electricity industry restructuring, threatens the balance of the development of DSM programs. This is caused by the long-standing relationship between monopolistic providers or a protected franchise. Customers have been replaced by a new set of relationships between retail electricity suppliers and customers are now free to choose providers. In the countries where restructuring is under way, the traditional ways of providing public purpose programs are being re-examined in the early phases of restructuring.

Growth of electricity systems of most developing countries are constrained by capital, performance, access and environmental crisis. The capital performance crisis is characterized by the serious deterioration in the technical and financial performance of the electricity utilities. The access crisis arises based on the significant number of the population which does not have access to electricity. The environmental crisis is caused by every new electricity generation project. Hence proper implementation of DSM objectives might minimize the negative energy related impacts.

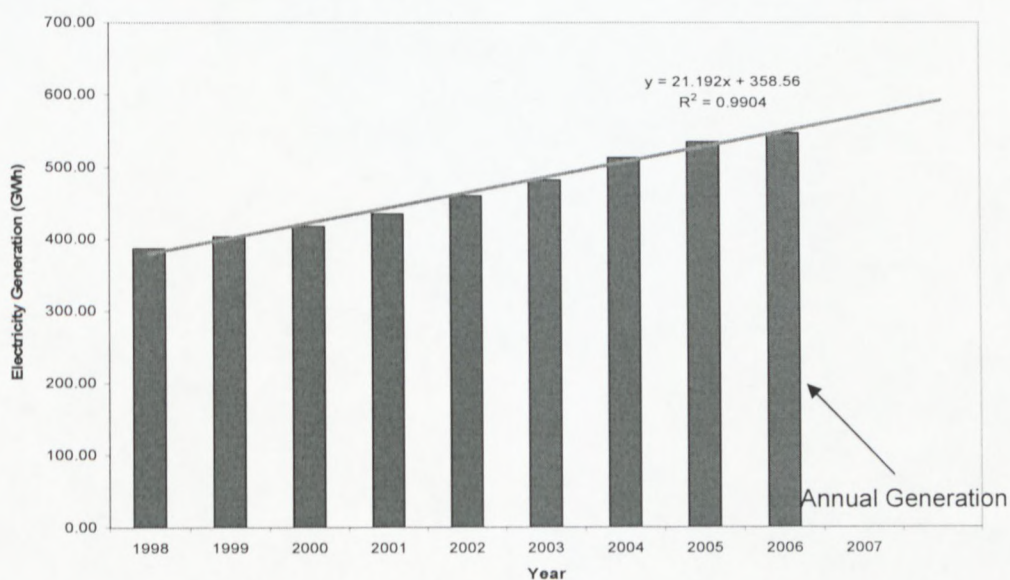
#### **4.6 The Need for DSM in SSA Manufacturing Industries**

The growth of the oil prices has threatened the overall energy security around the world especially SSA countries where electricity generation and percentage access to electricity is slowly increasing, refer to Figure 4.2. In that figure the blue line shows the trend of the increase of power generation in Sub-Saharan Africa. In order to meet the power demand and to minimize energy consumption, DSM programmes have to be introduced in most SSA countries just as it has been practiced in most

developed and some developing countries in the world (Gellings, 1992, Jyoti, 1996, ESKOM DSM, 2002 and Yang, 2006).

Satish (2004) disclosed reasons for an energy customer to opt a certain DSM activity to include economic, environmental, marketing or regulatory. The benefits of DSM to consumers, enterprises, utilities and society can be realized through reductions of customer energy bills; slower the need for new power plant, transmission and distribution networks; stimulation of economic development; creation of long-term jobs due to new innovations and technologies; increases in the competitiveness of local enterprises; reduction in air pollution; reduced dependency on foreign energy sources; reductions in peak power prices for electricity.

The additional aspect discussed in (Satish, 2004) is the enhancement of energy security through a diminished dependency on foreign energy sources. While the vulnerability of the volatility of international energy markets may not be the concern of an individual utility, industry or commercial company, at the national level, decreased dependency on energy imports can have important security of energy supply implications. Implementation of DSM enhances efficient utilization of available energy resources that provides greater benefit to the national economy.



**Figure 4.2:** Generation Situation in SSA 1998-2006

There is a dearth of information available on the performance of energy conservation technologies in SSA countries. Energy conservation designed via a DSM plan has important contribution to utilities and to the demand side (Jyoti, 1995). However, the

goals of DSM programs are to cut the consumption of energy which can be translated as a reduction of the direct profit to energy suppliers and retailers. But the energy surplus generated through DSM activities can be sold to other customers or supplied to other authorities, while ensuring the stability of the system (Reddy, 1996).

Deok Ki Lee et al., (2007) proposed Demand-side management investment planning (DSMIP) to be conducted by the energy suppliers so as to establish appropriate indicators to correctly assess the effectiveness of DSM. This idea is applicable to the case of development and establishment of DSM in SSA as well.

The Limited electricity generation in most SSA countries fails to anticipate the increased demand. This is dictated by the small percentage of population who access the electricity and per capita electricity consumption in the region. Although SSA countries are not industrialized, this shortage of power causes some few existing industries to suffer from an unreliable and steady supply. The development of DSM programs in the regions is needed so as to increase the security of the supply and allow the surplus saved to be used to other customers. It provides opportunities to save the utility and end user money while reducing the impact on the environment and securing energy resources.

DSM programs provide opportunities to a better understanding of how escalations in fuel prices affect the local industries. Intermittent power disruptions caused by power crisis in SSA countries also call for the need for DSM programs in the region. Implementation of DSM objectives in the industrial sector results in the following benefits:

- It saves the end user money;
- It improves the environment by reducing air pollution caused by over consumption of natural resources. For each megawatt-hour (MWh) of electricity that the end user consumes, a substantial amount of coal was burnt, thousands of litres of water was consumed and a substantial amount of relative particulate matter is emitted by local power stations.
- It contributes significantly to the saving of natural resources (Molefhi & Grobler, 2007).

#### **4.6.1 Procedures for Development of Tools for Assessing DSM Programs Options**

A tool for assessing DSM programs was developed to study the benefits, viability and adoptability of the proposed DSM programs options. This tool gives a clear picture of how DSM program options are realized in industries. Before the development of the tools, the assessment of DSM options was carried out. Reddy (1996) presented methods used to select DSM options. The mentioned options

include the use of CFLs, high efficient fluorescent lamp, low loss ballast, high efficient motors, high efficient air conditioners, TD tariff, interruptible tariff, power factor correction, variable speed drive, high efficient fans and efficient space heating and air conditioning.

Adopting Reddy's concept, the DSM opportunities were assessed. The procedure for assessing DSM option was started by undertaking plant survey, followed by preliminary energy auditing and accounting and lastly carrying interview with technical personnel of different levels. Through that process, various energy saving opportunities were mentioned. We listed all options that were mentioned and seen to have the possibility of energy saving, whereby the next step was screening of the options. DSM screening was performed to identify the potentials of each option; it involves analysis of the following:

- Capital, installation, operational and maintenance costs, efficiency, useful life time and peak coincidence factor.
- Utility characteristics; utility data base include information on discount rate.
- Market diffusion; level of customer's awareness, extent of cost sharing required by the customer and discount rate of the customer.

In evaluation of DSM options, each selected option is compared with a standard option. The annual energy savings of each option are multiplied by number of options to obtain the total energy savings. Similarly, peak demand reduction is obtained by multiplying the maximum peak demand reduction using peak coincident factor with the number of options. The avoided capacity savings are calculated by multiplying the avoided marginal capacity costs with the peak coincident demand reduction (Reddy, 1996). Figure 4.3 shows the algorithm developed for developing DSM.

#### **4.6.2 Assessment of DSM Program Options: Case Study of SSA Cement Industries**

The assessment of DSM options in cement manufacturing industries started by conducting industrial surveys, doing preliminary energy audits that monitor energy use pattern and loads that consume energy. Compare the amount of energy consumption with true one and analyse the potential areas for energy saving.

In order to find the viable DSM options, all opportunities should be listed and then screened. The objective of DSM screening is to quantitatively rank the most promising DSM options before a detailed cost-effective analysis. Among item to be considered in the DSM screening include, easy implementing, easy to maintain, maximum system loss reduction, easy to rehabilitate, easy to operate, least implementation cost, least maintenance cost, maximum benefit for consumer,

maximum positive impact on economy, Least incremental capital cost, widest consumer acceptance.

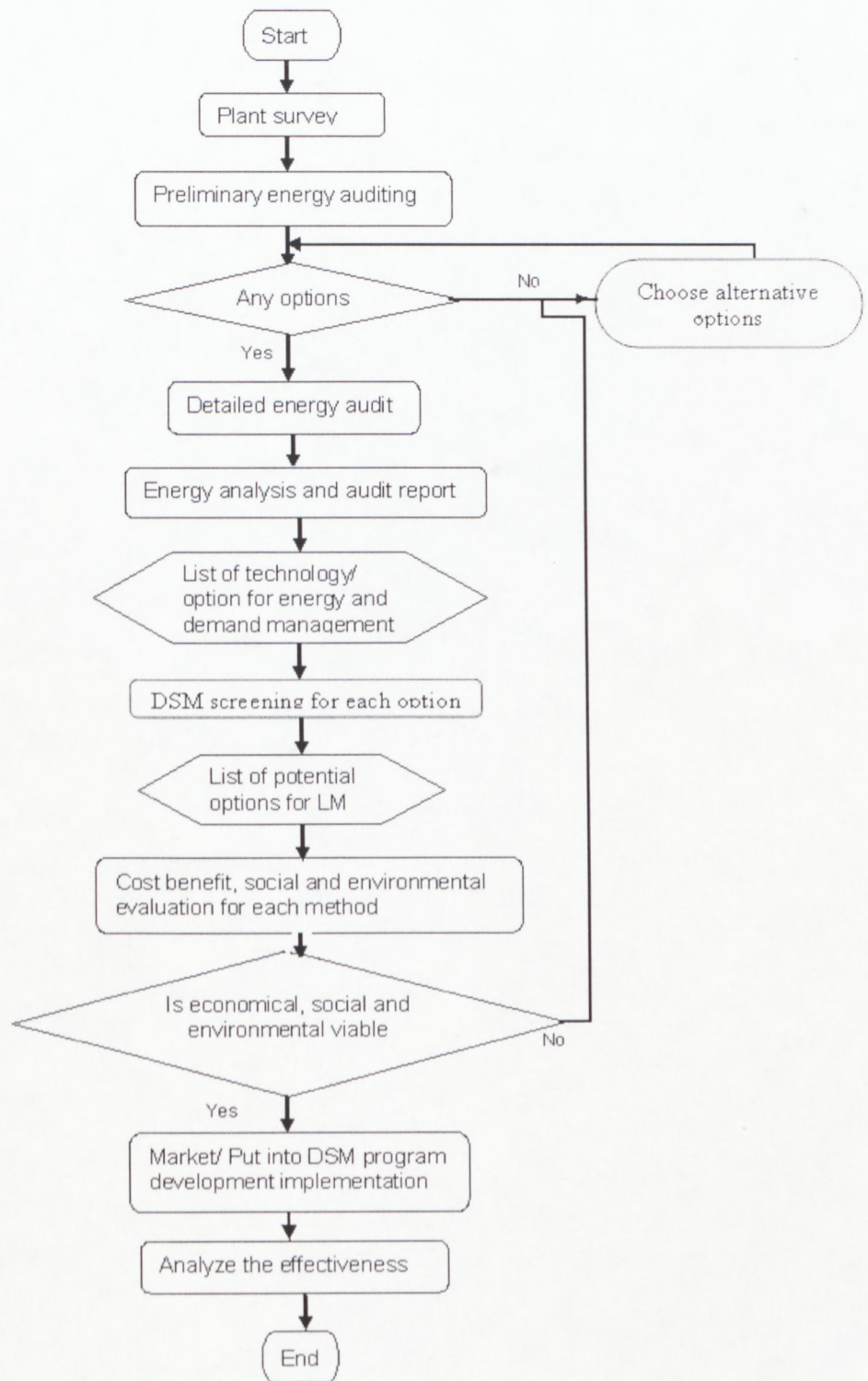


Figure 4.3: Algorithm for the Development of DSM Program

Three cement industries were visited (Mbeya Cement, TPCC and Tanaga cement) and discussions on energy management techniques with key technical personnel were made. The summary of survey and interviews results is shown in Table 4.2. Column two shows the different types of technology used world wide to reduce energy consumption in different industries. The DSM screening was used to select the most ranking DSM option in cement industries.

Table 4.2 shows that, among the viable DSM program options the power factor correction is one of the most widely adopted options by many industries. Standard efficient motors are widely used but their efficiency is lower compared to EE motors. The survey results showed that, technical personnel somehow have information on the technical options that can be used for electrical energy management or, to save electrical energy but most of the options are partially adopted or not adopted at all

**Table 4.2:** Screening DSM Program Options

S/N	Technology	Known	Most Implemented	Known – Not implemented	Partially implemented	Not applicable
1	Energy Efficient lighting	x			x	
2	Energy efficient fluorescent lamp					x
3	Time dependant metering					x
4	Intelligent motor control	x		x		
5	Standard efficient motors	x	x			
6	Energy efficient motor	x		x		
7	Intelligent Lighting control					x
8	Intelligent motor control	x			x	
9	Power factor improvement	x	x			
10	Load scheduling	x			x	
11	Intelligent load scheduling					x
12	Starting sequence (manual)	x	x			
13	Intelligent starting sequence					x
14	Energy storage					x
15	Use of renewable energy					x
16	Use of standby generator	x	x			
17	Maintenance	x	x			

**Key:**

**X**—Applied

From the table it can be concluded that, 58.82% of the techniques used for end use energy saving is known and 41.18% is not applicable by technical personnel. Among 17 analysed techniques, five are most implemented and three are partially implemented. The remaining techniques are not applicable at all. Thus, most of the techniques and equipment applicable to cement industries are inefficient. Hence development of DSM option is most important in the initial steps of energy saving awareness and adoption and implementation of energy saving techniques.

#### 4.6.3 Barriers to the Development of DSM Programs

The assessment of DSM shows the opportunities of utilities to establish DSM and achieve a considerable saving. It has been identified that, even though most of the manufacturing industries have many DSM technical potentials, they are not adopted due to a number of market and institutional based barriers that must be overcome. The efficacy of utility DSM initiatives and strategies is directly related to the ability to overcome the barriers in their service territories.

##### 4.6.3.1 Market Barriers

The market barriers are associated with the specific perceptions and behaviours of final customers, intermediaries and distributors of energy-efficient equipment, energy efficiency service providers and electric utilities. Their characteristics are given in Table 4.3.

**Table 4.3:** Market-Based Barriers to DSM

Origin of barriers	Barriers
Customers	Ignorance or disbelief regarding DSM programs, fear of loss of comfort, quality or productivity, lack of knowledge about efficient equipment, lack of financial resources, High up-front costs and unavailability of DSM technologies or services in regions.
Intermediaries	Apprehension of market and profit losses, lack of information, training and know-how about DSM applications, lack of capital availability to carry out or introduce new efficient product, Limited influence on decision-making processes by the end-user.
Electric utilities	Apprehension of negative rate impacts, lack of available resources to allocate to DSM program, lack of appropriate DSM culture and know-how.

The prominent of the barriers are:

- Lack of awareness and general misinformation about the benefits of DSM programs and technologies.

- Lack of technical information and expertise characterized by information gaps in the specific sector and industry
- Inertia in established patterns of behaviour and slow acceptance of new technologies

#### **4.6.3.2 Institutional Barriers**

The institutional barriers refer to conditions created by the nature and scope of interventions by government and regulatory agencies to influence the marketplace according to public policy objectives and budgets. Institutional barriers are usually combined with market-based barriers and include:

- Lack of effort on a national level to coordinate energy efficiency actions initiated by different players
- Lack of fiscal incentives for DSM investments
- Lack of high energy performance standards and deficiencies in their enforcement
- Lack of continuity in institutional energy efficiency incentive programs
- Imposition of taxes and tariffs on imported manufactured goods, including energy efficient equipment

#### **4.6.4 Techniques to Overcoming Barriers to DSM Programs**

The experience from other countries reveal that the barriers described above can be overcome through a mixture of programs which are grouped into pricing and non-pricing mechanisms.

**4.6.4.1 Pricing Mechanisms;** Among pricing mechanisms are pricing and taxation policies that reflect the real cost of energy and that provide financing mechanisms for DSM program related activities. Rate options such as time of use rates or interruptible rates can also be used to address the specific needs and opportunities of different market segments.

**4.6.4.2 Non- Pricing Mechanisms;** These include:

- Promotional and educational programs, such as labelling programs and energy audits that are useful vehicles for the dissemination of DSM-related information to customers.
- Financial incentives (including rebates) that lower barriers related to customers' lack of up-front capital.
- Technical assistance and training programs targeting individuals and firms involved in energy efficiency at all levels to assist in establishing and implementing DSM programs.

## **4.7 International Experiences of DSM Programs**

More than 30 countries around the world have successfully applied DSM to increase energy savings, reduce the need for new power plants, improve economy and reliability in power network operation, control tariff escalation, lower customer electric expenses, save energy resources, and improve environmental quality. DSM has become an important strategy for achieving sustainable energy and electricity development. Specific applications of DSM differ from one country to another depending on local conditions (Babra et al., 2003). Few countries experiences are elaborated in the next sub sections.

### **4.7.1 USA**

The DSM programs developed in the United States were based primarily as utilities demand-side resource investments. Utilities designed and implemented energy efficiency programs for their customers. This has been used to avoid more expensive supply-side alternatives (Harrington & Murray 2003).

In the United States, more than 500 utilities implemented DSM programs since 1985. Savings was more than 29 GW (about half of SSA countries generation) of peak load and reduced air pollution emissions from stationary sources by approximately 40 percent (Nadel, 2000). Many states and utilities have realized the benefits of DSM programs in providing long-term solutions to electricity system reliability concerns (Kushler & Witte 2001).

DSM increased the amount of energy saved, reduced the need for new power plants, improved economy and reliability in power network operation, it controlled tariff escalation, it lowered customer electric expenses, it saved energy resources and improved environmental quality. Since then, it has become an important strategy for achieving sustainable energy and electricity development.

### **4.7.2 Thailand**

Thailand has been recognized internationally for its success in designing DSM programs that fit within an Asian context. In 1993, Thailand initiated a \$189 million U.S. Dollar fund for DSM programs to help curb electricity demand growth and promote more energy-efficient equipment and cost-effective energy services.

The program was successful and substantially exceeded its original peak reduction and energy conservation targets. From 1993 to 2000, the DSM programs succeeded

in reducing peak load by an aggregate of 556 MW or 4 percent of Electricity Generating Authority of Thailand's total capacity. Cumulative annual energy savings were 3,140 GWh that was more than double the original energy savings program targets. The program also reduced carbon dioxide emissions by 2.32 million tons per year (Singh & Mulholland, 2000). DSM is proved to be a useful action to many countries.

#### 4.7.3 Vietnam

Another relevant Asian example is that of Vietnam. Vietnam is experiencing unprecedented economic growth, which averaged 8.2 percent annually from 1992 to 1997. During this period, energy demand grew 30 percent faster than GDP and electricity 70 percent faster. The ability of Vietnam to continue to meet such an aggressive economic growth rate required substantial expansion of the electric power sector as well as aggressive demand reduction efforts.

GEF, (2003) reported that, World Bank business scenario estimates the power utility and concluded that, the Electricity of Vietnam (EVN), faces a threefold increase in demand from 25,700 GWh in 2000 to more than 77,400 GWh by 2010, with an annual demand growth of 10 to 13 percent if special efforts have not been made. Generation level peak power demand is also projected to increase from the 1999 level of 5,700 MW to about 16,000 MW by 2010. Meeting this demand through supply-side resources alone would require a capital investment of about \$18 billion U.S dollar. The Global Environment Facility (GEF) assisted Vietnam in the development of DSM programs as part of the country's long-term power sector strategy. This was achieved by:

- Developing a large-scale DSM programs within Electricity of Vietnam to reduce loads during peak periods and in congested networks;
- Testing, developing and expanding a commercially sustainable EE service industry; and
- Developing domestic sources and mechanisms for project financing to support a large-scale EE investment program (Barbar et al., 2003).

The project was expected to achieve major reductions in peak load and improve system load factors. Detailed estimates of direct energy savings benefits over a 10-year period is about 120 MW of peak load reduction and 2,928 GWh, resulting in more than 724,000 tons of oil equivalent (toe) and 3.5 million tons of carbon. In addition to the environmental benefits, EVN was substantially benefiting from reduced peak loads, network congestion and new investment requirements (GEF, 2003).

#### 4.7.4 South African Experience

The electricity supplier in South Africa is Eskom. It supplies 95.7% of the national electricity of which 92% is from coal. The country has been experiencing an economic growth period. This growth causes consistently high rate of national electricity demand growth of which the authority has failed to meet the anticipated increased demand which lead to supply shortages this has forced power outages in the country. This made Eskom to start considering DSM programs as part of their utility planning (Ebenhard, 2002). The overall Eskom generation, transmission, distribution and utilization status is given in Figure 4.4.

The Eskom has been facing the challenges of insufficient power demand during evening peak from 18 to 21 hours. In a way to solve that, Eskom has embarked on a national demand-side management (DSM) initiative in the industrial, commercial and residential sectors. Eskom's overall DSM target/objective, as per the National Integrated Resource Plan (NIRP), was to save 4,255 MW over a period of 20 years, to mitigate the negative impacts on the environment via energy efficiency targets and to support local job creation ([http://www.wbcd.org/energy\\_efficiency.pdf](http://www.wbcd.org/energy_efficiency.pdf)).

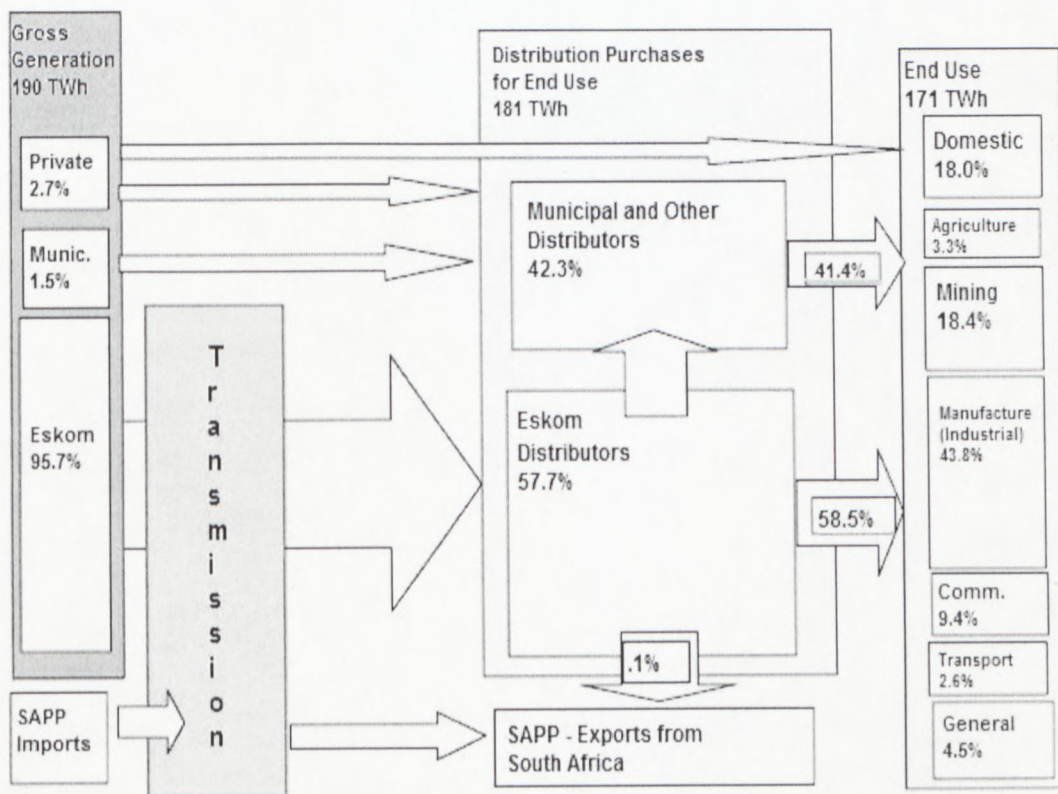
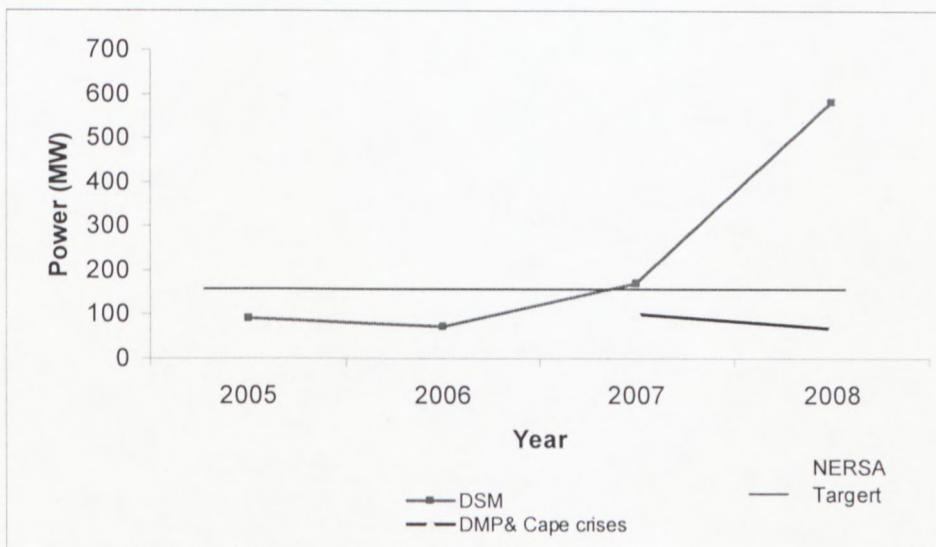


Figure 4.4: Overall Eskom Generation, Transmission, Distribution and Sale

The Eskom has set the DSM target in different phases. In the first phase, annual DSM target was 152 MW and is being increased to higher levels as the markets gain momentum in DSM implementation. This annual target was divided into energy efficiency and load management. The projects that fall under the scope of DSM programs form part of Eskom's long-term strategy to reduce South Africa's electricity demand during peak periods.

The demand saving continue to be realized especially in evening peak period. It has risen exponentially in line with the growing requirement for demand reduction as shown in Figure 4.5. The total evening peak savings over the period is 1082 MW of which 650MW was achieved in the year 2008. Of this amount, 67MW were realized from demand market penetration. Initially DSM programs department focused on the realization of savings within the evening peak utilizing ESCO related projects in the industrial, mining and commercial sectors.



**Figure 4.5:** Demand Saving Achieved from the Period 2005 to 2008

Considering the cost implications of new generation capacity, DSM became an extremely attractive alternative. If DSM can be used to limit industrial demand growth by provision of incentives to remove load out of the peak periods, substantial benefits for all customer groups could be derived. Inevitably high price increases would be avoided through the deferment and probable avoidance of certain generation capacity construction.

## 4.8 Maintenance Program as a Part of DSM

The decision between equipment maintenance and replacement is a managerial activity and must be made more often to sustain production at minimum cost. It is a key financial parameter that determines the performance of the industry. There are a number of costs that must be considered in evaluating various options related to equipment maintenance and replacement decisions. The effects of incorrect decisions are:

- Negative impact on selected equipment performance
- Increased maintenance and operating costs
- Limitation in targeted production output

There are several costs that must be considered in selecting the right equipment replacement/maintenance option from all the alternatives. Maintenance costs incurred by replacement of a piece of equipment are only one part of the costs. Many industries restrain themselves from making investment in new equipment and run the existing one. In a bid to make them effective, maintenance policies for industrial systems should be properly established according to their occasion (Toshio, 2005).

### 4.8.1 Importance of Maintenance in Electrical Energy Management

Maintenance is a critical part of facility's operation. Properly maintained equipment and processes are necessary to keep the plant functioning at its optimum capability. Maintenance help keeping energy cost within the limited value and prevent excess expenditure. Maintenance should be an integral part of the energy management program.

To practice energy management via maintenance management, the industry should develop an energy management maintenance programs. The following are four steps used for the development of a maintenance program:

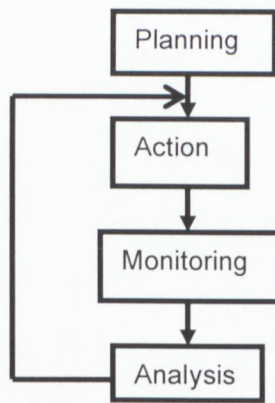
Step 1; is to determine the present condition of the facility. It includes detailed examination of major energy consuming systems.

Step 2; is the presentation of a list of routine maintenance task with an estimate of the number of times which each task must be performed.

Step 3; incorporates information from step 2 used to accomplish the desired maintenance

Step 4; is the monitoring,

The proposed model of the program is as given in Figure 4.6. The model consists of four main parts as: planning; estimate present energy related maintenance costs; determine present condition of the major energy related systems and set goals for the maintenance function.



**Figure 4.6:** Overview of Maintenance Energy Management Function

#### 4.8.2 Types of Maintenance System

The primary role of maintenance is to control the condition of plant equipment. The objective of maintenance as presented by (Wireman, 1990) includes:

- Maximum production at the lowest cost, high quality, and optimum safety
- Identify and implement cost reduction
- Provide accurate maintenance repair records
- Optimize maintenance resources
- Optimize capital equipment life
- Minimize energy usage

Types of maintenance include breakdown, preventive and predictive maintenance. Breakdown maintenance; is the maintenance and repair of machines only after failure has occurred while the preventive maintenance; is the performance of inspection and or servicing tasks that have been pre-planned for the accomplishment at specific points in time to retain the functional capabilities of operating equipment or systems. It can be planned in no busy time so as to allow the full utilization of the plant and prevent failure and related costs (Parsaei & Wilhelm, 1989).

Corrective maintenance is the performance of unplanned maintenance task to restore the functional capabilities of failed or malfunctioning equipment or systems. Poor maintenance system has many problems including energy losses. Hence proper adoption of maintenance services leads to energy saving (Narayan, 2004).

#### 4.8.3 Assessment and Development of the Maintenance Strategy in Cement Industries

In order to overcome energy loss caused by poor maintenance, life cycle maintenance have been used and promising energy saving. The life cycle maintenance involves:

- Reliability and maintainability design
- Maintenance strategy planning
- Maintenance task control
- Evaluation of maintenance result
- Improvement of the maintenance if required

In cement industries, big consumers of electrical energy are motors and lightings. Energy savings can be achieved if these loads are properly maintained so as to minimize associated loss caused by un maintained system. For example Motor can consume excess amount of energy if they are not hooked up to their load or in the case of three phase motors if the voltages in the opposing legs are different (Wayne & Donald, 2006). Preventative maintenance programs could have prevented more than half the losses associated with electrical equipment failure and improve a facility's overall efficiency.

#### **4.8.3.1 Maintenance of Motors and Related Components**

A good maintenance program contains elements of both predictive and preventative maintenance (PPM). Both involve scheduled actions to the motors and controls as well as record keeping. Motor cleaning is one of the important maintenance activities in the motor system. A clean motor runs cooler than a dirty motor. Dirty motors reduce air flow and increase the motor operating temperature which leads to inefficient operation. Good maintenance program start by recording of motor parameters and operating condition such as speed, voltage, current and power factor.

Inspection checklist; It assists to identify the equipment or motor malfunction in early stage. The following items are inspected during maintenance check:

- Lubrication and vibration;
- Ventilation and the presence of dirt or other contaminants;
- Alignment of motor and load;
- Possible changing load conditions;
- Belts adjustment and tightness of hold-down bolts.
- Sheaves and couplings

The key maintenance issue for electric motors that cause energy loses includes inadequate lubrication; this may increase the consumption of electrical energy by 4%-8%.

Loose electrical connections result in increased temperature and therefore, increased Ohmic resistance. Inadequate mechanical alignment increase energy consumption by 6% and reduce bearing life, (Zoran & Gvozdenac, 2006).

#### 4.9 Conclusion

This chapter presents DSM programs performance and measure for energy management in manufacturing industries. It has been observed that the overall concept of DSM was derived in response to the prospective problems of energy security, global warming and the need for sustainable development. Due to its abilities to link its activities between the utilities and customers, there can be an increase in the efficiency of energy generation and utilization.

The important steps for DSM programs process were presented in this chapter. The study on electricity load profile was discussed as an important step to this process. This is because it gives an understanding of end-user electricity consumption and helps identify end-use options that can offer maximum DSM potentials. The method for screening DSM options was developed by the use of the survey information and response of technical personnel on energy matters. The case study that analyses DSM options and potentials in cement industries in SSA countries was also presented in this chapter. The analysis was done by the use of DSM screening algorithm.

DSM programs have been used in many countries to manage the escalating energy consumption in industries. The benefits which the utility industry and demand side can obtain by using DSM programs have been explained. By developing and implementing DSM programs strategies, there are potential monetary savings which can be achieved. Experience of DSM implementation with other countries reveals the benefit of implementation of this program. Despite the benefit of DSM, many countries in SSA have yet developed DSM. This chapter also highlighted some barriers that hinder the development of DSM in this region. DSM program can be used in the region to defer the construction of new generation and at the same time minimize the GHG emission.

## **CHAPTER 5: Analysis of Energy Efficiency Technologies and Development of Performance Based Indicators.**

### **5.1 Introduction**

Industries that implement strategic energy management programs have potentials to achieve sustainable energy savings. Escalating energy costs and high competitiveness of cement industries call for the need for increasing operational efficiency. The use of energy efficient techniques in industries is more prominent because it secures energy resources, reduces energy cost and diminishes harmful emissions caused by the power plants. Energy efficiency techniques have significantly gained stature and have become recognized as one of the most cost-effective ways of meeting electric demands in many countries.

The benefits of using energy efficiency (EE) techniques are of particular relevance and have positive contributions to the physical and economic levels, alleviation of poverty, job creation, improvements to human health and better working conditions. Therefore, there is a need for industries in SSA countries to develop energy efficient indicators, which can be implemented in the development of energy efficiency strategies.

This chapter analyzes the potentials for energy efficient techniques existing in cement industries. The analyses are based on economical viability and adoptability consideration. The energy consumption model and the energy efficient benchmarking has been also developed that can be used to identify best practice electrical energy requirement for the production of cement (t/kWh). Energy efficient performance based indicators are used to set energy efficiency targets. This comprehensive approach shows a significant reduction in specific energy consumption.

### **5.2 Assessment of Energy Efficiency Potentials in Cement Industries**

Energy utilization efficiency in a given process is an important measure of overall productivity or efficiency. If a firm can produce twice the output using the same input of energy in a given process, it would have a significant comparative advantage relative to its rivals. Apart from pure economic benefits, the use of energy efficiency techniques reduces negative environmental emissions per unit of output. In addition, the use of energy efficiency equipment and processes is a matter of business survival in many industries.

During the period of energy crises, improving energy efficiency has been researched and documented (Department of mineral and energy South Africa, 2005). Energy conservation in industries is accomplished by considering the following steps:

- Efficient in-house management, this is done through maintenance and housekeeping measures
- Improvement of equipment and systems efficiency and
- Processes improvement (ECCJ, 1994)

In general, energy reduction in industries can be achieved by using high-efficiency motors, high-efficiency transformers; variable speed controls; automatic power factor controls and demand controls. In some industries, modifications or improvements in lighting systems offer considerable energy savings.

The main types of industrial loads in cement industries include but not limited to electric motors, space heating and cooling loads, lighting loads and other miscellaneous loads such as computers, printers and X- rays for quality control. Worrel (1995) assessed the technical potentials of energy efficiency improvements in cement industries and other energy intensive sub-sectors and concluded that, energy savings of up to 30 to 40 % are technically possible. In line with Worrel's work, this thesis analyses efficiency of the most influential loads in cement industries.

### **5.2.1 Energy Efficient Lighting Systems**

Lighting is an important electrical end use service in every sector. The commercial sector consumes the majority of the electricity for lighting. 19 percent of the electricity consumed worldwide is used for lighting (Technical guide of energy efficient lighting, 2001). The commercial sector consumed approximately 51% of total electricity used for lighting, the residential sector consumed 27% and the industrial sector consumed 14%. Fluorescent, incandescent, and halogen lamps have dominated the market of the lighting system. Table 5.1 shows the different types of lighting systems with different applications.

There is great potential for saving electricity, reducing the greenhouse gases emission associated with electricity production through the use of more efficient lighting technologies as well as advanced lighting design practices and control. This section, provide an overview of both conventional and efficient lighting technologies.

**Table 5.1:** Use of Different Lighting Systems for Different Applications

Application	Incandescent lamp	Incandescent tungsten Halogen lamp	CFL	Fluorescent tube	High pressure mercury	High pressure sodium vapor
Office			x	x		
Industrial				x	x	x
Domestic	x	x	x	x		
Industrial security					x	x
Shops	x	x	x	x		

An incandescent lamp produces light when electricity heats the lamp filament to the point of incandescence. 90% of an incandescent lamp's emissions are in the infrared (thermal) rather than the visible range of the electromagnetic spectrum. Incandescent lamps have a very low conversion efficiency of 5 to 10% of the actual energy input. Introduction of an energy efficient lighting system is a significant practice for the optimization of energy used for lighting systems. Incandescent lamps have relatively simple installation, maintenance, and disposal practice.

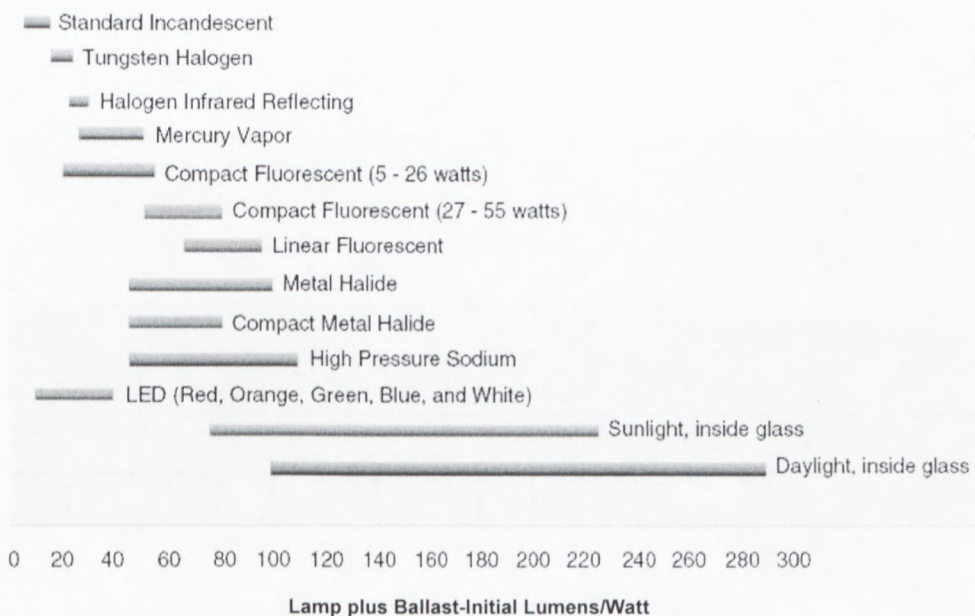
Tungsten–halogen and tungsten–halogen infrared-reflecting (HIR) lamps are more efficient than standard incandescent lamp. Like standard incandescent lamps, tungsten-halogen lamps produce light when electricity heats the tungsten filament to the point of incandescence. In a standard incandescent lamp, tungsten evaporating from the filament deposits on the glass envelope. Generally, tungsten–halogen lamps use a quartz envelope rather than a glass envelope, which allows the lamp to operate at a much higher temperature.

Fluorescent lamps came into general use in the 1950s. In a fluorescent lamp, gaseous mercury atoms within a phosphor-coated lamp tube are excited by an electric discharge. As the mercury atoms return to their ground state, ultraviolet (UV) radiation is emitted. This UV radiation excites the phosphor coating on the lamp tube and causes it to fluoresce, thus producing visible light. Early fluorescent tubes, and current compact fluorescents lamps use preheat start with an automatic or manual starting switch. Currently electronic ballasts are available, that can instant-start fluorescent lamps.

High-intensity discharge (HID) lamps produce light by discharging an electrical arc through a mixture of gases. In contrast to fluorescent lamps, HID lamps use a compact arc tube in which both temperature and pressure are very high. Compared

to fluorescent lamps, the arc tube in an HID lamp is small enough to permit compact reflector designs with good light control.

Energy efficient (EE) lamps are available in different forms and sizes. Some of them have an electronic control gear incorporated inside the lamp so that they can be installed in a conventional light fitting. Lighting system components fall into four basic categories which are lamps, ballasts, fixtures, and lighting controls. The efficacy of different types of light sources is shown in Figure 5.1.



**Figure 5.1:** Efficacy Comparison of Light Sources for General Lighting.  
**Source:** NBI 2003. Advanced Lighting Guidelines, 2003

Compact fluorescent lamps (CFL) are much more efficient and last up to 20 times longer than incandescent lamps. They are available in an extremely wide range of sizes, colours, brightness and relative insensitivity to voltage fluctuation

Fluorescent lamps are far more efficacious than incandescent lamps. The efficacy of a fluorescent lamp system depends on the lamp length and diameter, the type of phosphor used to coat the lamp, the type of ballast used to drive the lamp, the number of lamps per ballast, and the temperature of the lamp.

Fluorescent lamps are commonly used in industrial applications. The T8 fluorescent lamp was the standard for fixtures in commercial and office buildings and a substantial portion of industrial lighting. The T5 fluorescent tubes were developed for higher system efficiency in an effort to reduce lighting energy costs.

Currently, T12 and T8 fluorescent light with magnetic ballast are used in many industries. Considering the advantage and efficiency of the T5 lamps, high amount of energy savings could be realized if T12 or T8 are replaced with T5. Table 5.2 shows the performance of different rating T5 fluorescent lamps.

**Table 5.2:** Performance of T5 Fluorescent Lamp's Maximum Luminous Output

T5 Power rating W	Length mm	Design lumen lm	Luminous efficacy Lm/w	Max luminous output lm
14	549	1200	96	1350
21	849	1900	100	2100
28	1149	2600	104	2900
35	1449	3300	104	3650
24	549	1750	83	2000
39	849	3100	90	3500
54	1149	4450	93	5000
80	1449	6150	88	7000

### 5.2.1.1 Comparison of T5 and T8 System

T5 tubes are smaller in diameter than T8 tube. T5 fluorescent tube produces a relatively higher luminous flux than the T8. Table 5.3 shows the comparison of a 28W T5 with 32W T8 fluorescent tube.

**Table 5.3:** comparison of T5 fluorescent lamp with T8

	T5	T8
Initial rated output (lumens)	2,900	2,950
Nominal lamp (Watts)	28	32
Initial lamp efficacy (Lm/w)	104	92
Initial system efficacy (Lm/w)	89	90
Lumen maintenance (%)	97	93
Maintenance system efficacy (Lm/w)	86	84
Rated life (Hours)	16,000	20,000
Optimum operating temperature (F)	95	77

Source: Knisley, (2003)

### 5.2.1.2 Benefits of Using T5 Fluorescent Tubes

T5 lamps are specially designed for high frequency operation with electronic ballasts. They provide higher energy efficiency and longer life due to lower lumen depreciation. In addition, the T5 fluorescent lamps are more environmentally friendly because they contain less mercury than the T8 lamps.

### **5.2.1.3 Energy Efficiency Potentials in Lighting Control Methods**

Energy consumed for lighting systems can be effectively reduced by exploiting daylight. Effective use of day lighting has a strong potential for reduction of energy demand especially in commercial buildings. Energy savings resulting from day lighting lowers the electrical energy bill due to reduced peak electric lighting demand, reduced cooling loads which can result in smaller heating, ventilating and air conditioning (HVAC) plants. However, electric lighting must usually be provided at the period when the availability of natural light is not enough. During its exploitation, a control system is needed to switch off the artificial lighting when the day lighting is sufficient or otherwise.

The lighting control may be manual or automatic. Manual controls are simpler and less expensive, but not as reliable as automatic controls. Automatic controls normally can be achieved by different methods such as timer control, occupation control and local switching control. The timer control method is applied by setting time to switch off or on artificial lighting for inactive or active periods.

Photocell sensors are normally used to control daylight systems that measure the illumination level and switch lights on, off or dim depending on the level of daylight detected in a room. The occupation control method uses personnel sensors to detect whether a space is occupied by sensing the noise or the motion of the occupant. The sensors turn lighting on when there is person in the room and off again after a time delay if the people leave the room. Industries energy consumption for lighting can be effectively reduced by turning off lights when they are not needed, matching the amount of lighting required to do the job, using high efficiency lighting, cleaning and replacement of failed lamps.

### **5.2.2 Efficiency Improvements in Electric Motors and their Systems**

At the period when energy conservation was not a major concern, electric motor technology was only required to provide durable products with extended service life. In the era of energy crises, power saving approaches was emphasized in every manufacturing process due to the significant amount of energy consumed by motors. In this case energy conservation can be accomplished by introducing energy efficient motors in industries.

There are two broad categories of electric motors. These are AC and DC motors. DC motors are commonly used in traction and industrial applications where the wide speed control is required by the process being driven. AC motors are grouped into

two general categories thus: synchronous and asynchronous or induction. The induction motors are the largest user of energy in cement industries. The synchronous speed of the motors is determined by the number of poles and frequency of the power supply as:

$$N = \frac{120 \times f}{P} \text{ rpm} \dots\dots\dots 5.1$$

Where N is the speed in rpm  
 f frequency in Hz  
 P number of poles

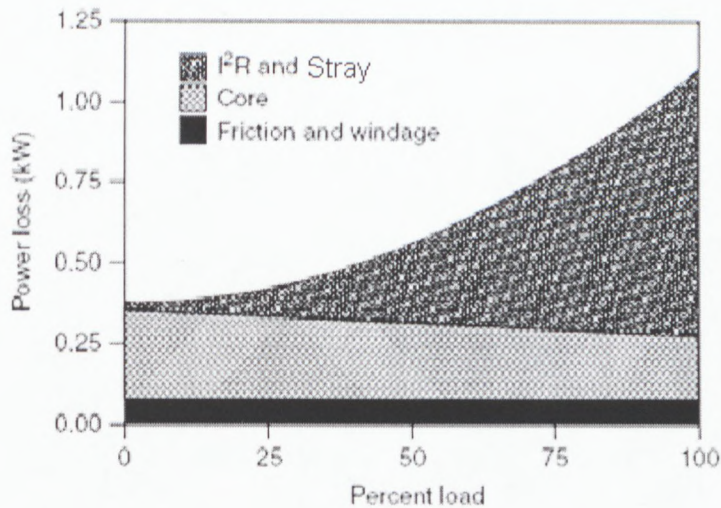
Squirrel cage and slip ring motors are commonly used in cement industries due to their durability and their direct use of the AC power supply system. Currently the motors used in SSA industries are of standard efficient types. This evidence is from the survey results which revealed that, energy efficiency motor technology appear to be new in many industries. The discussion made with the technical personnel shows that, this technology is neither adopted nor existed in most industries, some plants do not have even a single EE motor.

Motor efficiency is defined as the ratio of mechanical power output to the electrical power input, usually expressed as a percentage:

$$\text{Efficiency} = \frac{\text{Output Power}}{\text{Input Power}} = \frac{\text{Input Power} - \text{Losses}}{\text{Input Power}} = \frac{\text{Output Power}}{\text{Output power} + \text{Losses}} \times 100\% \dots\dots 5.2$$

From the equation it is seen that, reduction of motor loss can improve motor efficiency. This is achieved by improved design, materials and manufacturing techniques. Improved motor efficiency enable motors to accomplish more work per unit of electricity consumed.

In SSA countries electric motors consume about 70% of the total electrical energy consumed in industries, hence special saving mechanisms should be taken to reduce consumption by the motors. The improved efficiency of the motor leads to high electricity saving. Energy-efficient motors offer other benefits like having higher service factors, longer insulation and bearing lives lower waste heat output and less vibration because they are constructed with improved manufacturing techniques and superior materials. The use of energy efficient motors results in increase of reliability of the plant.



**Figure 5.2:** Composition of Power Losses in a Three Phase Induction Motor

Induction motor losses are generally categorized into: conductor (copper) losses, magnetic, mechanical and stray losses. Conductor losses are due to the current passing through the stator and rotor windings. Figure 5.2 shows a typical composition of motor losses and their variation with load. From the figure it is seen that, the motor copper losses increases on increase of load.

Most motors used in cement industries use copper conductors. In order to increase the efficiency of motors, the following design modifications are used to minimise losses and improve efficiency:

- Winding loss (stator): use of thicker windings reduces the conduction losses ( $i^2r$  losses). This requires a modified slot design to accommodate the extra copper. These are usually estimated at about 35% of the total losses.
- Winding losses (rotor): for squirrel cage motors, the use of bigger copper bars and modified shapes reduces losses. These losses are usually about 20% of the total losses (Mthombeni, 2007).
- A magnetic or iron loss occurs in the stator laminated steel core due to the combination effect of the hysteresis and eddy currents (Boglietti et al., 2004). These losses are the result of the magnetic field in the stator core which oscillates at line frequency. It can be reduced by reducing magnetic flux density by adding length to the stator core and the use a better grade of steel for the laminations and reduce the thickness of the laminations. This loss is accounting for about 30% of the total losses.

- Mechanical losses are divided into friction and windage losses. They are those losses associated with rotation and subtraction from new power delivered to the load. Windage losses are created by rotor fan blade which circulates air internally within the motor and some frictional losses due to the bearings. Modified fan design and proper greasing (type and amount) are remedies to reduce mechanical losses. These account for about 10% of the total losses.
- Stray losses accounting for about 5%, and defined as the difference between the total motor losses and the sum of other losses. The air gap flux density is usually considered to be sinusoidal, but it contains many imperfections due to slotting of stator and rotor as well as saturation effects. These imperfections result in high frequency currents in the rotor bars and high frequency iron losses in the rotor and stator teeth near the air gap. These harmonic rotor currents provide little useful torque, but close to the magnetic field of coil end turns can be responsible for additional iron losses which are classified as stray-load losses. The control of stray load losses must be accomplished by a combination of design and careful manufacturing practices (Jordan, 1982).

EE motor performance is monitored by using labels and standards. There is no single standard efficiency testing method that is used throughout the industry. The most common standards are:

- IEEE 112 -1984 (United States)
- IEC 34-2 (International Electro technical Commission)
- JEC - 37 (Japanese Electro technical Committee)

Most of the motors used in SSA adhere to the above standards. South Africa DSM programs preliminary studies have shown that most electric motor suppliers in South Africa and in other countries in SSA use the European Union (EU) efficiency standards that is, Eff 1, Eff 2 and Eff 3. Eff 1 is categorised as a premium efficiency motor, Eff 2 a high efficiency, and Eff 3 standard motor (Mthombeni, 2007).

As mentioned, standard efficiency motors are the motors predominantly used in the industries. In order to replace them with EE motors, the criteria and mechanism for adopting it has to be set, for example, energy efficient motors can be replaced when purchasing new motors, when replacing failed motors and when retrofitting operable but inefficient motors. For the reduction of electrical energy consumption, the research proposes the following motor replacement measures to be considered in all SSA cement industries for the use of energy efficient motors:

- For all new installations
- When major modifications are made to existing facilities or processes

- For all new purchases of equipment packages that contain electric motors, such as air conditioners, compressors and filtration systems
- When purchasing spares or replacing failed motors
- Replace with a new EE motor instead of rewinding old or standard-efficiency motors
- Replace grossly oversized and under loaded motors

Use of variable speed drives (VSDs) in motor system enable motors to save energy since many motors are designed to operate at full load condition thus without VSDs, change of load means increase of energy loss, hence variable speed drive also improve energy efficiency consumption.

#### **5.2.2.1 Characteristics of Motor Loads and their Control for Energy Saving**

Motor characteristics depend on the types of loads and mechanism used to drive load. In general, industrial loads are divided into continuous, short time and intermittent loads. The selection of motors depends on the type of loads. According to Ali Emad, (2005), the proper selection of motors and driven equipment contributes to energy conservation.

In cement industries most of its loads are continuous loads. Energy losses caused by equipment connected in the plant are inherent from the following:

- Electrical transmission losses from the metering point to the system
- Conversion losses in any power conditioning equipment
- Motor losses to convert electrical to mechanical power
- Mechanical transmission losses in devices such as gear belts, and clutches to change the output speed of the motor
- Losses in the driven unit such as crushers and fans

The speed of a motor is controlled by controlling the number of poles, frequency of the supply and applied voltage. The traditional techniques used in speed control of motors such as resistance connected in the rotor circuit (slip ring) are not favourable as the high loss caused by the connected resistance contributes to lower efficiency. Some of the cement industries loads driven by motors are fans. These loads need fine speed variation for its proper operation. Variable speed drives should be adopted in the plant in order to support the improvement of efficiency.

#### **5.2.3 Assessing Cost Effectiveness of Energy Efficient Motors**

There are a number of motors in SSA cement manufacturing industries. The rating of the motors varies from fractional to several MW. Most of these motors have standard efficiency. Although, the standard motors are cheaper compared to EE motors, they consume more energy for the same output. For this reason replacement of

standard motors to high efficiency ones has big potentials for energy saving. Industrial and individual users could benefit from the use of well designed high efficient motor driven systems. The saving that accrues when EE motors are used is given by:

$$L_s = hp \times 0.747 \left[ \frac{1}{\eta_1} - \frac{1}{\eta_2} \right] \dots\dots\dots 5.3$$

- Where:
- $L_s$  Saving in motor losses, kW
  - $hp$  Horsepower output
  - $\eta_1$  Efficiency expressed as a decimal for the lower efficiency value
  - $\eta_2$  Efficiency of the high value

If the load is varying, the saving is calculated piecewise for each operating interval over which the load is considered. The efficiency of the motor under different loading conditions is as shown in Figure 5.3. The money saved on monthly basis is calculated using equation 5.4 and the simple payback period (PBP) determined by equation 5.5. The economical payback is calculated by considering machine operating hours and cost of electrical energy. Figure 5.54 shows the variation of payback period with machine operating hours and cost of electrical energy.

$$S = L_s \times H \times C \dots\dots\dots 5.4$$

$$PBP = \frac{CD}{S} \text{ (Years)} \dots\dots\dots 5.5$$

- Where
- $S$  Saving of money per year or month (\$)
  - $H$  Operating time per year month or hours
  - $C$  Cost of electrical energy (\$/kWh)
  - $CD$  Cost difference between the two motors

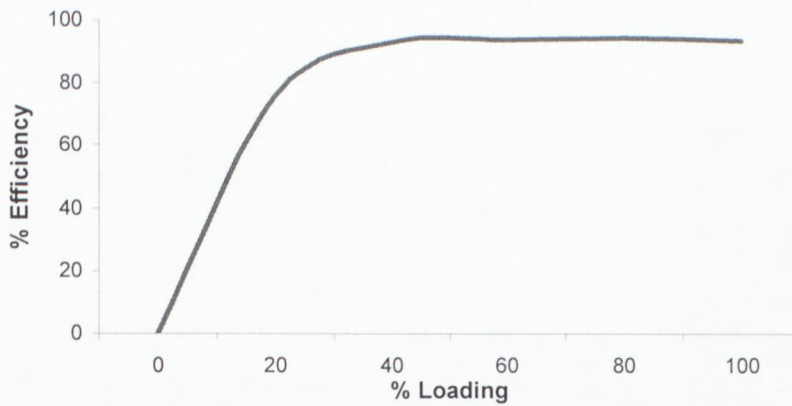


Figure 5.3: Efficiency Vs % Load

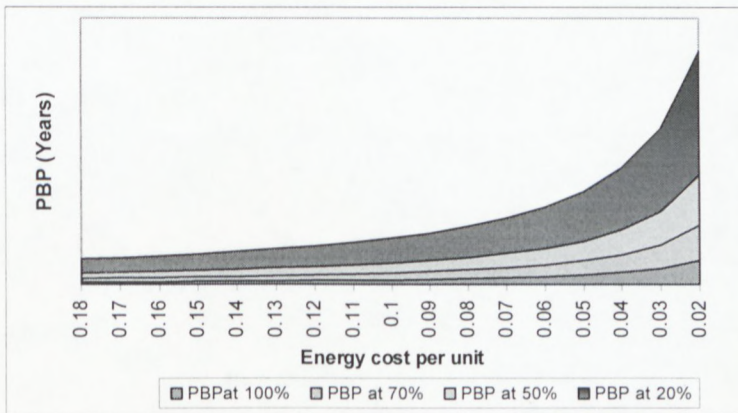


Figure 5.4: PBP as a Function of % Change of Operating Hour and Different Energy Charge Rate

### 5.2.3.1 Benefits of Energy Efficient Motors

The benefit of energy efficient motors includes reduction of the monthly electrical bill of the plants. It can postpone the need for expansion of supply system capacity within the plant. On a larger scale, installing energy efficiency devices defer building expensive new generating plants (McCoyet et al., 1993). The use of Energy efficiency motors reduces downtime, replacement and maintenance costs.

Special design feature of EE motors results in lower operating temperatures, which increase operating life of the motors and reduces the maintenance costs. These motors have inherently low noise and vibration and help in conservation of the environment. The power factor of energy efficiency motors is high compared to standard motors (refer chapter 6).

Considering EE benefits, some countries in SSA, like South Africa have started special efforts on the use of energy efficient motors in their industries. Eskom DSM provides financial incentives to attract industrial customers to use energy efficient motors. This is a special program designed and aimed at reducing the use of inefficient motors. This DSM program is encouraging industrial users to abandon standard motors by installing EE motors by subsidizing the price differential of the standard motor by up to 50 %. Currently this program covers up to 90kW motor ratings. The financial incentives assist users reduce their payback period (Mthombeni, 2007).

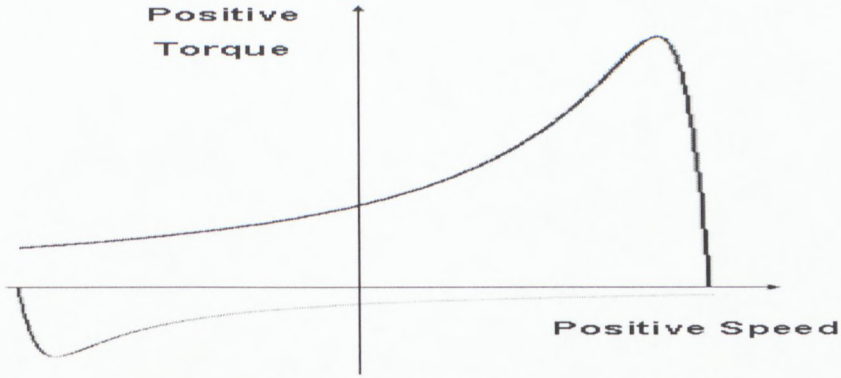
### **5.3 External Factors Influencing Inefficient Operation of Electric Motors**

Energy losses were mentioned as among the factors which contribute to the inefficiency of the electric motors. Apart from the mentioned energy loss, there are some operating conditions like unbalanced voltage, under or over voltage and frequencies, un maintained system that also influence losses.

#### **5.3.1 Unbalanced Voltage**

It can be shown that, the influence of unbalanced supply voltages considerably affect induction motors' efficiency and life of motors. The adverse effects of unbalanced voltages on induction motors have been studied since the 1950s. Positive and negative sequence components produced when an unbalanced supply voltage is applied produces a positive torque and reversing torque. Hence the motor behaves like a superposition of two separate motors, one running at slip "s" with terminal voltage  $V_p$  per phase and the other running with slip "2-s" and a terminal voltage of  $V_n$  as shown in Figure 5.5. The result is that the net torque and speed are reduced. Due to the low negative sequence impedance ( $R'_2/(2-s)$ ), the negative sequence voltage gives rise to large negative sequence currents which in turn increase losses. At normal operating speeds, the unbalanced voltages cause the line currents to be unbalanced in the order of 6 to 10 times. The unbalanced voltage has the largest influence on the copper losses and the lowest on the mechanical losses.

Faiz, (2006) analysed the performance of a 7.5 kW, three phase motor, supplied by an unbalanced voltage. The motor operates with 4% slip. The motor was analysed over a full load and 0-6% unbalanced voltage whereby the stator and rotor copper losses, core and mechanical losses were taken into account.



**Figure 5.5:** Graphical Representation of the Positive and Negative Sequence Torques of an Induction Motor

The variation of the stator and rotor loss vs unbalanced voltage condition can be analysed as follows:

The shaft power can be calculated as:

$$P_{sh} = P_{conv} - P_{FW} \dots\dots\dots 5.6$$

Where:

$P_{conv}$  Conventional power which is calculated as:

$$P_{conv} = V_{Ta} \times I_{Ta} + V_{Tb} \times I_{Tb} + V_{Tc} \times I_{Tc} \dots\dots\dots 5.7$$

$V_{Ta}, V_{Tb}$  and  $V_{Tc}$  Terminal voltage at phase a, b and c respectively

$I_{Ta}, I_{Tb}$  and  $I_{Tc}$  Supply current in phase a, b and c respectively

$P_{FW}$  rotational loss

Rotor copper and stator copper loss are calculated as follows:

$$P_r = |I_{Ta}|^2 R_r + |I_{Tb}|^2 R_r + |I_{Tc}|^2 R_r \dots\dots\dots 5.8$$

$$P_s = |I_{sa}|^2 R_s + |I_{sb}|^2 R_s + |I_{sc}|^2 R_s \dots\dots\dots 5.9$$

From the equations it is observed that, power losses are dependant on the square of the current. According to the experimental results obtained by Faiz, (2006), unbalanced voltage can cause considerable reduction of efficiency and power factor,

which may have direct impact to industry and the power system. In order to overcome this effect, measurement should be carried out so as to test the health of the system.

### **5.3.2 Poor Maintenance**

Motor maintenance is more than making sure the motor itself is operating correctly. It must ensure that, power supplied to the motor is within acceptable tolerances, that the motor's output power is efficiently transmitted to the load and that the load itself is properly maintained so as not to make the motor work harder than necessary. Motors eventually become less efficient through wear, tear, breakdown of lubricants and falling out of alignment.

Scheduled maintenance is the best way to keep the whole system operating within acceptable tolerances. Properly applied maintenance provides valuable information on potential motor failure so that unscheduled downtime is minimized (refer section 4.8). In hot, dirty and humid conditions, more frequent checks of performance and attention to maintaining the physical condition of the motor is recommended. Improper installation or adjustments of the motors reduce efficiency of the operations.

### **5.3.3 Voltage and Frequency Variation**

It is common practice that, in industries, the local power grid voltage varies around rated values as influenced by the connection (disconnection) of other loads and of capacitors used for power factor correction. Higher supply voltages influence the induction machine under various load conditions. Permissible limits for voltage and frequency are also defined by different standards including NEMA. Both ac and dc motors operate satisfactorily over a range of  $\pm 10$  percent of rated voltage although motors have to be designed to incur such voltage variations without excessive temperature rise at a rated power. Boldea & Nasar (2002) stated that, if the voltage increases above the rated value, the core losses in the machine increase notably, whilst the power factor also decrease. The standards also permit a frequency variation of  $\pm 5$  percent of rated frequency. The voltage and frequency fluctuation have adverse effects on the efficiency of the motor.

## **5.4 Assessment of Energy Efficiency Indicators in Cement Industries**

Indicators of energy efficiency are used as screening tools. The improved energy performance indicator is used to reveal the effectiveness of an energy management program. This may be facilitated by the implementation of high-efficiency

technologies and processes, hence lower electricity expenditures and improvement in the competitiveness of energy intensive industries (Bernow et al., 1999).

Wen-Shing (2008) presented two basic methods used to evaluate the performance of energy consumption namely, simulation and statistical analysis method. In order to evaluate the performance of energy consumption, the simulation method use a mathematical model to calculate the theoretical energy consumption and makes a comparison between simulated and observed energy consumption, whereas, statistical analysis exploit the data collection information and compare them with other data. Chung et al. (2006) used multiple regression analysis to build a benchmark table by investigating the relationship between energy use indicators (EUIs) and the explanatory factors. Evaluation of energy efficiency developments in manufacturing industries by physical or monetary indicators increases an understanding of energy efficiency developments.

Analysis of energy efficiency developments in manufacturing industries using physical indicators (especially the energy-intensive manufacturing industries) is given by (Worrell et al., 1997; Phylipsen et al., 1998 and Persson et al., 2006). Farla & Blok, (2000) mentioned the close relationship between the concept of specific energy consumption (energy use at the process level) and energy efficiency indicators as arguments advocating the use of physical indicators in the manufacturing industries. The general methodology to monitor the development of energy efficiency in the industrial sector is by using an energy efficiency indicator (EEI) as given by (Marten et al., 2007) as:

$$EEI_{j,k} = \frac{E_{actual,j,k}}{E_{reference,j,k}} \dots\dots\dots 5.10$$

Where:

- $k$                     The year of analysis,
- $j$                      The type of energy demand (electricity, fuels/ heat, non-energy use),
- $EEI_{j,k}$              The energy efficiency indicator for type of energy demand  $j$  in year  $k$ ,
- $E_{actual,j,k}$         The actual energy use from energy statistics for type of energy demand  $j$  in year  $k$ ,
- $E_{reference,j,k}$      The reference energy use for type of energy demand  $j$  in year  $k$ .

The reference energy use represents the amount of energy that the industrial sector would have used with respect to a certain base year. The reference energy is based on the physical production of products.

The evaluation of EE indicators is carried out in either physical or monetary units. The variation depends on the nature of analysis. Indicators calculated in monetary units are economic indicators which are applied to the analysis of energy efficiency at a macroeconomic level and are calculated as:

$$EI_i = \frac{E_i}{PE_i} \dots\dots\dots 5.11$$

While energy efficiency indicators analysed in physical units (physical indicators) are calculated as:

$$SEC_i = \frac{E_i}{P_i} \dots\dots\dots 5.12$$

Where:

- $EI_i$  Energy intensity for industrial activity  $i$ ;
- $E_i$  Energy consumption required for industrial activity  $i$ ;
- $PE_i$  The measure of industrial activity  $i$  in monetary units,
- $SEC_i$  Specific energy consumption for industrial activity  $i$ ;
- $P_i$  Is a measure of physical production generated by industrial activity  $i$ .

Energy efficient indicators measure how well energy is used for the production of the output while energy intensity indicators measure the quantity of energy required to perform a particular activities such as the production of output ( Martin et al., 1994). It is obtained when two identical industries are compared. The difference between the actual and estimated specific energy consumption best practice (SECBP) for a given year represents an estimate of the energy savings potential (Worrell et al., 1997) and is given as:

$$Energy\ Saving\ Potential = \frac{(SEC_{actual} - SEC_{bestpractice})}{SEC_{actual}} \times 100 \dots\dots\dots 5.13$$

Energy efficiency indicators can also trigger functions to include; monitoring, energy efficiency policy, analysis and evaluation to appraisal of new technologies.

Energy consumption that could be saved if energy efficiency is improved to match the best practice value is a potential for energy saving. Therefore lower percentage would imply a higher level of energy efficiency and lower improvement potential. In this regards, the best practice reference is mainly considered if the plant has developed its benchmark as it is defined by (Yogesha et al., 2006). It refers to establishing

reference energy trends across a group of similar facilities. This is useful for identifying Best practice across an industrial sector that aim to establish realistic achievable energy efficiency goals.

### 5.5 Benchmarking of Industrial Energy Consumption

A benchmarking is defined by Wireman (2004) as the process of continuously comparing and measuring industrial energy performance in order to gain information that may be used to improve energy performance of industries. Industries which have not benchmarked their energy use make it difficult to determine how well their plants are or might perform. In this thesis energy performance benchmarking was established in order to develop a methodology for examining energy efficiency indicators of the plant and monitor changes in energy efficiency. Benchmarking can be used to improve and track performance over time hence it is a useful tool for energy efficiency improvement.

In this chapter the energy consumption model was developed for the purpose of identifying opportunities for efficient improvement and controlling energy use in the future. A statistical approach was also used to develop benchmarks. The main goal was to develop an estimate indicator for energy efficiency across the industry. The measure of best practice is took these conditions into account.

The tool used to identify the best practice is stochastic frontier regression analysis. Standard multivariate linear regression model was used to analyse the energy performance indicators. A simple linear equation of the plant energy was proposed by considering production processes and energy components, where energy components consist of non controllable and controllable elements as represented in equation 5.14.

$$E_i = \alpha + \beta y_i \dots\dots\dots 5.14$$

Where  $E$  Energy use of plant  $i$   
 $y$  Production of plant  $i$

Given energy use and production data, the parameters  $\alpha$  and  $\beta$  were determined by linear regression model. The model took cognisance of the fact that the actual data may not be perfectly measured and hence this simple relationship between energy and production may be an approximation of the true relationship. The actual relationship implied in the model includes an error term  $\varepsilon$  that follows a normal distribution with a mean of 0 and variance of  $\sigma^2$ . In other words, about half of the

actual values of energy used are less than equation 5.14 would predict, and half would be greater. Hence the plant i energy used per unit production and other external factors can be calculated by equation 5.15.

$$E_i = \alpha + \beta_1 y_1 + \beta_2 y_2 + \dots + \beta_n y_n + \varepsilon_i \quad \dots\dots\dots 5.15$$

$$\varepsilon \sim N(0, \sigma^2)$$

The regression model gives a straight line that best explains the average response of energy use per unit of production. The relationship between the lowest energy use per unit of production and changes in utilization can be obtained by shifting the line downward so that all actual data points are above the line. This is called Corrected Ordinary Least Squares (COLS) regression and is used to determine constants.

Statistical noise ( $v_i$ ) is also included (random error) in the analysis and a random component ( $u_i$ ) is added to reflect energy inefficiency. Statistical noise may be positive or negative while the second error term follows one sided distribution. If equation 5.14 is expanded to cover a wide range of potential effects, the stochastic frontier model is written as:

$$E_i = h(X_i, Y_i, Z_i; \beta) + \varepsilon \quad \dots\dots\dots 5.16$$

$$\varepsilon_i = u_i - v_i$$

$$v \sim N\left[0, \sigma_v^2\right],$$

Where

- $E$  Energy use, either electricity or non electric energy;
- $Y$  Production, measured by physical production;
- $X$  Systematic economic decision variables (labor hours worked, materials processed, plant capacity, or utilization rates);
- $Z$  systematic external factors (i.e., heating and cooling loads); and
- $B$  Regrest constant

Given data for any plant, the difference between the actual energy use and the predicted energy use is given by:

$$E_i - h(X_i, Y_i, Z_i; \beta) + v_i = u_i \quad \dots\dots\dots 5.17$$

Equation 5.18 represents the probability that the plant inefficiency is greater than this computed difference:

$$\text{Probability} \left[ \text{energy inefficiency} \geq E_i - h(X_i, Y_i, Z_i; \beta) + v_i \right] = \dots\dots\dots 5.18$$

$$1 - F \left[ E_i - h(X_i, Y_i, Z_i; \beta) + v_i \right].$$

$F \left[ E_i - h(X_i, Y_i, Z_i; \beta) + v_i \right]$  is the cumulative probability density function of the appropriate one-sided density function. The value  $1 - F \left[ E_i - h(X_i, Y_i, Z_i; \beta) + v_i \right]$  defines the EPI score and may be interpreted as a percentile ranking of the energy efficiency of the plant.

Energy performance indicators have been developed to minimize energy consumption in industries. The developed EPI of a single line cement plant allows the plant to compare its energy performance. It intends to help cement plants operators identify opportunities to improve energy efficiency, reduce GHG emissions, conserve conventional energy supplies and reduce production costs.

**5.6 Model Development and Testing – Mbeya Cement Factory**

Electricity and heat energy are the main types of final energy demand used in cement industries. In this research, only electricity energy demand was analysed. Due to the different forms of energy requirement for production processes, it is not accepted to generalize analysis of EPI in industrial processes. However, a similar theoretical assessment of a specific process can yield similar conclusions.

In this thesis the energy consumption model was developed based on two scenarios. First the system considers the development of the energy consumption model and hence EPI based on cement mill alone. This was performed because the cement mill section is among the sections of the cement industry that consume large amounts of electrical energy than other sections. Secondly, the analysis considered the overall plant energy consumption model and analysed the monthly energy performance based indicators of cement industry. This model considered the overall industrial energy consumption and other factors that influence energy consumption such as operating hours and plant utilization efficiency.

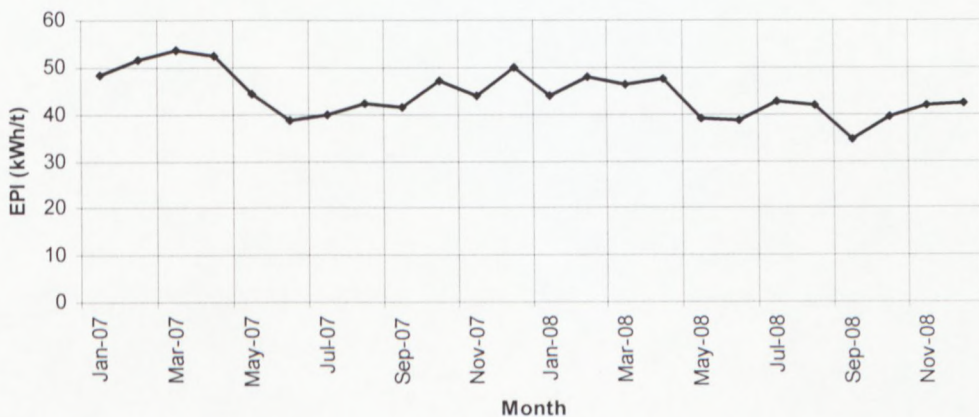
### 5.6.1 Cement Mill Section Energy Analysis

The energy consumption data for the cement mill section was used in the analysis of energy performance indicator. In this thesis, the historical energy, production and operational hours' data are presented graphically as shown in Figure 3.13. The historical monthly energy performance indicator of this section has been calculated and presented in Figure 5.6.

Using the historical data from the cement industry, an energy consumption model was developed. The analysis of the available energy consumption data is also used to identify the opportunities for efficiency improvement and control of energy use in the future. Three basic methods used in establishing the energy model are:

- Previous years' data
- Regression analysis
- Simulation model

In this research, the regression method was used, this is a statistical approach based on historical energy consumption and the factors influencing them. The model was generated from the data given in Table 5.5.



**Figure 5.6:** Monthly Energy Performance Indicators of Mbeya Cement Industry

Simulation analysis using a spreadsheet program and numerical computation was carried out and produced similar results. The model parameters were calculated and tabulated as shown in Table 5.4, the x and y columns in that table are the measured values and the remaining parameters have been calculated. In this analysis only two parameters were used namely energy and production (cement mill). Hence in Table

5.5, y- is energy in kWh over the specified period and x- is the production in tons for the specified period.

The Pearson's coefficient of correlation (r) is calculated numerically by:

$$r = \frac{n \times \sum xy - \sum x \times \sum y}{\sqrt{[n \times \sum x^2 - (\sum x)^2][n \times \sum y^2 - (\sum y)^2]}} \dots\dots\dots 5.21$$

The value of r was found to be;  $r = 0.865324388$  and

The coefficient of determination,  $r^2 = 0.748786297$

By using the least square method, the predicted linear regression equation was developed based on the following structure:

$$\hat{y} = \alpha + \beta x \dots\dots\dots 5.22$$

Where:  $\hat{y}$  = the estimated y variable for the value of x variable;  
 $\alpha$  = the interception on the y- axis, indicates the value of  $\hat{y}$  when  $x = 0$ ;  
 $\beta$  = the slope (the average change in  $\hat{y}$  for each change of 1 unit in x) it tell us the amount of increase in  $\hat{y}$  that occurs for one unit increase in x, the independent variable is calculated as:

$$\beta = \frac{n \times \sum xy - \sum x \sum y}{n \times \sum x^2 - (\sum x)^2} \dots\dots\dots 5.23$$

$$\beta = 33.3437944$$

$$\alpha = \bar{y} - \beta \bar{x}$$

$$\alpha = 250220.8604$$

Therefore the prediction equation is:

$$\hat{y} = 250220.8604 + 33.3437944x$$

This model generated a straight line plot that compared favourably with that obtained using the simulation software (spreadsheet) as shown in Figure 5.7.

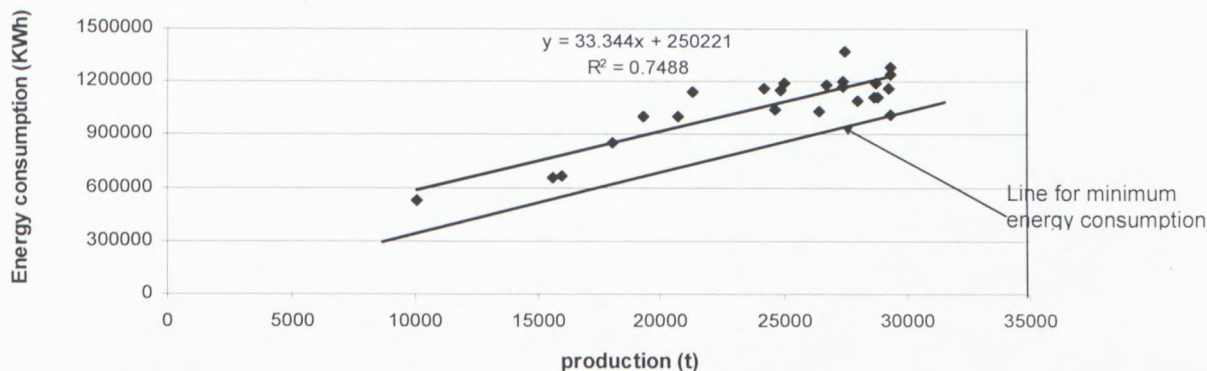


Figure 5.7: Regression Analysis Linear-Fit

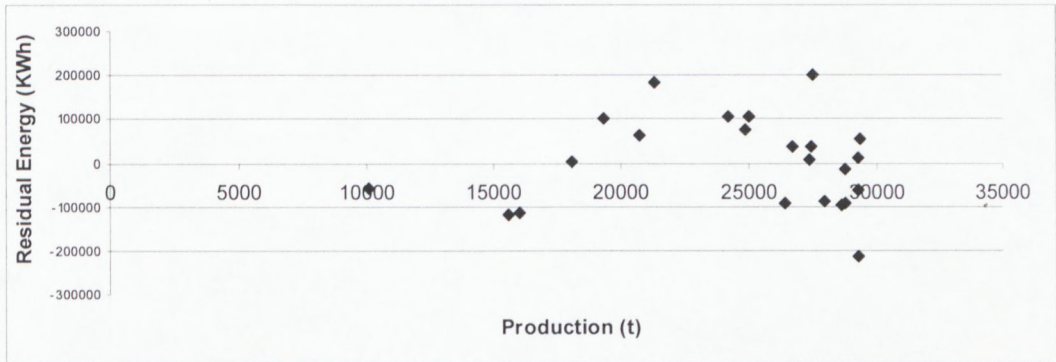
It is important to find the standard error estimation (se) that measures the reliability, or scatter of the observed values around the regression line. The more widely scattered the points, the larger value of error.

Table 5.4: Calculated Model Parameters

S/N	MONTH	Cement Mill Output (t)	Cement Mill Power (kWh)	Cement Mill Run hours			
S/N	MONTH	Production (x)	Energy (y)	time (hours)	$x^2$	$y^2$	xy
1	Jan-07	20745	1006372	530.5	430355025	1012784602384	20877187140
2	Feb-07	19347	998574	518.9	374306409	997150033476	19319411178
3	Mar-07	21325	1144790	586.5	454755625	1310544144100	24412646750
4	Apr-07	10071	527833	279.8	101425041	278607675889	5315806143
5	May-07	26707	1178252	647.0	713263849	1388277775504	31467576164
6	Jun-07	28605	1108806	602.4	818246025	1229450745636	31717395630
7	Jul-07	29235	1160792	623.2	854685225	1347438067264	33935754120
8	Aug-07	29275	1237198	661.4	857025625	1530658891204	36218971450
9	Sep-07	28731	1194762	630.3	825470361	1427456236644	34326707022
10	Oct-07	18070	853038	384.9	326524900	727673829444	15414396660
11	Nov-07	29307	1283403	653.2	858900249	1647123260409	37612691721
12	Dec-07	27465	1367173	681.7	754326225	1869162011929	37549406445
13	Jan-08	27412	1200556	613.4	751417744	1441334709136	32909641072
14	Feb-08	24217	1162743	574.0	586463089	1351972425739	28158159120
15	Mar-08	24882	1157117	609.7	619113924	1338920424052	28791392423
16	Apr-08	25010	1189470	616.4	625500100	1414838880900	29748644700
17	May-08	27963	1092459	571.4	781929369	1193466666681	30548431017
18	Jun-08	28762	1116131	604.2	827252644	1245748409161	32102159822
19	Jul-08	27384	1169381	641.3	749883456	1367451923161	32022329304
20	Aug-08	15613	653394	358.2	243765769	426923719236	10201440522
21	Sep-08	29295	1011913	547.9	858197025	1023967919569	29643991335
22	Oct-08	26408	1037572	586.7	697382464	1076555655184	27400201376
23	Nov-08	16002	669122	375.1	256064004	447724250884	10707290244
24	Dec-08	24674	1040751	572.0	608806276	1083162644001	25679490174
Sum	24	586505	25561603	13470.1	14975060423	28178394901587	646081121532
mean		24438	1065067				

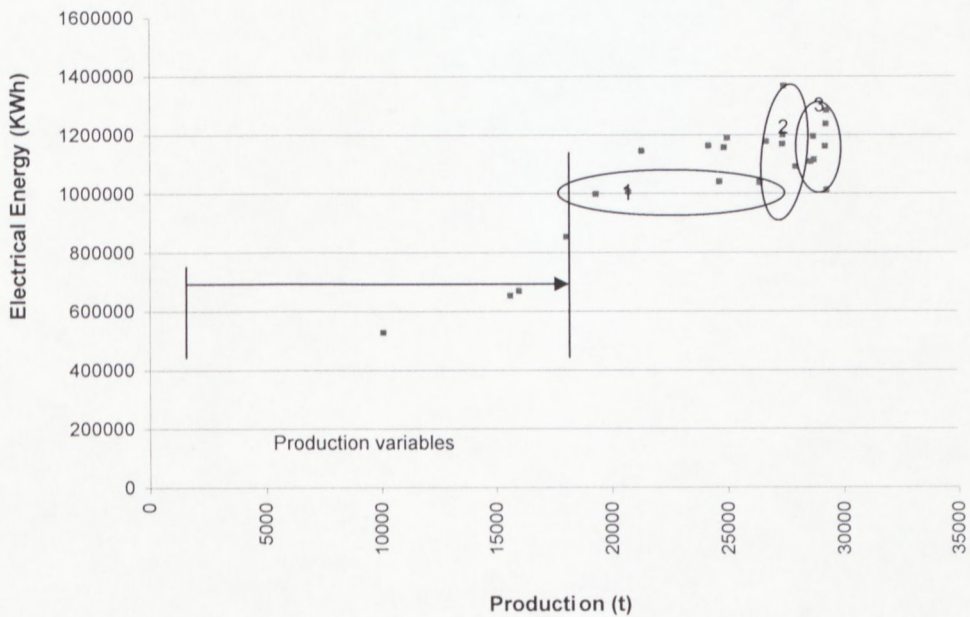
$$se = \pm \sqrt{\frac{\sum y^2 - a \cdot \sum y - b \cdot \sum xy}{n-2}} \dots\dots\dots 5.25$$

$$se = 104349.1912$$



**Figure 5.8:** Residual energy Vs Production analysis

The calculated value of standard error (Se) is presented in Figure 5.8 which shows that 62.5% of data points fall within the band. The width of the band gives a measure of the variability.



**Figure 5.9:** Energy Consumption Vs Production Analysis

The energy vs production is visualized and the variations in performance become visible immediately. In this case it is possible to act on this variation. There is a variation in production from 10071 to 29307 t/ month for almost the same amount of energy utilization (1). Different amount of energy is also used to produce about 28000t/month, see curve (2); in Figure 5.9.

The validation of the model results was generated by the spreadsheet tool, analysis of variance (ANOVA). This gave us the results which did not deviate much as the one obtained in the numerical analysis. The comparison of the measured and predicted energy use is shown in Figure 5.10. The ANOVA result and measured data are given in Table 5.5

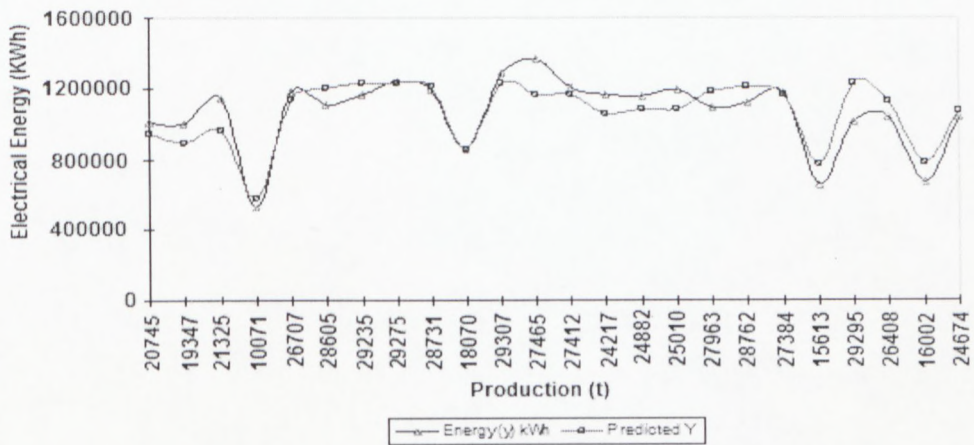


Figure 5.10: Measured and Predicted Energy Consumption

Figure 5.11 shows the predicted and measured energy consumption as a function of production of the cement mill section. It is observed that, the measured energy consumption curve indicates high consumption compared with predicted curve. This is an indication of inefficiency of energy consumption. The developed cement mill energy consumption model shows the area where high energy consumption can be reduced. Based on the predicted curve, best practice energy performance indicator can be set.

**Table 5.5: ANOVA Results**

SUMMARY OUTPUT

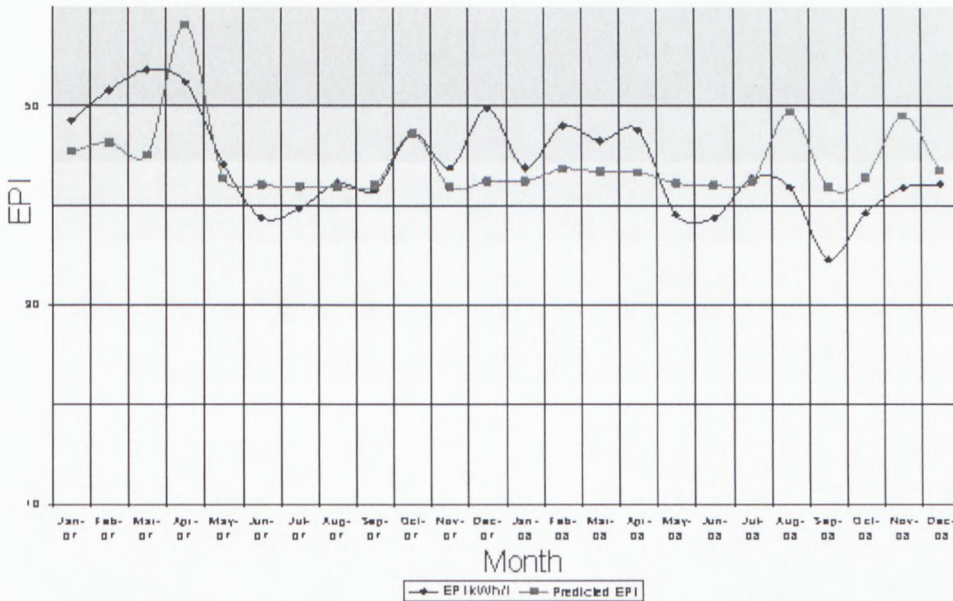
<i>Regression Statistics</i>	
Multiple R	0.865324388
R Square	0.748786297
Adjusted R Square	0.737367493
Standard Error	104349.1912
Observations	24

ANOVA					
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	1	7.14028E+11	7.14028E+11	65.57484068	4.82174E-08
Residual	22	2.39553E+11	10888753694		
Total	23	9.53581E+11			

	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>	<i>Upper 95%</i>	<i>ower 97.0%</i>	<i>Jpper 97.0%</i>
Intercept	250220.8604	102854.9194	2.432755399	0.023571327	36912.81417	463528.9	11581.04	488860.69
X Variable 1	33.3437944	4.117621257	8.097829381	4.82174E-08	24.80437061	41.88322	23.79026	42.897333

RESIDUAL OUTPUT

<i>Observation</i>	<i>Predicted Y</i>	<i>Residuals</i>
1	941937.8751	64434.12487
2	895323.2506	103250.7494
3	961277.2759	183512.7241
4	586026.2138	-58193.21376
5	1140733.577	37518.42268
6	1204020.099	-95214.09908
7	1225026.69	-64234.68955
8	1226360.441	10837.55867
9	1208221.417	-13459.41717
10	852743.2251	294.7748754
11	1227427.443	55975.55725
12	1166008.173	201164.8265
13	1164240.952	36315.04763
14	1057707.529	105035.9617
15	1079881.153	77236.13799
16	1084149.158	105320.8418
17	1182613.383	-90154.38308
18	1209255.075	-93124.0748
19	1163307.326	6073.673876
20	770817.5223	-117423.5223
21	1227027.317	-215114.3172
22	1130763.783	-93191.78279



**Figure 5.11:** The Comparison of EPI of the Measured and Predicted Value

Figure 5.12 shows the comparison of the energy performance indicators of the measured and predicted energy consumption. The result of the analysis shows that, four of the 24 analysed data points are parts of the other predicted indicator. This is equivalent to 16.6 % of the points which deviate much from the other point. Analysing why the value gave us high indication, it is observed that, in these months the production of some sections was stopped. That is, kiln section was switched off for the planned maintenance, concurrently some other machines in raw mill section also were switched off for the major maintenance. Hence without application of energy efficiency measures, the predicted cement mill EPI is 42kWh/t while the plant budgeted was 45kWh/t. If efficiency of machinery and equipment is improved, The EPI would be more improved.

### 5.6.2 Industrial Energy Consumption Model: Development and Analysis

The energy consumption model of the overall cement industry was developed based on monthly production, operating hours and utilization efficiency. Excel/ regression software analysis tool was used to calculate the coefficient of the energy consumption model. MATLAB software was used to validate the model coefficient. The data used in this analysis include the total industrial energy consumption, the production capacity, the plant operating time and utilization efficiency. The production capacity considered in this simulation taken from the cement mill production output, because cement mill output product is the final product.

The production section is the most crucial section in the plant. It involves machinery, raw and processed material and manpower. It is the section where implementation of any energy conservation measure, will influence plant energy consumption. Hence the predicted industrial energy consumption model is based on multiple linear regression models as presented in the following structure:

$$E_i = \alpha_i + \beta_1 Pr + \beta_2 T + \beta_3 \eta \dots\dots\dots .5.26$$

Where:

- $\alpha$  The intercept, that is the constant of industry i
- $\beta_1 - \beta_3$  The regression coefficients
- $P_r$  Production quantity (t)
- $T$  Plant operating time and
- $\eta$  Plant utilization efficiency measured in terms of time of plant operation

Using Excel regression analysis tool the results from the regression output was obtained and have three components namely, regression statistics table, ANOVA table and regression coefficients table. Table 5.6 is the summary of the output of regression model for 24 observant. The plant historical data is given in Appendix 5.2. The correlation between energy consumption is given by R square.

**Table 5.6:** Summary of Regression Output

Regression Statistics		Explanation
Multiple R	0.843934151	R = square root of R <sup>2</sup>
R Square	0.712224851	R <sup>2</sup>
Adjusted R Square	0.669058579	Adjusted R <sup>2</sup> used if more than one x variable
Standard Error	317.1133186	This is the sample estimate of the standard deviation of the error u
Observations	24	Number of observations

Table 5.7 is the ANOVA (Analysis of Variance) Summary of Regression Coefficient

**Table 5.7:** Summary of the Regression Coefficient

	Coefficients	Standard Error
Intercept	111.153374	362.8687
X Variable 1	0.06239985	0.014164
X Variable 2	1.59218396	4.700777
X Variable 3	1.54317776	33.83179

In conclusion, let  $\beta_j$  be the regression coefficient, it is the coefficient of the  $j^{\text{th}}$  regression variable (intercept, production, operating hour and utilization efficiency).

Then the columns in Table 5.7 show:

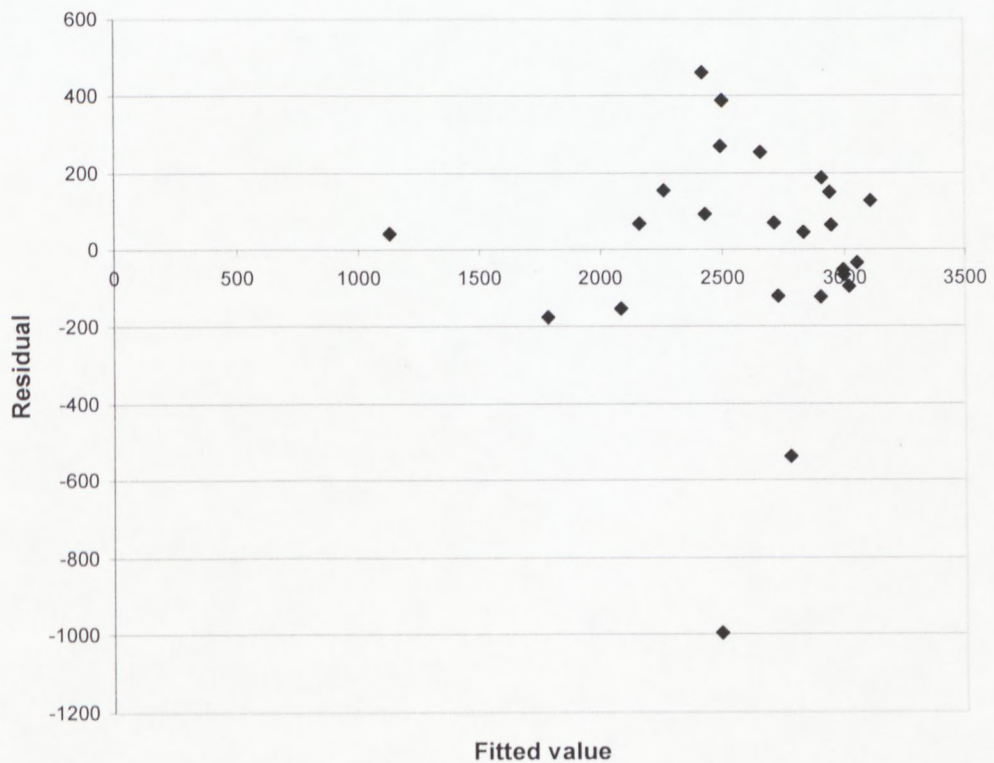
**Coefficients**; this give the least squares estimates of  $\beta_j$ .

**Standard error**; gives the standard error of the least squares estimates of  $\beta_j$  and

The developed fitted line or (equation) is:

$$\hat{E} = 111.153 + 0.0624 \times Pr + 1.592184 \times T + 1.5432 \times \eta \dots\dots\dots 5.27$$

The parameter obtained in regression analysis tool used to testify the validity and significance of the model based on assumption such as residuals having constant variance and being normally distributed. Graphical analysis of residuals was used to check the validity of the model as shown in Figure 5.12. The analysis demonstrated satisfactory results since 83.3% of residuals were within the horizontal band and the normal probability plot is almost a straight line as given in Figure 5.14



**Figure 5.12:** Residual versus Fitted Value

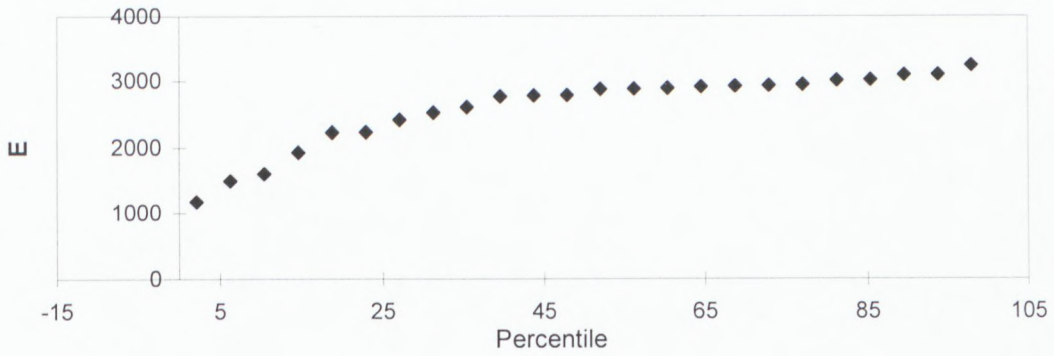


Figure 5.13: Normal Probability Plot

The model also seems to be reasonably representing the behaviour of the data since the values of the coefficient of multiple deterministic R,  $R^2$  and adjusted  $R^2$  are 84.4%, 71.2% and 67% respectively. These are the accepted measure of good fit.

Figure 5.14 shows, the monthly historical and predicted electricity consumption of Mbeya Cement Industry. Again as shown in figure, the developed models simulate the historical data adequately. The analysis of the predicted energy consumption versus production compared with historical trend showed that, the energy consumption has been reduced for the same value of production. It has been also observed that, in the historical energy model, some months consumed high energy for the same amount of production where it is minimized in the predicted model.

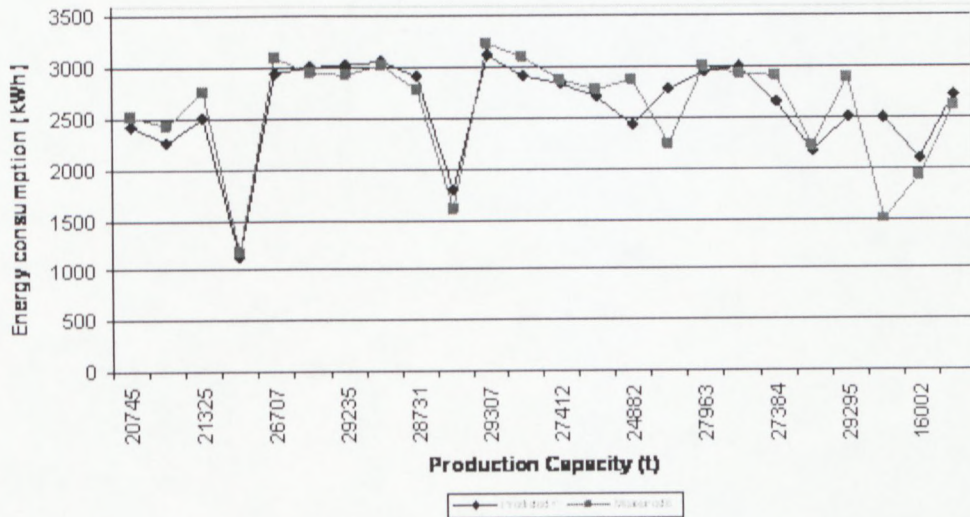


Figure 5.14: Simulation of Energy Consumption Model

The energy performance indicator of the historical and developed model was analysed and given in Figure 5.15. The monthly energy efficient indicator for historical and developed model was calculated, from this analysis it was observed that, the annual best practice EPI without implementing any EE measure is 107.7303kWh/t, while the plant had set 125kWh/t this was equivalent to the reduction of energy 17.2kWh/t. The world best practice energy performance indicator for cement industries is 77kWh/t.

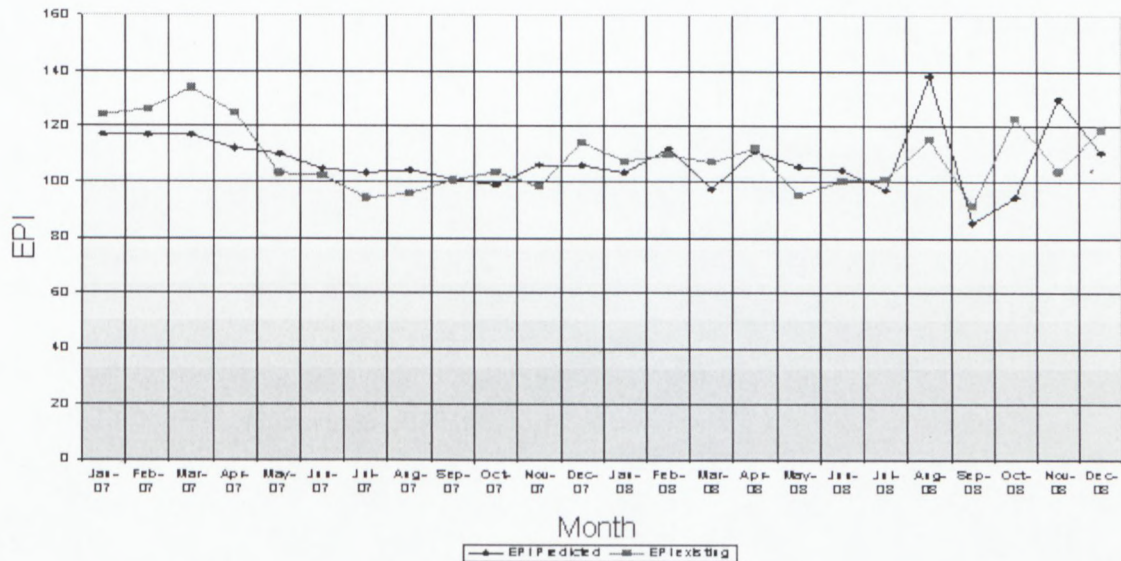


Figure 5.15: Evaluation of Energy Performance Indicator

The developed energy consumption model therefore might be used for the plant's economical analysis like amount of money required for producing of a ton of cement, for example \$/t or R/t.

The validation of the model coefficient was done by the use of MATLAB Software where editor was used for the computation of the coefficient of which the results shows the similarity with the one obtained in Excel. Hence the coefficients obtained are:

$$\alpha = 111.1534; \beta_1 = 0.0624; \beta_2 = 1.5922; \beta_3 = 1.5432$$

As mentioned, the benchmarking system can be used for planning purpose, using this model, it is possible to analyse other measures that can lead to a reduction of the EPI.

Currently, the equipment and machinery used in cement industries are of the standard type. Hence use of more efficient equipment, process and machinery will enhance more improvement of EPI due to the reduction of energy consumption for the same activity. From the model it was also realized that, energy consumption contributes much to the production process. Whereas the plant production process involves a number of activities, viz processes, machinery and raw material. Integration of these activities gives the production output considered in the model.

The electric motors play a central role for the production of cement, hence the use of more efficient motors, process and transmission can result in reduction of electrical energy consumption of the plant. Improvement of the machines, process and transmission efficiency also increases demand saving as demand saving is direct proportional to the energy saving. Therefore, if efficient improvement is considered in the developed model and for the same production, it will lead to the reduction of energy consumption.

## **5.7 Energy Efficiency Improvement Barriers**

One of the main means of reducing the threat of increased global warming and reduction of energy consumption in industries, caused by human use of fossil fuels, is to reduce the industrial use of energy (IPCC, 2007). Studies show that, energy efficient conservation is not always possible due to the existence of barriers that hinder the implementation of EE programs. This results in energy efficiency gaps.

The types of barriers include those related to the assessed profitability of an investment, and others that are purely psychological. DeCanio (1993) addressed most common profitability based barriers for the application of energy-efficient technologies as split budgets, risk of failure, lack of internal incentives and market structures.

Besides, these barriers are divided into the economic and knowledge barrier that involve limited capital availability and lack of skilled personnel (Reddy, 1991 & Velthuisen, 1995). In view of this, the following was observed during the industrial survey:

The survey on cement industries and discussions with engineers in the industries reveal that, most cement industries are not implementing any of the methods of load management stated in previous chapters for the aim of managing energy. PFC capacitor and manual sequential starting of motors (for reduction of inrush current during the start up) are implemented in order to manage maximum demand.

Energy efficient lightings have never been adopted in the industry. Many industries use T12 florescent lamps in the workshops and in other plant areas. Security and street lighting, high-intensity discharge (HID) lamps are used with manual switching control. Depending on the area of application, some lamps are left on for 24 hours a day 7 days a week. Some lamps in the office are running idle even when the office is not occupied for several hours. In many cases conveyor motors are found to run idle for long time. Under loading of motors is a common case in industries of which high energy losses has been proven.

In many cases, in most manufacturing industries of SSA the energy management program is not yet developed, this makes the industry to consume more energy for a given production output, for example, the current energy performance indicator is about 125kWh/t while world best practice is 77kWh/t. In some industries there is no single energy efficient motor.

## **5.8 Conclusion**

Energy issues such as climate change and air pollution, energy security and high price of energy are the major concern of sustainable development. These call for the need for energy efficient system. Energy efficiency program plays an essential role in many developed countries because it is a vehicle for meeting future energy needs which can be fulfilled by any of the two options; increasing supply or decreasing demand.

This chapter presents the analysis of potentials of energy efficiency technology existing in cement industries of SSA countries and developed an energy consumption model that was used to determine an energy consumption benchmarking thus determining an energy performance indicator. The energy consumption benchmarking can be used to create an energy policy strategy.

Through analysis, it has been observed that, there is a big potential saving in energy efficient motors as 70% of loads are driven by standard motors. Another potential saving can be achieved through good housekeeping and the use of efficient and controlled lighting.

The case study results showed that, the rate of energy consumption per month is varying for the same amount of production. Some months consume large amounts of energy while others are moderate, this shows that, there is over consumption of energy and that, there are opportunities for improvement. Hence energy

benchmarking can be used to set optimum level of consumption that is suitable for the production levels.

It has been observed that, energy efficiency improvements can be achieved through enabling interventions including economic and legislative means, awareness activities, energy labels, energy performance standards, energy management techniques and the promotion of efficient technologies. Performance evaluation that involves regular review of energy consumption data and the activities carried out by industries for production of goods is very important for monitoring the developed energy efficiency program.

## **CHAPTER SIX: Alternative Energy Management Techniques in Cement Industries**

### **6.1 Introduction**

Energy Management (EM) program is a useful scheme in industries for the reduction of electrical energy consumption. In practice, successful energy management requires the co-operation and participation of all actors.

This chapter presents the influences of alternative techniques that can be executed in a plant and manage a considerable amount of energy consumption in industries. The proposed techniques include the use of brushless synchronous motors in place of induction motors especially for mill drives. The motor is proposed because of its characteristic of having high efficiency and the possibility of varying its power factor. In order to analyze the viability of the techniques, the analysis of the plant loads is very important.

In this thesis, the industrial energy pattern has been analyzed in Chapter Three. Implementation of Alternative technology/ equipment is analyzed and showed saving potentials. Although the payback period is high, enormous saving of energy as well as money spent for purchasing energy was observed. Energy management by different tariff structure was also presented. It has been observed that, flexible tariff structure has big contribution in energy management. Two part tariffs are found to be the common tariff structure used in many SSA countries. Energy storage and renewable energy techniques also were considered as an alternative method for EM.

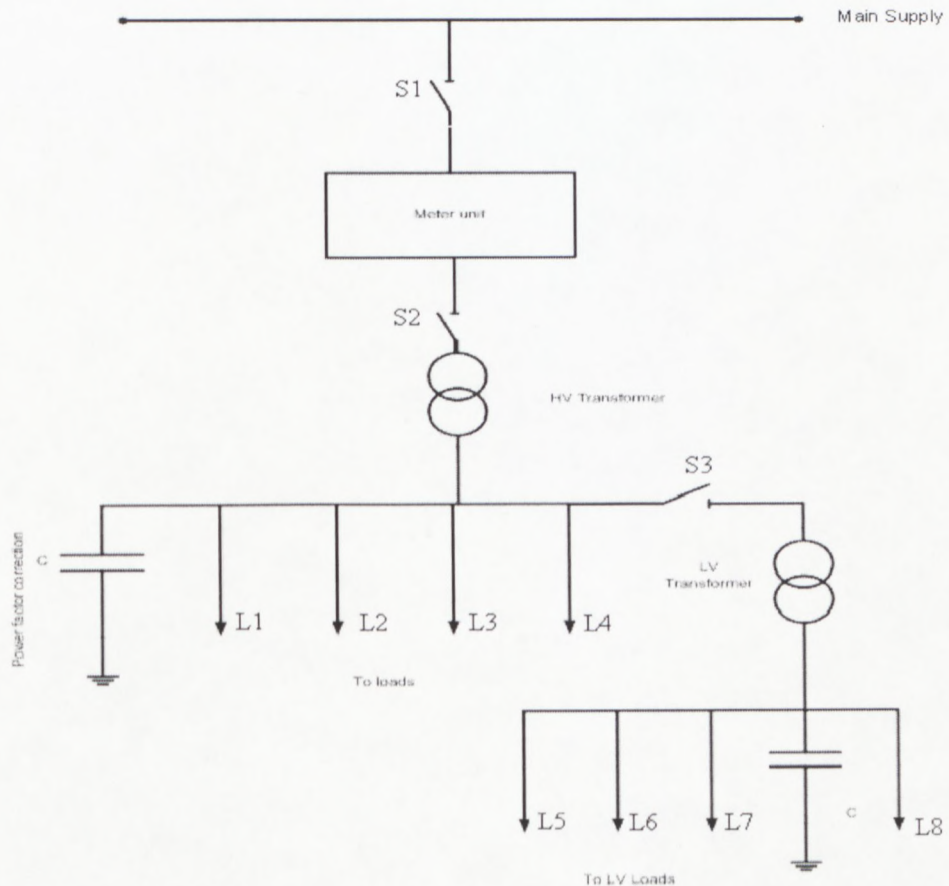
### **6.2 Strategies for the Implementation of Alternative Technologies as Energy Management Techniques**

Electrical energy in cement industries is mainly dissipated in the motor systems. Only a small percentage is dissipated in lighting and other auxiliary loads. Based on the operating principle and characteristics of motors, these motors tend to lose some energy during conversion.

In cement production, traditionally, most motors used to drive mills in many countries including SSA are wound rotor induction motors. Before the era of power electronics, the starting characteristics of these motors were better compared to that of squirrel cage induction motor. Besides, the speed regulation and torque of these types of motors were also improved due to the resistance connected in the rotor circuit.

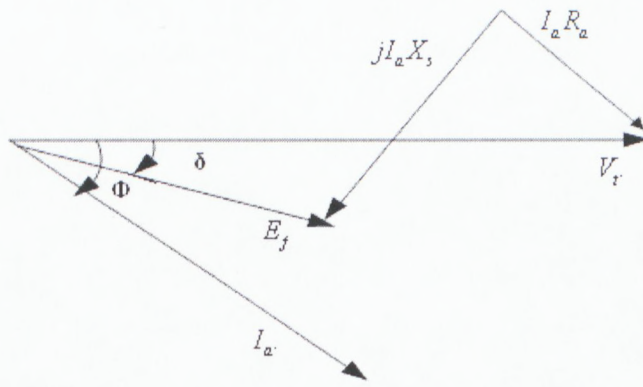
Although the additional resistance increases loss to motor, the starting torque and starting current characteristics were improved.

In this chapter the application of synchronous motors in cement industries was evaluated. The viability and possibility of replacing induction motors to synchronous motors (especially big size motors) in terms of energy management was analysed. These motors have high power factor and high efficiency compared to induction motors. Brushless type motors (brushless exciter) were considered in this study. Electrical and mechanical characteristics of motors and their compatibility with the system were analyzed. The analysis presented is based on the power factor level, starting current as well as efficiency of the motor. The torque capability was also calculated. The industrial layout showing the possible connection of the motor loads is given in Figure 6.1. Among the loads connected in this figure more than 70% of the loads are driven by induction motors.



**Figure 6.1:** Plant Layout of the Industry

**Key:** L1.....L8 are loads  
S1.....S3 sectioning switch



**Figure 6.3:** Phasor Diagram of Synchronous Motor at Lagging Power Factor

From Figure 6.2 the power equation is derived, that is, the per phase value as:

$$S = V_t \times I_a \dots\dots\dots 6.3$$

$$I_a = \left| \frac{E_f - V_t}{Z_s} \right| = \frac{E_f}{Z_s} - \frac{V_t}{Z_s} \dots\dots\dots 6.4$$

Hence

$$S = \frac{V_t E_f}{Z_s} \angle \theta_s - \delta - \frac{V_t^2}{Z_s} \angle \theta_s \dots\dots\dots 6.5$$

$$Q = \frac{|V_t E_f|}{|Z_s|} \text{Sin}(\theta_s - \delta) - \frac{|V_t|^2}{|Z_s|} \text{Sin}\theta_s \dots\dots\dots 6.6$$

$$P = \frac{|V_t E_f|}{|Z_s|} \text{Cos}(\theta_s - \delta) - \frac{|V_t|}{|Z_s|} \text{Cos}\theta_s \dots\dots\dots 6.7$$

$$\text{When } R_a \cong Z_s = X_s, \theta_s = 90^\circ \dots\dots\dots 6.8$$

Therefore the Three phase active and reactive power is calculated as:

$$P = 3 \frac{|V_t| |E_f|}{X_s} \text{Sin}\delta \dots\dots\dots 6.9$$

motor speed reaches approximately 97% of nameplate rpm, the DC field current is applied to the rotor producing pull-in torque and the rotor pull-in step and synchronize with the rotating flux field in the stator. The motor runs at synchronous speed and produce a synchronous torque. After synchronization, the pull-out torque cannot be exceeded or the motor will pull out-of step. If the overload momentary occurs, the motor slip-a-pole and resynchronizes. Pull-out protection must be provided to protect the motor as it runs like an induction motor and draws high current which can cause severe motor damage. With the increase of modern power electronics technology, mechanical starting has been improved by the use of converters that starts and controls the speed of the motor.

### 6.3.2 Power and Torque Characteristics of Synchronous Motors

Synchronous motors are normally connected to a fixed bus with it's per phase voltage  $V_t$  and induced excitation voltage per phase being  $E_f$ . The equivalent circuit presented in Figure 6.2 was used to study the performance characteristics of motors.

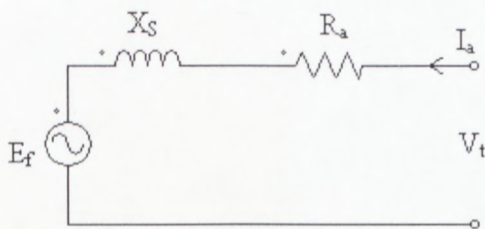


Figure 6.2: Equivalent Circuit of 3 Phase Synchronous Motor

From the circuit diagram, it is seen that,

$$V_t = E_f + I_a R_a + jI_a X_s \dots\dots\dots 6.1$$

Where:  $I_a$  Stator winding current, for producing stator winding flux  $\phi_a$

$X_s$  Synchronous reactance

$R_a$  Stator resistance

From equation 6.1, it is observed that,

$$E_f = V_t \angle 0^\circ - I_a R_a - jI_a X_s = |E_f \angle -\delta| \dots\dots\dots 6.2$$

The phasor diagram for this equation is:

## 6.3 Synchronous Motor vs Induction Motor Performance and Operation

### 6.3.1 Synchronous Motor.

Large size synchronous motors applied to industrial loads serve two important functions:

- It has a highly efficient means of converting AC energy to mechanical power compared to induction slip ring motors and
- It can operate at different (leading, lagging and unity) power factor, by which it can correct the power factor of the system.

Currently the common type of motors used in the cement industry are slip ring induction motors, these motors are used to drive mills, fans and other related load.

Through industrial survey, it was found that induction motor constitutes a big part of load in cement industries. The power supply system of plants and for most motors is 6300V, 3300V, 440V and single phase of 220V with the ratings ranging from fractional to megawatt value (British standard). The transformers are used to step down or up the voltage.

The loads indicated in Table 6.1 are the main (influential) loads in the industry under study. They operate at 6300V supply. Together with the mentioned load there are many small motors which operate at three and single phase supply of 440V and 220 volts respectively.

Synchronous motors (SM) operate at synchronous speed, but they are not self starting. They may be started by the use of a variable frequency supply or they may be started like the squirrel cage induction motors. The traditional starting procedure of the SM is as that of the squirrel cage induction motor.

**Table 6.1:** Rating of Main Motors of the Case Study

S/N	Load	Rating (KW)
1	Cement Mill	1820
2	Raw Mill	1280
3	Raw Mill fan	560
4	Kiln fan	540

The squirrel-cage amortisseur winding produces a starting torque and an accelerating torque to bring the synchronous motor up to speed. At the starting period the field winding remains unexcited and the winding often is shunted by resistance. When the

$$Q = 3 \frac{|V_t| |E_f|}{X_s} \cos\delta - 3|V_t|^2 \dots\dots\dots 6.10$$

Torque in a synchronous motor is also required to operate the driven machine at every moment between the initial breakaway to the final shutdown. The torques associated with synchronous motors are: starting torque, running torque, pull in torque and pull out torque. The detail of these torques are provided in Gupta, 2006, and the developed torque is calculated by:

$$T = \frac{P}{\omega_{syn}} \dots\dots\dots 6.11$$

In order to make a proper comparison between two motors, the efficiency of the motors were also analysed. Types and size of the losses in the machine are the main variables for calculating the efficiencies of machines. The main losses in synchronous machine include; winding Losses iron Losses and excitation and mechanical losses. Hence the efficiency of the machine can be calculated as:

$$\eta = \frac{P_{out}}{P_{in}} \times 100 \dots\dots\dots 6.12$$

### 6.3.3 Advantages of Synchronous Motors

The initial cost of a synchronous motor is higher than that of a conventional AC induction motor due to the cost of the field wound rotor and synchronizing circuitry. This initial cost is often off-set by:

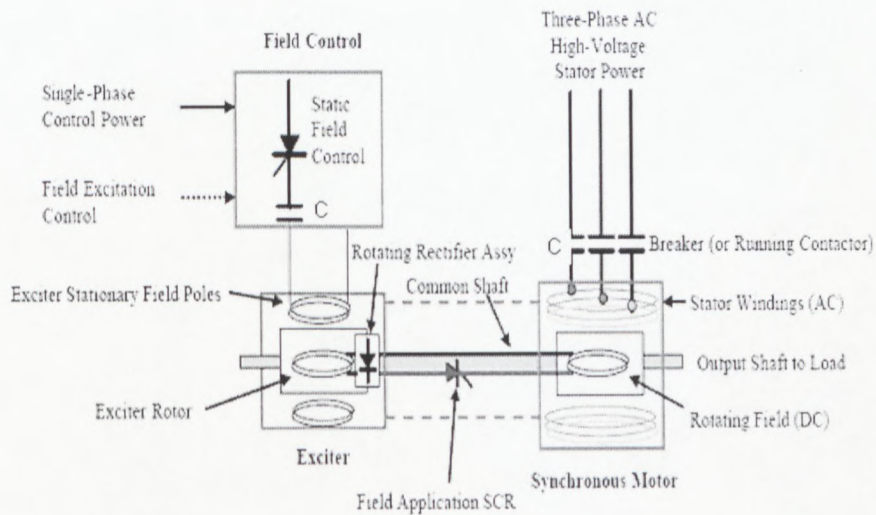
- Precise speed regulation which makes the synchronous motor an ideal choice for certain industrial processes such as prime mover for generators.
- Speed / torque characteristics which are ideally suited for direct drive of large horsepower and low-rpm loads such as reciprocating compressors.
- Ability to operate at an improved power factor, thereby improving overall power system power factor and eliminating or reducing utility power factor penalties. An improved power factor also reduces the system voltage drop and the voltage drop at the motor terminals.
- Ability to operate at higher efficiencies especially in the low speed unity pf ranges

### 6.3.4 Excitation System

Brushless synchronous (BLS) motors is the focus of this thesis. The BLS motor has more advantages than those with brushes. They are capable of operating in wide range of power factor that is lagging, unity and leading.

They do not have slip ring as well as brushes as in traditional synchronous motors. This leads to better performance and reduction in maintenance frequency and cost.

The brushless synchronous motor has an electronically controlled commutation system which eliminates the need for brushes in the excitation system. The rotor has a field winding fed from an electronic circuit as shown in Figure 6.4. When the motor is started the machine breaker C closes, and AC three-phase supply applies to the motor stator windings. The motor starts as an induction motor using the amortisseur winding in the rotor. The machine breaker C auxiliary contact also closes and applies the DC output of the solid state field control to the exciter stationary winding.



**Figure 6.4:** Excitation System of a Synchronous Motor

**Source:** SYNCMTRI, 2004

A three phase alternating current is induced in the exciter rotor windings and this induced voltage is rectified by the rotating rectifier assembly. When the rotor reaches near synchronous speed, the field application silicon controlled rectifier (SCR) is fired by the synchronizing control package and the rectified DC is applied to the synchronous motor rotating field (Theraja, 2006).

The torque of the motor is obtained by the interaction of the generated stator flux with the rotor flux. The voltage strokes must be properly applied to the two phases of

the three-phase winding system so that the angle between the stator flux and the rotor flux is kept close to  $90^\circ$  to get the maximum generated torque.

The control of brushless motors often incorporates either internal or external position sensors to sense the actual rotor position. A sensor mounted on the rotor shaft generates signals on the rotor position information. The common type of converter used to control the motors is Load commutated inverter. It consists of the isolation transformer, drive controller (source and load controller), DC link inductor and motor.

The main block diagram of the stator self controlled synchronous motor using load commutated thyristor inverter is given in Figure 6. 5. Two three phase bridge rectifiers are needed. One is connected to the source side which acts as a line commutated converter and operates at  $0 < \alpha < \pi/2$  to obtain a DC output voltage from an AC input supply. The other one is connected to the load side acts as a load commutated inverter with  $\frac{\pi}{2} < \alpha < \pi$  to obtain a three phase ac output to be fed to the motor.

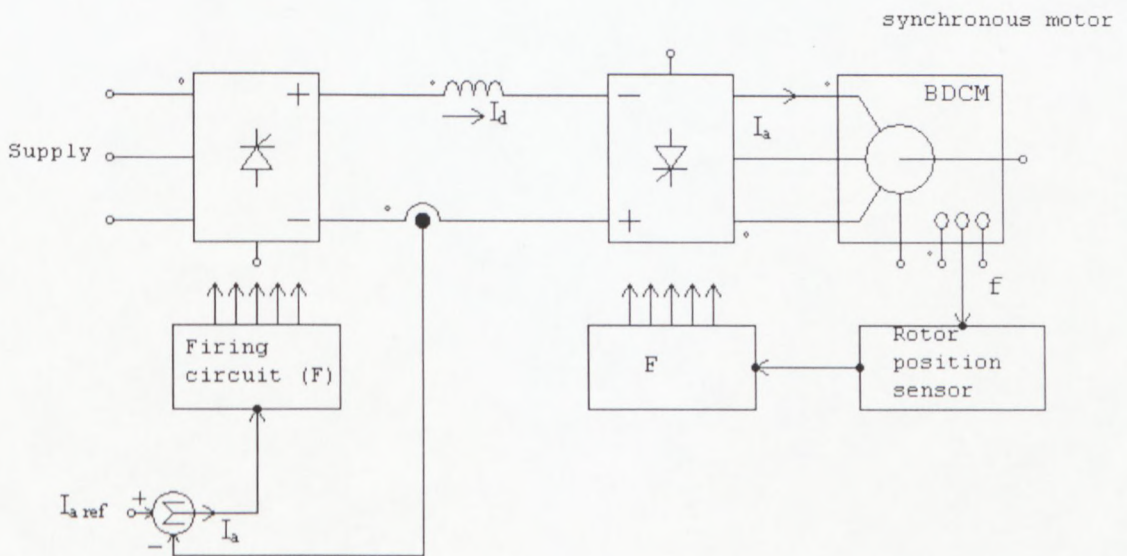


Figure 6.5: Main Block Diagram of a Synchronous Motor Control

#### 6.4 Synchronous Motor Economic Analysis

The study considered the possibility to replace wound rotor induction motors with the brushless excitation synchronous motor. In order to justify the replacement of the motors, economic analysis is needed for estimation of energy saving and viability of the system. This analysis compares motors in two scenarios i.e synchronous motor with:

- Standard induction motor
- Energy efficient induction motor

The method used to determine the performance of electric motors or systems can be done by economical comprehensive calculation depending on the user requirements. The commonly used methods for assessing the economic feasibility of investment alternatives include:

- Simple payback period
- Life cycle costing methodologies which considers the following:
  - Net present value (NPV)
  - Benefit cost ratio
  - Internal rate of return (ROR)

The simple payback period is defined as a period of time required for the savings from an investment to equal the initial or incremental cost of investment. The initial cost of motor is for purchasing a new motor. The simple payback period for the extra investment associated with energy efficient motor purchase is the ratio of the price of premium minus any available utility rebate, to the value of the total annual electrical savings. The factors used to determine economic viability of the motors include the following:

- Efficiency of the motor being compared
- Hours of operation per year
- Electrical energy cost \$ /KWh
- Percentage of motor or system loading

The life cycle of the motor may be calculated considering the operating life of the motor, the driven equipment and processes. The major failure factor in the electric motor is caused by the insulation failure. The factors that speed up the deterioration of the insulation life and hence the motor life include percentage loading, operating hour per year and voltage conditions. In order to make an adequate comparison of the energy cost, the system efficiency must be considered. Boldea & Nasar, (2004) presented the average life span of motors of above 200Hp rating as 29.3 years.

#### **6.4.1 Savings Calculation and Pay Back Analysis of SM vs IM Based on Efficiency**

The annual saving from energy consumption is based on the comparison between IM and SM of the same ratings. These motors as per their construction criteria have different efficiencies. For the same motor rating, the savings can be calculated as:

$$S = 0.746 Hp \times C \times H \times \left( \frac{100}{E_2} - \frac{100}{E_1} \right) \dots\dots\dots 6.13$$

Where:

- S Annual saving \$/year
- Hp Horsepower output
- C Energy cost, \$/ KWh
- H Running / operating time, Hrs/year
- E1, E2 Efficient of the motor being compared

Considering the data of the case study, the payback period in this research was calculated from the comparison of the synchronous motor (SM) and the induction motor (IM) of the same rating. In this case SM is more efficient than IM. The cement plant of the case study operates 24 hours per day, hence the cement mill section and its mill motor operates on the same hours as well. The plant maintenance criteria are set 8 hours per week. The total maintenance hours in a year is calculated as:

$$H_m = \text{Number of Weeks / year} \times Hw / \text{week} \dots\dots\dots 6.14$$

$$Hm = 52 \times 8 = 416 \text{ hours}$$

Where: *Hw* Predetermined maintenance hours and *Hm* are the annual maintenance hours

Unplanned shut down hours (*H<sub>u</sub>*) is calculated by considering the total number of operating hours in the year minus the planned maintenance hours. These shutdown hours occur as a result of power interruption from the supply company, malfunctions of some machinery or equipments, absence of raw materials or any circumstance that cause a shut down. Hence the annual operating hours (*H*) is the total hours during which the plant or section operated within the year.

$$H = H_y - (H_m + H_u) \dots\dots\dots 6.15$$

Where *H<sub>y</sub>* is the total annual hours =8760 hours

The years to pay back the premium cost for the synchronous motor can be calculated as:

$$\text{Payback in year} = \frac{\text{Premium cost}}{\text{annual saving}} \dots\dots\dots 6.16$$

Premium cost = cost difference between the two motors or systems being compared

The cost of the system being compared is expressed as:

### **6.4.3 Analysis of Operating and Maintenance Costs of the Machines**

This section examines some of the operating and maintenance considerations of the different drive systems. The cost of energy is assumed to be \$ 0.06 per KWh. No consideration has been made for demand charges or power factor charges so far.

#### **6.4.3.1 Wound Rotor Motor with Power Factor Correction Capacitor Banks**

Wound rotor motors are somehow similar to SM in many parameters to normal or squirrel cage induction motors. However, they have additional rheostat equipment for improving electrical characteristics and the slip rings which increase maintenance costs. The motors also need the power factor correction equipment for the power factor management in the system. The additional cost of maintaining capacitor banks has to be considered.

The rotor circuit resistors are used for starting in a stepped format aimed at reduction of starting current and increase starting torque. When stepping, this type of rotor control produces torque transients that are sometimes detrimental to the gear drive. In some drives, the liquid rheostat is used to ensure smooth continuous acceleration. The liquid rheostats also use solenoid controlled valves to control the level of the liquid and the starting ramp for the drive. They operate reliably as long as the valves are serviced on a regular basis. The control of the liquid level by pumping instead of the solenoid controlled valves has improved reliability and reduced maintenance frequencies and costs.

#### **6.4.3.2 Synchronous Motors**

Synchronous motors are similar in maintenance patterns to induction motors with the addition of the field application equipment including slip rings (for brush excitation). If the motor is supplied with a brushless exciter, it can reduce some maintenance costs, especially the maintenance of the slip rings and brushes. If the machine starts by the soft start drives, the maintenance cost should include the maintenance of the starting requirement. This adds the cost in the synchronous machine.

### **6.4.4 Use of Variable Speed Drive (VSD) and their Costing**

Due to the fast growing and sophistication in power electronic technologies, the use of variable speed drives (VSDs) has been increasing. The application of Variable

Speed Drives has most significant energy savings potential. The increased market and the use of VSD have resulted in the decrease of the cost of the drive. It is estimated that, the cost of VSD has decreased by 5% (Anibal et al., 2003). This makes the use of synchronous motors more profitable and adoptable in many applications.

#### 6.4.5 Motor Efficiency at Low Loading

The motor is assumed to operate at partial load when it has higher rating than the load it is driving; hence it reduces efficiency and power factor of the motors.

Figure 6.6 shows the relationship between power factor and efficiency at different percentage loading. It was observed that, efficiency and hence power factor are reduced when loading of the machine is small.

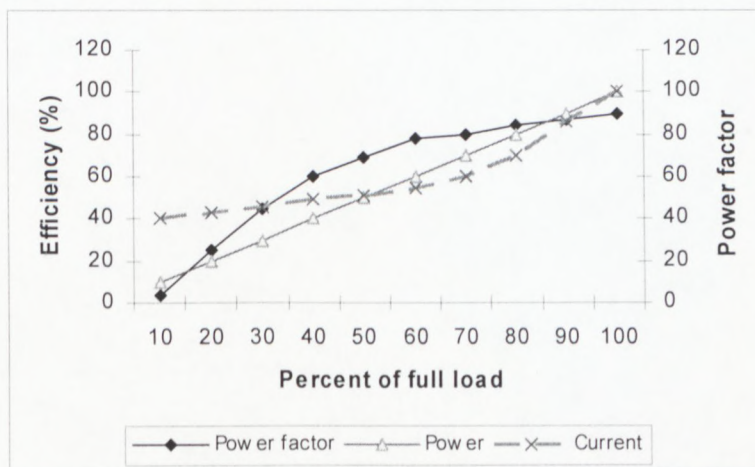


Figure 6.6: Relationship between Current, Power, and Power Factor with Percentage Loading

The use of oversized motors is commonly caused by the following:

- Person in charge may not know exactly the actual amount of the required load;
- Selection of motor larger than necessary;
- The need by the supplier to ensure that the unit supplies will have ample power; therefore, he/ she suggest a driver that is substantially larger than the real requirement (rating);
- Unavailability of a motor with the correct rating when a replacement is needed.
- For some loads, the starting or breakaway torque requirement is substantially greater than the running torque; thus, over sizing of the motor is used with penalties in the running operation.

Based on 6671 hours of operation per year, the annual energy cost for this drive can be calculated considering the percentage loading as:

Energy charges = 0.06\$/ kWh, Motor output / rating= 1820kWh (100% loading)

$$\text{Motor output at 75\%} = \% \text{ loading} \times \text{rating} \dots\dots\dots 6.19$$

$$= 75/100 \times 1820 = 1,365 \text{ kW}$$

The efficient at 100% is 94.1%

$$\text{Efficiency at 75\% loading} = \frac{P_{out}}{P_{in}} \dots\dots\dots 6.20$$

$$= 1,365/1,934.11 = 70.58\%$$

It is assumed that, the motor is operating at 100% loading

$$\text{Input power at 100\% loading is} = P_{out} / \text{efficiency} = 1820/0.941 = 1,934.11 \text{ kW}$$

$$\begin{aligned} \text{Total annual energy consumed for the given machine} &= \text{KW drawn} \times \text{hour of operation} \\ &= 1,934.11 \times 6671 = 12,902,447.81 \text{ kWh/ annum.} \end{aligned}$$

$$\text{Therefore the total annual energy cost for the machine} = 12,902,447.81 \times 0.06$$

$$= \$ 774,146.87$$

The saving obtained from operating motors at its full load can be obtained by taking total energy consumed by the motor operates at its rated load minus the energy consumed by the motor operates at under loading condition. This calculation is done on an annual basis.

### 6.5.1 Analysis of Annual Energy Cost for the Synchronous Motor

The motor has the same rating as an induction motor

The efficiency of the motor is 97%

Hence;

$$P_{in} = \frac{P_{out}}{\text{Efficiency}}$$

$$= 1820 / 0.97 = 1,876.29 \text{ kW (100\% loading)}$$

In real situation the maximum load is rarely developed. Furthermore, most integral horsepower motors can be safely operated above the full-load rating for a short period. Replacements of oversized motors with rated (sized) motors ensure good performance of the motor.

## 6.5 Case Study

The case study considers one of the motors used in the cement industry. It is a slip ring induction motor used for running the cement mill. The rating of the motor is as follows:

$$P= 1820\text{kW}$$

$$V=6.3 \text{ kV}$$

$$\text{Pf}=0.75$$

$$\text{Efficiency}=94.1\%$$

Annual \$ saving is calculated as per equation 6.13, page 145

The industrial data was used in this case study

In order to identify the number of annual operational hours, equation 6.15, page 145 is used whereby the maintenance hour is calculated as per equation 6.14, page 145.

In this case study the total operating hours was taken from the plant data as 6671 hours for year 2008.

Hours/year ( $H_y$ ) = 8760 hours. Hours served for maintenance activities are calculated as per equation 6.14 and hence the maintenance hour for the year 2008 is 416 hours and the unplanned shutdown hours is 1,673 hours.

Energy charge \$/ kWh is taken from the tariff structure of one of the utility company of SSA countries (TANESCO) that is, \$ 0.06; the other SSA countries tariff is given in Appendix 6.1. Currently in South Africa, the exchange rate of \$ is \$1= 7.5ZAR

Efficiency of SM = 97% and efficiency of IM 94.1%, hence

$$S = 1820 \times 0.06 \times 6671 \left[ \frac{100}{94.1} - \frac{100}{97} \right]$$

$$= 23,311.14 \text{ USD per year}$$

Hence;

$$\text{The annual energy saving} = \frac{S}{P} \dots\dots\dots 6.18$$

$$= 388.52\text{MWh}$$

This cost may even be reduced due to the simplicity of its controls system.

Maintenance cost is estimated to be 5% of the motor cost = \$36,911.42.

In order to calculate the payback period of the motor the premium cost is needed.

The premium cost is the cost difference between the two motors or system being compared hence the simple payback period (PBP).

$$PBP = \frac{\text{Premium cost}}{\text{annual saving}}$$

Premium cost = \$868,504 - \$738,228.4 = \$130,275.6

Therefore PBP = 130,275/23,143.03 = 5.6 years

The PBP was calculated based on the price of electricity (2008 TANESCO tariff) (TANESCO, 2008). The industrial tariff category of the said PSI is two part tariff and the price of energy vary as the kWh consumption is increased. This PBP may decrease due to the increase of the price of electricity which often rises after a period of time in most SSA countries (ESKOM, 2009; TANESCO, 2008). In addition, due to its ability of correcting power factor (Induction motors need the PFC equipment), the plant demand charge may be reduced, hence resulting in more monetary saving.

The PBP may be reduced if the price of electricity is high and a time dependant tariff structure is used. This variation of PBP depends on the motor rating, energy cost and hours of operation. The total life span of motors was taken as 29 years. If the PBP is computed, the remaining operating period of the motor life span (years) will be considered a profit in terms of energy and money saving. The total amount of money that could be saved by replacing one induction motor with a synchronous motor, for this case study, is about \$ 532, 289. 69

This analysis has been done by comparing the efficiency of the only one machine which has been considered in the plant. If the replacement could be done for many motors within the plant, an immense saving could be realized. The detailed analysis of the life cycle costing of the motor in different scenario has been done and the result is given in Figure 6.7 and Table 6.2.

Figure 6.7 shows the change of annual energy saving as a function of change of energy prices. The comparison on energy saving vs payback period is shown in Figure 6.8. From the figure it is observed that, energy saving is inversely proportional to the payback period and it decreases exponential. This means, when the cost of electricity is low, the period required for paying back the investment cost is larger.

$P_{out}$  at 75% loading = 1,365KW

$$\text{Efficiency at 75\% loading} = \frac{P_{out}}{P_{in}} \times 100$$

$$= 1,365/1,876.29 \times 100 = 72.75\%$$

Total energy consumption if synchronous of the same rating is used is: kW x hour of operation = 1,876.29 x 6671 = 12,516, 730.59 kWh/ annum

The annual energy cost = 12,516, 730.59 x 0.06 = \$751,003.84

The annual energy saving for the same rating machine = 385,717.22kWh. = 385.72MWh

The annual monetary saving = \$ 23,143.03 for only one motor of 1820kW

### 6.5.1.1 The Investment Cost of Synchronous Motor

The total price of motor per KW is 295 \$/kW

Installation cost 41 \$/kW

Others 20 \$/kW

Total 356 \$/kW

Therefore, the total price of 1820 KW motor is \$647,920. The cost of variable speed drive; the cost of inverter = \$96/kW

Hence, the total price = \$174,720

Installation cost is 25% of the price of the inverter = \$43680

General facility is 5% of the installed cost = \$2184

Hence the total cost of inverter is \$220,584

The price of the synchronous motor with its drive system is \$868,504

Annual maintenance cost is considered to be 5% of the total cost of the motor \$43,425.2

The conversion of South African rand is estimated to be 1\$= 7.5ZAR

### 6.5.2 Induction Motor Costing

The price of induction motor is lower than that of SM motors. The induction motor of the same rating (as synchronous motor) is cheaper by 15% lower than synchronous motor. Hence the cost of induction motor was calculated based on the mentioned percent and is \$738,228.4

The operating hours can be increased if unplanned shutdown period is decreased. The increase or decreases in these hours may be caused by the variation of a number of unplanned shut down periods within the month. This also causes a variation in energy saving. In this study, three scenarios were considered as:

- When the motor is operating at 90% of its annual hours
- When operating at 76% of its annual hours (Current operation)
- When operating at 50% of its annual hours
- When operating 20% of its annual hours

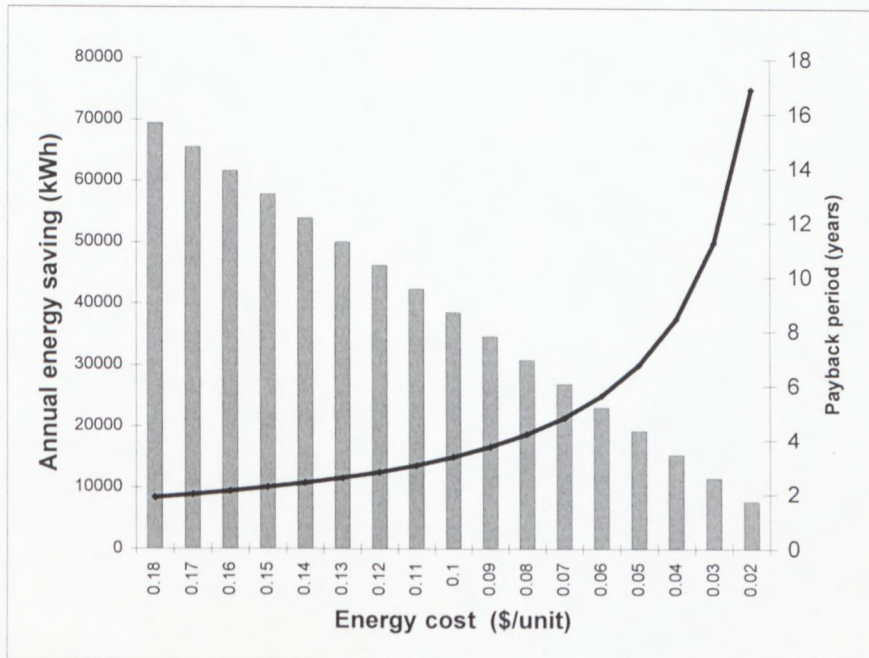


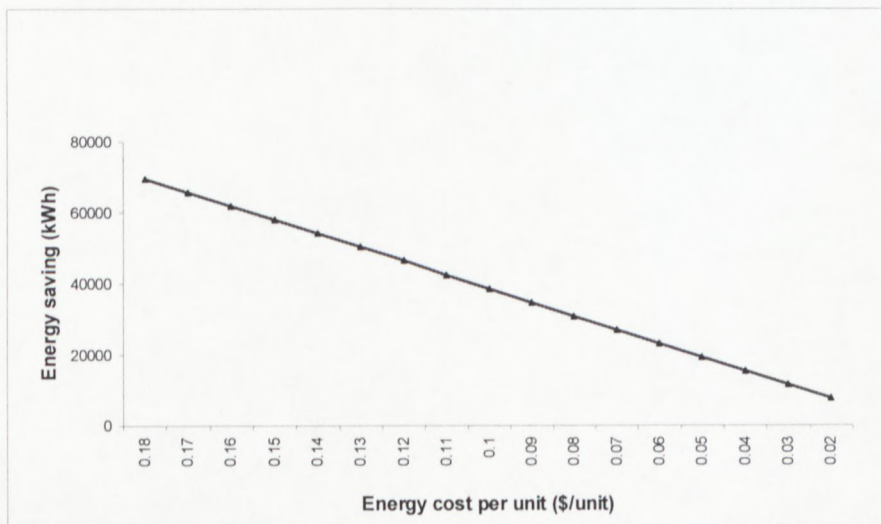
Figure 6.8: PBP vs Energy Cost

The data was analyzed and the final result is given in Figure 6.9. From the figure the following conclusion was made: When the annual operating hours of the plant is small (20%), the amount of energy saved for different electricity cost is very small and hence it is uneconomical to use energy management investment. In addition if the industrial operating hours is 90% of the annual hours, the amount of energy saving tremendously increases.

Hence, it is uneconomical to replace the existing machine with high efficiency. The analysis in Figure 6.8 shows that, the bigger the PBP, the lower the energy savings as well as money saved by purchasing energy.

**Table 6.2:** Results of Energy Saving Calculations

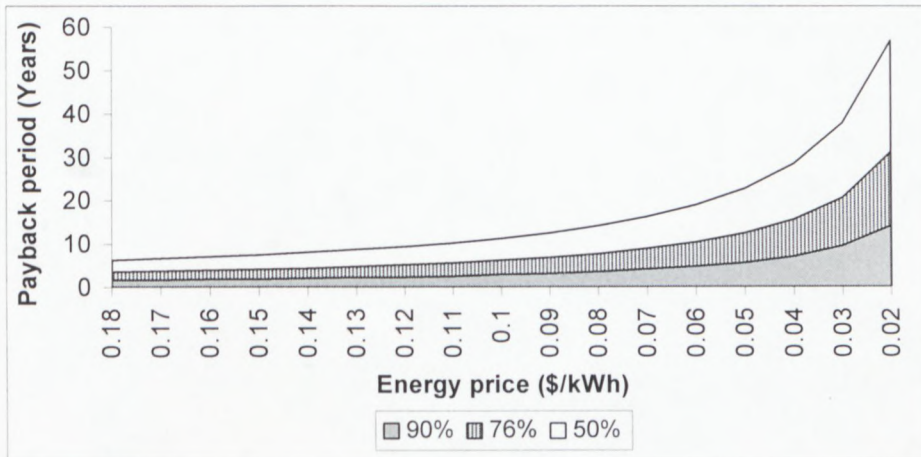
P(kW)	H(Hours)	P(\$/kWh)	E	S(\$) =P*H*p*E
1820	6671	0.18	0.031771	69433.8863
1820	6671	0.17	0.031771	65576.4482
1820	6671	0.16	0.031771	61719.01
1820	6671	0.15	0.031771	57861.5719
1820	6671	0.14	0.031771	54004.1338
1820	6671	0.13	0.031771	50146.6957
1820	6671	0.12	0.031771	46289.2575
1820	6671	0.11	0.031771	42431.8194
1820	6671	0.1	0.031771	38574.3813
1820	6671	0.09	0.031771	34716.9432
1820	6671	0.08	0.031771	30859.505
1820	6671	0.07	0.031771	27002.0669
1820	6671	0.06	0.031771	23144.6288
1820	6671	0.05	0.031771	19287.1906
1820	6671	0.04	0.031771	15429.7525
1820	6671	0.03	0.031771	11572.3144
1820	6671	0.02	0.031771	7714.87626



**Figure 6.7:** Energy Cost vs Annual Saving

The relationship between monetary saving and operating hours for the selected motor is given in Figure 6.9. Presently the motor is operating at 76% of the annual hours.

In conclusion, this study analysed and compared synchronous and induction motor of the same rating, that is 1820 KW in term of efficiency and performance. As per construction, the efficiency of synchronous motor is higher than induction motor. Another advantage of synchronous motor is capability of variation of power factor by varying the excitation voltage, while for induction motors needs to have an arrangement for power factor correction which can cost more money for purchasing, installation and maintenance of the equipment or for paying penalty charged to the customers who operates their plant at low power factor.



**Figure 6.11:** PBP as a Function of Percentage Change of Operating Hour and Different Rates of Energy Charge

Improved performances of synchronous motors (power electronic the soft starter and speed variation) add to the advantages of motors. In order to justify the benefit of replacing the inherited type of motor (slip ring induction motor) to another type, all scenarios that may provide a clear picture of the motors and its possible saving should be considered.

In this chapter, cost benefit and life cycle analysis between SM and standard IM have been worked out. The cost benefit analysis of standard motor and energy efficient motor has been also analyzed in Chapter 5 where the results showed that high efficiency motors have a promising energy saving. However, compared to synchronous motors, the synchronous motors can bring enormous saving due to its power factor correction advantage. This analysis considered only the motor efficiency aspect. More saving can be obtained if factors like the ability of the motor to correct its pf or power factor of the system were considered. With the aid of electronic control circuit, some modifications of the starting characteristic circuit can be done.

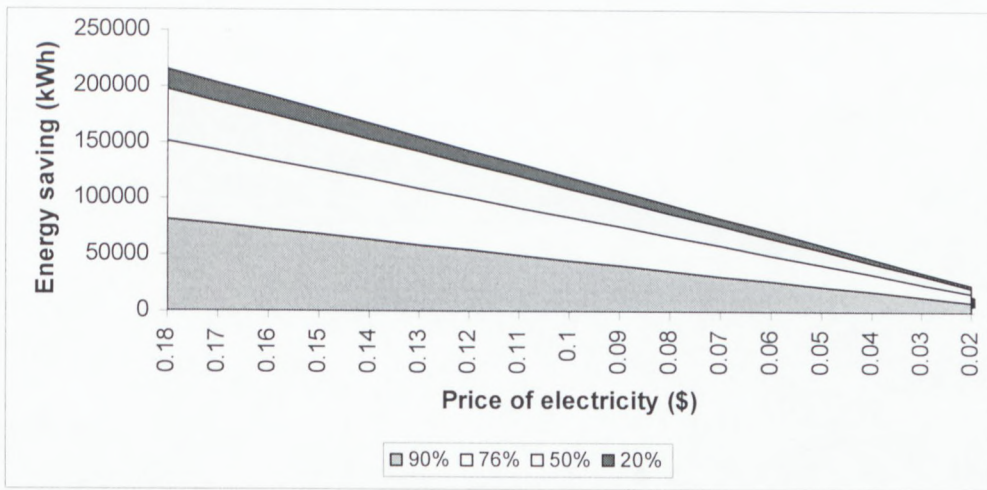


Figure 6.9: Energy Saving vs Percentage Change of Operating Hours of the Machine

### 6.5.3 Influence of Operating Hours of Motor vs Payback Period

Analysis on the influence of operating hours on the payback period of the system was also undertaken. Figure 6.10 shows that, in order for the equipment or machine to provide the allowable payback period for the aim of attaining electric energy saving, the number of operating hours should be considered. When the operating time of the machine is high, the PBP is low; therefore, under that circumstance it is economical to use the machine /equipment. The analysis in this figure has considered the energy cost of \$ 0.06/kWh. Figure 6.11 considers the combined analysis of PBP at different energy cost and different annual operating hours.

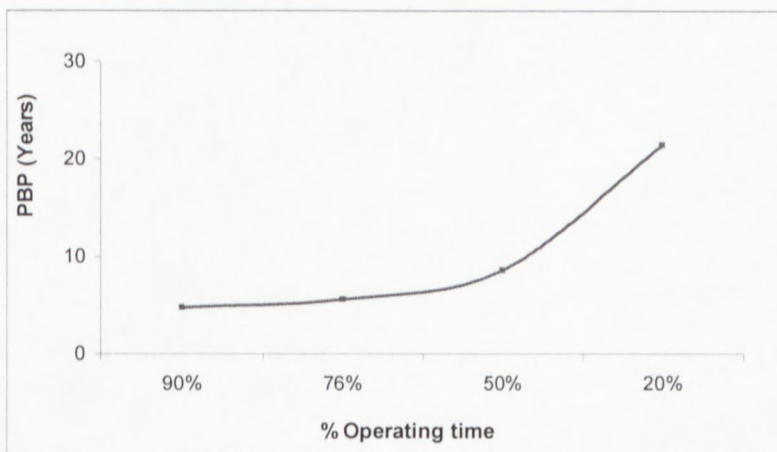


Figure 6.10: Variation of PBP vs Operating Hours of the Machine

In this analysis it is shown that, payback period for the machines operating at many hours per year is very low compared to the one operates for few hours.

- Block meter rate
- Hopkinson demand rate
- Doherty rate
- Demand tariff which consists of a maximum demand charge and an energy rate
- Time-of-Use (TOU) Tariffs which apply different rates at different times of the day and for different seasons (high and low demand periods)
- Real-Time Pricing (RTP) is when the energy price changes in real time (e.g. on an hourly basis).

The tariff rates are the actual rate per unit amounts payable for any of the tariff charges. These tariff charges include:

- Basic charge; a fixed charge (payable every month) irrespective of usage,
- Energy charges for active or reactive energy consumption (For example kWh or kVAh) and
- Demand charges levied for the maximum demand.

The common methods used for load management are Time of use Tariff (TOU), Time dependant tariffs (TDT) and spot price tariffs. These different rates are normally determined by the electrical utility management in concurrence with Government through energy regulatory authority and are imposed on the demand side.

Energy charges can be made to vary seasonally or on a daily basis. Time-of-Use tariffs often have demand charge associated with them. This demand charge, like the consumption charge, is also differentiated with time. Time-of-Use tariffs offer greater energy management opportunities than two-part tariffs (particularly to customers who can shift their loads).

Park et al. (1983) studied response to time of day tariff used by large business customers based on ten electricity utility databases and 6000 customers on mandatory TOU rates. The results are summarized as:

- Overall benefit of introducing TOU rates for large customers exceeded the incremental costs.
- Although benefits that could be obtained are slightly higher in the short run, the resulting savings in metering costs would be small compared to the probable long run gain from wider applications

### **6.6.2 Real-Time Pricing**

Real-Time Pricing (RTP) achieves the objectives of load management better than any technique and tariff structure proposed to date (Goldman et al., 2006). RTP is an hourly variable price determined from the forecast system and load conditions and posted either on a day-ahead basis for 24 hours or an hour ahead for the next hour. It is a dynamic pricing methodology which maximum demand charge plays a less important role, and results in no penalties for additional loads.

## 6.6 Different Electricity Tariff Structure and Metering System

This section explains how the implementation of different electricity tariff in industrial sector contributes to electrical energy management. Researches on energy management by differential electricity rates have been done and they show successful results (Soliman et al., 2007; Lo, et al., 1991). Both researchers concluded that, the differential rate tariffs are the best incentive factor for industrial customers today and can be used to reduce the peak load. Tariff system is defined as a unified price structure proposed in demarcated areas for the same group of consumers, for example domestic, agriculture and industrial customers.

The configuration of the structure differs from one country to another. The tariff structure considered for load management includes time of use tariff. The objective of modern electricity tariff structure is to encourage less consumption during peak hours which helps reduce generation and distribution cost in the long run.

The design of the tariff structure depends on the utility and electricity regulatory board structure. Tariff designed in the public utilities monopolies (which are dominant in SSA), are subject to the Government regulations. The public utilities monopolies have to sell their services in a given area and the tariff rates are governed by the government.

### 6.6.1 The General Type of Tariffs

Equation 21 represents the general type tariff model.

$$Z = AX + BY + C \dots\dots\dots 6.21$$

- Where:
- Z= total amount of bill for the period considered
  - X= maximum demand in kW
  - Y= energy consumed during the period considered
  - A= rate per kW of maximum demand
  - B= energy rate per kWh
  - C= constant amount charged to the customer during each billing period

The variation of different parameters of the model, form different tariff category as given below:

- Straight line meter structure, the price charged per unit is constant
- Fixed charge (Flat demand rate) structure; is a fixed payment made per month independent of consumption

On the demand side, the aim of using energy storage equipment is to attain energy saving. It can also be used to limit the maximum demand to be drawn by the plant, at the instant when many loads are required to operate at the same instant. Using energy storage equipment, some load can be powered from the energy storage device.

A storage media that can take and release energy in the form of electricity have the most universal value because electricity is efficiently converted either to mechanical or heat energy, whereas other energy conversion processes are less efficient. The common technology used for storing direct electrical energy is known as Ultracapacitors and batteries. In the issue of electrical energy management, thermo energy can also be stored to be used during the peak time.

### **6.7.1 The Principal Applications of Energy Storage Technology on Supply and Demand Side**

The principal application of electrical energy storage is as follows:

- 6.7.1.1 Utility Shaping;** the use of very large capacity storage devices to take care of electric demand, when renewable resource is not producing sufficient generation.
- 6.7.1.2 Power Quality;** the use of very responsive storage devices (capable of large changes in output over very short timescales) to smooth power delivery during switching events, short outages, or plant run-up. Uninterruptible power supplies (UPS) are examples of this category.
- 6.7.1.3 Distributed Grid Technologies;** enable energy generation and storage at customer locations, rather than at a central (utility) facility.
- 6.7.1.4 Additional energy storage applications;** exist in most notably and portable electronics and in industrial applications.
- 6.7.1.5 Energy saving;** that can be used in various area of applications.

### **6.7.2 Energy Storage Device**

Every energy storage technology, regardless of category, can be roughly characterized by a fairly small number of parameters namely: self-discharge time, unit size and efficiency used to differentiate technology of various categories of the device. Within a category, finer selections of storage can be made by paying attention to life cycle, specific energy, specific power, energy density and power density.

RTP has been used successfully by utilities as a Demand-Side Management tool. Significant load shifting out of peak periods is achieved for the utility while customers benefit from using electricity at low prices. It improves the efficiency of the power system. Some of the advantages of RTP include:

- Reduction of system peak demand and consequent reduction of installed capacity
- Lower average costs for both utility and consumer
- Elimination of supply cuts and rationing
- Reduction in the use of more expensive fuels such as oil and gas

The cost reflective of RTP encompasses the cost of both the utility and the community of customers, who are at risk of being interrupted when the system is constrained. The price, therefore, includes a reliability component, which increases proportional to the probability of an interruption occurrence. In general, the tariff structure of many industrial customers of many SSA are two part tariff. Due to the penalty imposed for exceeding the maximum demand, customers are conscious on exceeding maximum demand as a result they opt to participate in energy management. Although the technique has proven to contribute to energy savings, the main challenge for the implementation of this tariff in SSA is its requirement for an over overhaul of the traditional metering system or technology which relate to the investment and also requirements for the new legislation.

## 6.7 Energy Storage

Demand and supply side have the same target of using energy storage equipment. On the supply side the energy storage is used to store energy when there are extra resources and used during the shortage. Also the storage can be made during off peak periods so as to be used during peak period. It has an essential role in renewable energy future. Due to the increase in renewable energy development and commissioning, deployment of energy storage will continue to grow. This is caused by the fact that, many renewable energy sources are intermittent and dependant on natural resources.

The rate of generation of electricity from any resource is normally determined by the amount of that resource generated in the season. For example, there is low power generation during drought from hydropower plants. Hence energy storage is required to store energy generated at the peak source and to be used at the peak consumption period. Energy can be stored in many forms as follows:

- Mechanical energy
- Thermal and
- Electrical energy.

### 6.7.2.1 Direct Electric Storage (Ultracapacitors)

A capacitor stores energy in the electric field between two oppositely charged conductors. The dielectric prevents arcing between the plates and allows the plates to hold more charge, hence increasing the maximum energy storage. Ultracapacitor known as supercapacitor, electrochemical capacitor or electric double layer capacitor (EDLC) differs from traditional capacitors. Ultracapacitors' have the ability to effectively equalize voltage variations with quick discharges; this makes them useful for power quality management and for regulating voltage (Frank & yogi, 2008). Its limitations lie in the inability of Ultracapacitors to maintain charge voltage over any significant time, losing up to 10% of their charge per day.

### 6.7.2.2 Superconducting Magnetic Energy Storage

Superconducting magnetic energy storage (SMES) system is well suited to storing and discharging energy at high rates (high power). It stores energy in the magnetic field created by direct current in a coil of cryogenically cooled, superconducting material.

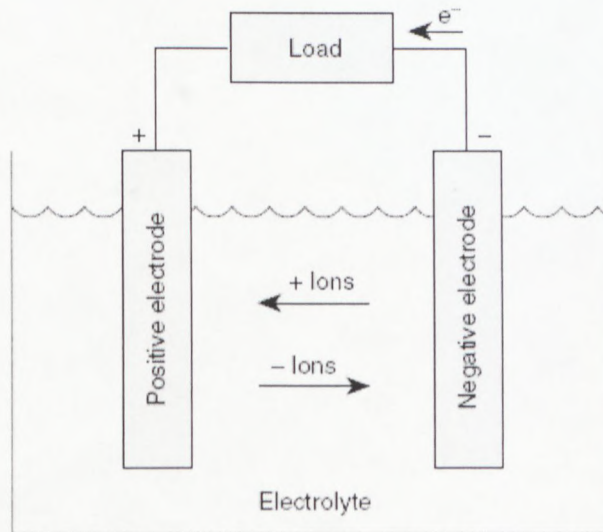


Figure 6.12: Schematic of a Generalized Secondary Battery.

### 6.7.2.3 Electrochemical Energy Storage

The secondary battery allows electrical energy to be converted into chemical energy, stored and converted back to electrical energy. The main parts of battery are shown in Figure 6.12. The negative electrode gives up electrons to an external load and the positive electrode accepts electrons from the load. The electrolyte provides the pathway for charge to transfer between the two electrodes. Chemical reactions

between each electrode and the electrolyte remove electrons from the positive electrode and deposit them on the negative electrode. This can be written as an overall chemical reaction that represents the states of charging and discharging of a battery.

#### 6.7.2.4 Pumped Hydro storage

Pumped hydro is the oldest and largest of all of the commercially available energy storage technologies, with existing facilities up to 1000 MW in size. Conventional pumped hydro uses two water reservoirs, separated vertically. Energy is stored by moving water from the lower to the higher reservoir and extracted by allowing the water to flow back to the lower reservoir. Energy is stored according to the fundamental physical principle of potential energy. The stored energy,  $E_s$ , in joules, is given as:

$$E_s = Vdgh \dots \dots \dots 6.22$$

Where  $V$  is the volume of water raised ( $m^3$ );  
 $d$  is the density of water ( $1000 \text{ kg}/m^3$ );  
 $g$  is the acceleration of gravity ( $9.8 \text{ m}/s^2$ ) and  
 $h$  is the elevation difference between the reservoirs (m) often referred to as the head.

Though pumped hydro is by nature a mechanical energy storage technology, it is most commonly used for electric utility shaping. During off-peak hours electric pumps move water from the lower reservoir to the upper reservoir. When required, the water flow is reversed to generate electricity. Some high dam hydro plants have a storage capability and can be dispatched as pumped hydro storage.

Pumped hydro is most practical at a large scale with discharge times ranging from several hours to a few days. There is over 90 GW of pumped storage in operation worldwide, which is about 3% of global electric generation capacity (Frank & yogi, 2008).

### 6.8 Conclusion

This chapter presents alternative techniques that can be used to influence energy management in industries. The techniques presented include the use of brushless synchronous motors (mills machines) instead of slip ring induction motor. This is because, these motors can operate at variable power factor and more efficient than slip ring motors. The analyses compared the efficiency of SM motors and the

payback period of replacing induction motor to SM. It was observed that, if an induction motor was replaced by SM, the payback period was about 5 years and the remaining operating period (more than 10 years) will be the profit.

Energy management by differential tariff structure has been discussed in this chapter, whereby TOU and real time pricing were found to be more applicable for energy management in many countries. It seems that these types of tariff structure were not used in many SSA countries but those few countries that have been using this structure, especially in the industrial sector, realized energy and money savings. The overhaul of the metering system and legislation for the implementation of charging procedure were considered as a barrier to this energy management techniques in many countries within the SSA. This research proposes other countries of SSA to study their utility customer's behaviour to find the viability of introducing and implementing this system which is mostly promoted for the efficient use of electrical energy.

Use of energy storage system is another alternative means presented as an energy management technique. Several methods of energy storage have been mentioned including capacitors, batteries. This device can store energy during off peaks and use same at the peak periods. They are widely used in various applications and industries.

## CHAPTER SEVEN: An Overview of Industrial Power Factor Correction Methods

### 7.1 Introduction

The power factor (PF) of an AC power system is defined as the ratio of the real power to the apparent power drawn by the system. It varies from 0 to unity but is expressed in percentages. Real power is the capacity of the system to perform work in a given time while reactive power represents electricity that does not execute useful work.

Through industrial survey, it has been observed that, the capacitor bank power factor correction method was traditionally used for the power factor improvement and is still being used in many SSA industries. Due to the increase of modern power electronic technology and solid state control systems, the characteristics of some of loads have changed to nonlinear type. This needs proper analysis on the power factor correction method to be used for its proper performance.

This chapter provides an overview of industrial power factor. The analysis of the existing methods used for power factor correction (PFC) in the industrial sector has been, carried out. An economic evaluation and proposed cost effective measures for the improvement of the existing power factor correction techniques for achieving more demand saving and more stable power system have been analysed.

The chapter also analyses the effectiveness of using of high efficiency motors instead of power factor correction unit for the aim of attaining high power factor and high efficiency. The results show that, small EE motors are cost effective to use compared to the capacitor bank because they have high efficiency and their power factor is improved.

### 7.2 Power Factor Concept

In industrial systems, the power is consumed in a number of electric loads. Depending on the type of industries, the nature of the loads is either resistive or reactive (capacitive and inductive). Except for pure resistive loads and synchronous motors, most of equipment and appliances connected to the supply system have inductive characteristics.

In an AC system, the current and therefore the power are made up of a number of components based on resistive, inductive and capacitive loads. In case of a purely

resistive load, the current and the voltage are in phase, while in inductive loads, the current is out of phase with the voltage and it lags behind the voltage.

The delivered power is converted into a useful work and the remaining power used to establish an electromagnetic field, in case of motor loads. In the circuit/ system, reactive power occurs when electrical current is out of phase with voltage. To obtain the best possible economic advantage from electric power, both the utility system and end users should operate their facilities at high efficiency and high power factor. Hence the power factor can be mathematically expressed as the ratio of active power over the apparent power.

$$Pf = \frac{kW}{kVA} \dots\dots\dots 7.1$$

Where: *kW* - Active power and

*kVA* - Demand or apparent power, is the product of the rms value of current times the rms value of voltage.

The active power is measured as the average value over a cycle of the instantaneous product of current and voltage, that is

$$P = \frac{1}{T_i} \times \int_{T_i} v_{ii} \times i_{ii} dt \dots\dots\dots 7.2$$

Where:  $v_{ii}$  Instantaneous voltage

$i_{ii}$  Instantaneous current

If both current and voltage are in phase and sinusoidal over the cycle, the power factor is termed unity pf. Unity pf is the highest possible power factor. If both are sinusoidal but not in phase, the power factor is the cosine of the phase angle and is less than unity.

The power in traditional industries is mostly used to supply inductive loads. Induction motors are the most widely used load. Traditionally these motors were controlled using conventional control method which had little influence on harmonic generation. Most modern industrial technologies (loads and control systems) are characterized by nonlinear loads (power electronics equipment such as adjustable speed drives and UPS form common types of nonlinear loads) that tend to generate harmonics in their operation resulting to reduction of PFC.

In this case, the power system delivers current to nonlinear loads at the fundamental frequency and loads returns some of the current at high frequencies (harmonics).

In modern technology, power factor is categorised as displacement power factor (DPF) and true power factor (TPF) or distortion power factor. DPF is the ratio of the active power of the fundamental wave to the apparent power of fundamental wave. This is the cosine of the phase angle by which the fundamental current lags or leads the fundamental voltage. TPF is the ratio of fundamental circuit current to total root mean square current (Bose, 2002). This value is less than unity, when nonlinear loads are part of the loads in the circuit while when there is no harmonics source  $DPF = TPF$ . Recently, many industries and utilities measured only DPF.

It has been observed that, low PF is not only caused by industrial loads but also domestic consumers contribute to low power factor to the system (Alexandra von Meier, 2006). He proposed the capacitors or other means of VAR compensation to be installed in the system to minimize the losses caused by low PF. This ensures the industrial system operate at high power factor that contributes to the power system stability and avoid penalty charge.

### **7.3 Techniques to Improve Power Factor**

Power factor of a given system is improved by reducing the amount of reactive power components that is, eliminating low PF loads such as unloaded motors and transformers or by applying external compensation capacitor or other devices to correct low PF condition. In most cases, the power factor correction can be accomplished by installing the capacitor banks in the circuit to be corrected, by connecting synchronous motor or using Var compensator.

#### **7.3.1 Capacitor Application**

Shunt capacitors were first employed for power factor correction in the year 1914 (Frank & Ivner, 1981). The leading current drawn by the shunt capacitors compensates the lagging current drawn by the load. The selection of shunt capacitors depends on the amount of lagging reactive power taken by the load.

The advantages of capacitor power factor correction is given by (IEEE std 141, 1993) includes easy installation, low losses, low cost and are manufactured in a variety of sizes. The algorithm shown in Figure 7.1 is used to determine if installation of capacitor power factor correction (PFC) is economically viable. This algorithm involves several steps that should be followed so as to attain the final decision on the PFC installation. These steps are represented in blocks form and involve the

preliminary evaluation (1, 2), design section (3, 4, and 5), capacitor selection and installation (6, 7, and 8).

The preliminary evaluation is used to ascertain whether the application of capacitors will be successful and economical. The evaluation and economical screening is done considering the plant survey as given in (Bonneville power administration, 1995) and the case study for cement industries. The flow chart for the preliminary evaluation system is given in Figure 7. 2.

The design phase is accomplished by conduction of plant survey and loads monitoring process. The acquired information is useful for providing a rough guide on where to locate the capacitor bank for optimum losses. Another step is to find the economical viability of the capacitor scheme that meets operational constraints such as harmonics distortion and voltage. Finally, the selected capacitor scheme is installed, there after the measurement of the parameter are normally done so as to identify the validity of the system.

Figure 7.2 depicts the steps for evaluating economic viability of PFC. From the data collection stage, the measurement was carried out in the significant feeds within the plant and the information was compared with the value obtained by the other method or estimated so as to identify the possible saving. These data were used to evaluate the economic viability by analysing the utility bill so as to obtain necessary information for determining the total amount of capacitance needed and the saving possible. In this research, monthly electrical energy consumption was evaluated and is given in Appendix 7.1.

In the case of widely fluctuating loads, the reactive power also varies over a wide range. Thus, a fixed capacitor bank may often lead to either over-compensation or under-compensation. Variable VAR compensation was introduced; it can be achieved using switched capacitors or synchronous static compensator. Depending on the total VAR requirement, capacitor banks are switched into or switched out of the system. The smoothness of control is solely dependent on the number of capacitors switching units used. The switching is usually accomplished by relays and circuit breakers. However, these methods which are based on mechanical switches and relays have the disadvantage of being sluggish and unreliable. They also generate high inrush currents, and require frequent maintenance.

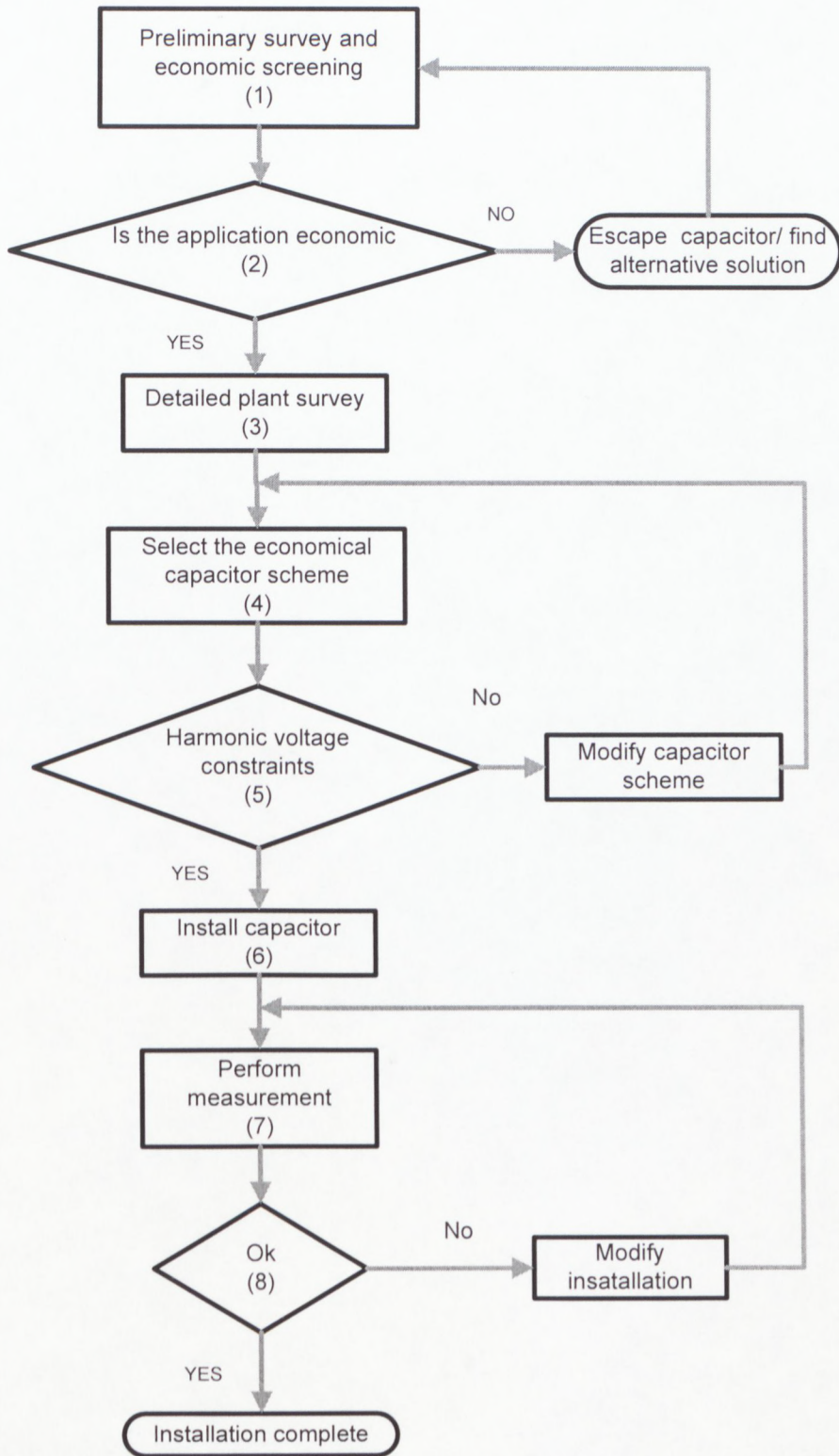


Figure 7.1: Basic Capacitor Application Flow Chart

### 7.3.1.1 Optimal Location of Capacitor in the Circuit

Although capacitor banks can undoubtedly provide many benefits on the demand side and supply side, there are several situations where they can cause deterioration of the capacitor itself and connected equipment in the system. Selection of optimal placement and sizing of shunt capacitor banks is important in this matter.

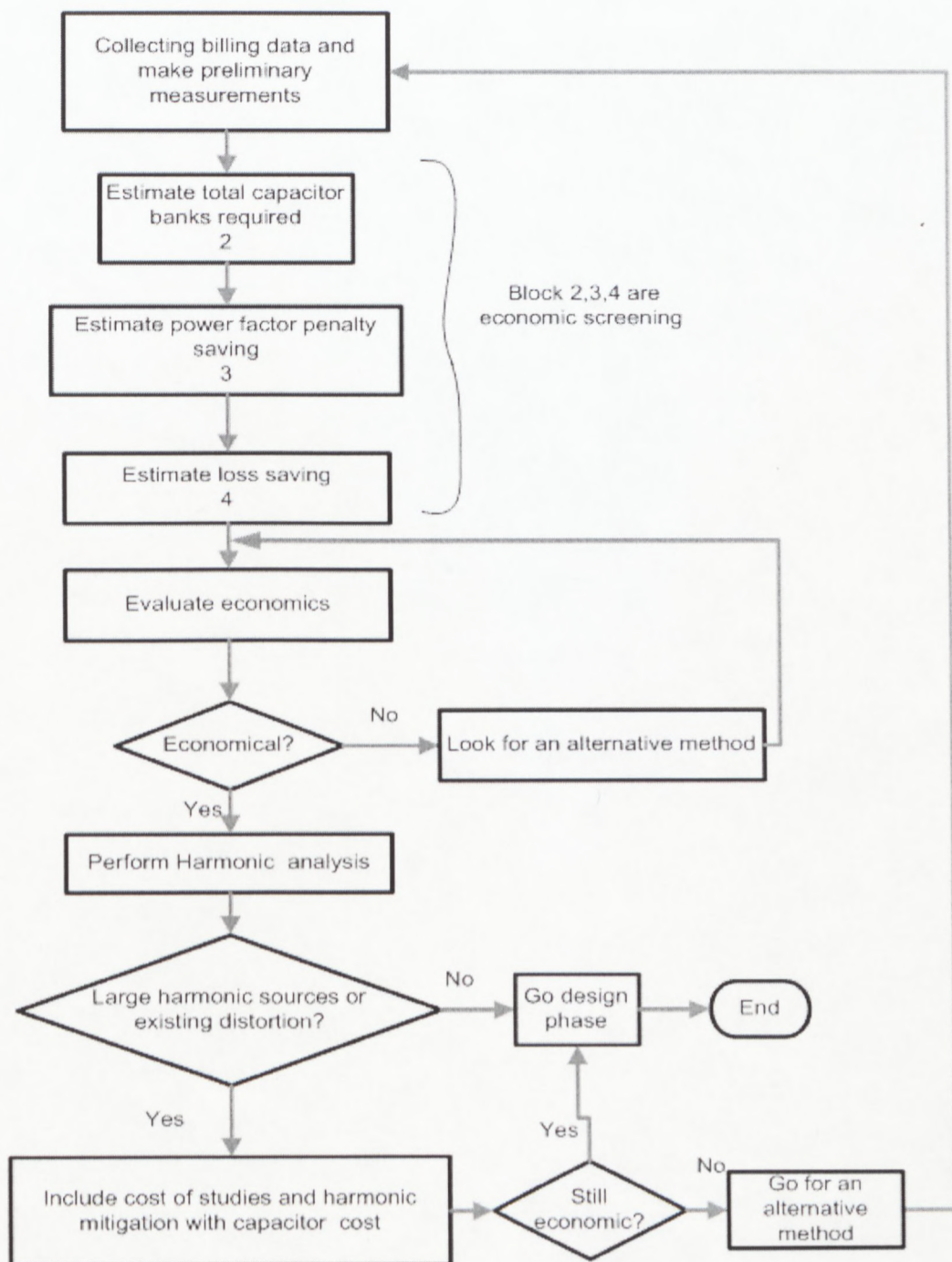


Figure 7.2: Capacitor Evaluation System

Among the drawback of fixed capacitor power factor correction include: The possibility of increasing current caused by resonance condition; increase of voltage and current due to harmonic resonance frequency ( $f_h$ ) and magnification of switching transients caused by switching condition of large capacitor in high voltage side.

The different method of industrial capacitor installation is given by (Whitaker, 2007), and revealed that, the location of the capacitor depends on the costs of purchasing and installing the equipment, controller/switch of the equipment and combination of the system needed to control harmonic voltages and current.

The power factor correction equipment should be installed as close as possible to the load for which the power is being improved. However, connection of low voltage capacitor (on line) can produce unpleasant phenomenon due to the resonance therefore the capacitor connection is grouped as shown in Figure 7.3. In small motors it is economical to switch in a group of motors. For big motors the capacitor is installed near the motor as a fixed bank. In large plants capacitor banks are installed at the primary voltage bus as shown in Figure 7.4.

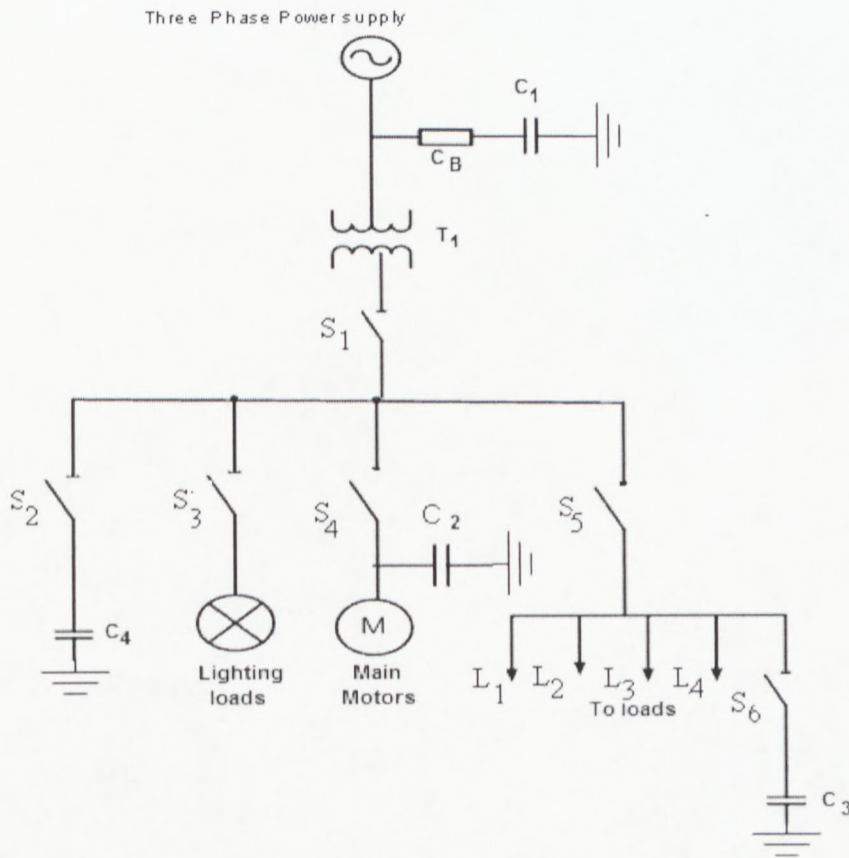


Figure 7.3: Capacitor Placement

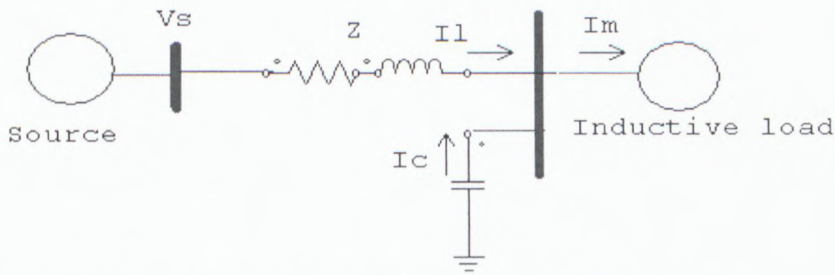


Figure 7.4: Arrangement of Capacitor Connection in the Main Line.

### 7.3.1.2 Types of Correction

**7.3.1.2.1 Bulk Correction;** the capacitor banks are installed at the main bus and controlled in the distribution board.

**7.3.1.2.2 Static Correction,** capacitor banks are installed and controlled across the starter of induction motor, that is when the motor is off, the capacitor bank also is out of the supply system. The advantage of this method is that it eliminates the need for using expensive monitoring and control of equipments. The main disadvantage is its possibility of generating resonance frequency when the motor is switched off and generates voltage by decelerating the motor (IEEE.1993). This leads to high current and voltage across the motor and capacitor circuit which result in severe damage to the capacitor and motor.

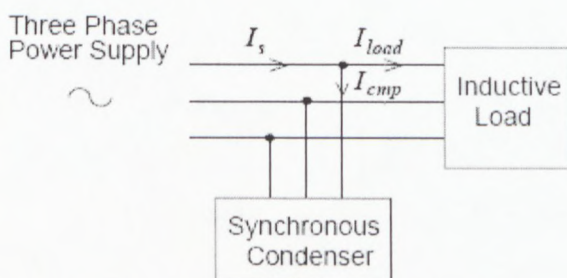
Gramamurthy (2003) presented the survey that had been done in various industries to identify the power factor of the loads and came up with the following: most of the power factor of single phase appliances and equipments varies between 0.5- 0.75 while for the medium sized 3 phase electrical installation industries are 0.5-0.8 but among the industries only few of them have power factor above 0.7. He further investigated the relationship between kVar of specific motors and speed variation and found, that they are indirectly proportional, for example the motor of 187kW when running at 3000 rpm draws 46 kVar while when the speed is regulated to 500 rpm the same motor draws 76 kVar from the supply. In many practice, the calculation of power factor correction capacitor did not consider the variation of the kVar when the speed of the machine is varied.

### 7.3.2 Synchronous Condensers

These provide variation of compensating reactive power by varying the excitation of rotor circuit. The kVar available from fully loaded machine depend on rated kW and power factor, hence the reactive power in kVar is given by:

$$kVar = kW \sin[\arccos(pf)] \dots\dots\dots 7.3$$

When a synchronous machine runs for power factor correction, it is also called synchronous condenser. It works under no load condition and delivers the kVar to the connected circuit as in Figure 7.5. The advantage of this technique is, it does not cause harmonic resonance as capacitors sometimes do, but it is expensive, the application of this is given in (Gupta, 2006). It is economical for large loads, but the disadvantage is that, it requires large maintenance compared with capacitor.



**Figure 7.5:** Power Factor Correction of Using Synchronous Condenser

### 7.3.3 Static Var Compensator (SVC)

SVC is a variable impedance device where the current through the reactor (capacitor or inductor) is controlled using a back to back connected thyristor valve. It is an electronic switched circuit used for switching the capacitor or inductor in the circuit. It was used for load compensation (Padiyar, 2008). It may also be used for minimization of voltage flicker caused by the loads like arc furnace due to the rapid change of current demand which result in fluctuation of the bus voltage. The common configurations of SVCs are TSC, FC-TCR and combinations of TSC and TCR.

#### 7.3.3.1 Thyristor-Switched Capacitors (TSC)

These types of compensator perform switching of capacitors on and off by using a thyristor switch. Figure 7.6 shows a single phase static compensator of the thyristor-switched capacitor (TSC) type. The shunt capacitor banks are split into small steps, which are individually switched in and out using bidirectional thyristor switches. Each branch consists of the capacitor C, the thyristor switches Sw1 and Sw2 and small surge current limiting inductor L Figure 7.6.

This inductor is used to limit the rate of rise of the current through the thyristor and to prevent resonance with the network. The capacitor may be switched with minimum

transients if the thyristor is turned on at the instant when the capacitor voltage and the network voltage have the same value. Under steady-state conditions when the thyristor valve is closed and the TSC branch is connected to a sinusoidal ac voltage source of the instantaneous voltage of:

$$v = V \sin \omega t \quad \dots\dots\dots 7.4$$

And it does not generate harmonics. The current in the branch is flowing and proportional to the value of the capacitance is shown as:

$$i(\omega t) = V \frac{n^2}{n^2 - 1} \omega C \cos \omega t \quad \dots\dots\dots 7.5$$

Where:

$$n = \frac{1}{\sqrt{\omega^2 LC}} = \sqrt{\frac{X_c}{X_l}} \quad \dots\dots\dots 7.6$$

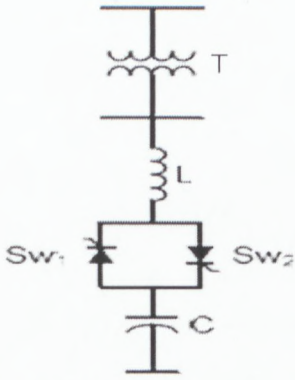
$X_c$  and  $X_l$  are the compensator capacitive and inductive reactance respectively

The amplitude of the voltage across the capacitor is calculated as:

$$V_c = \frac{n^2}{n^2 - 1} V \quad \dots\dots\dots 7.7$$

Static compensators of the TSC type have the following properties: stepwise control, average delay of one half of a cycle (maximum one cycle) and no generation of harmonics since current transient component can be attenuated effectively. It can be disconnected from the circuit at zero current by prior removal of the gate drive valve.

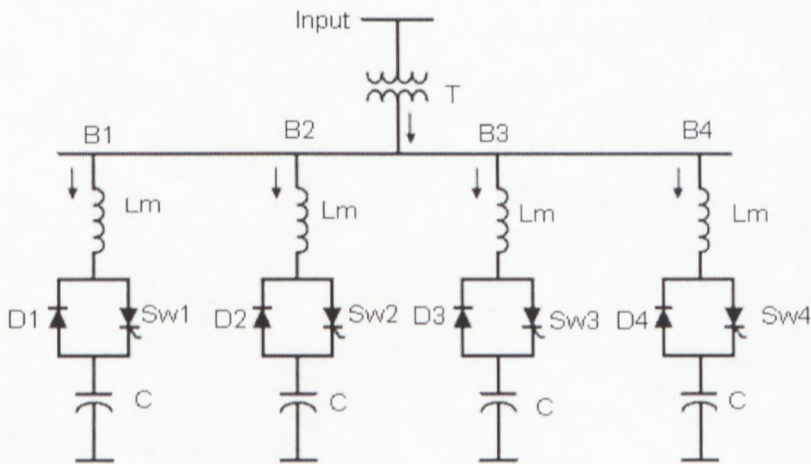
Dixon et al (2005) highlighted the main problem of this switch, indicating that each capacitor bank requires a separate thyristor switch and therefore it is not economical. Besides, the steady state voltage across the non-conducting thyristor switch is twice the peak supply voltage and the thyristor must be rated for or protected by external means against line voltage transients and fault currents. Dixon et al (2003) also proposed the replacement of one thyristor to a diode in each branch so as to limit the transient voltage and fault current. In this case, inrush currents are eliminated when thyristors are fired and a more continuous reactive power control can be achieved if the rated power of each capacitor bank is selected following a thyristor binary combination.



**Figure 7.6:** Schematic Diagram of Thyristor Switched Capacitor

In this case, the configuration combine ant parallel of thyristor-diode connection and the viability of suceptance is based on chain of binary scaled capacitors and one inductor whose value is chosen according to the reactive power that the capacitors can generate if they are all connected .

The configuration of TSC is shown in Figure 7.7.



**Figure 7.7:** Thyristor Switched Capacitor Configuration

### 7.3.3.2 Fixed Capacitor - Thyristor-Controlled Reactor (FC-TCR)

One of the main characteristics of static VAR compensators is that, the amount of reactive power interchanged with the system depends on the applied voltage. In most cases, the compensator consists of a fixed capacitor and a filter for low order harmonics. Each of the phase branches consists of an inductor L and the thyristor switches Sw1 and Sw2 as given in Figure 7.8. The current in a TCR can be continuously varied from zero to maximum by phase control in which the firing angle

is varied from  $180^\circ - 90^\circ$  (Padiyar, 2008; Hingorani, 2000). The instantaneous value of current is given by:

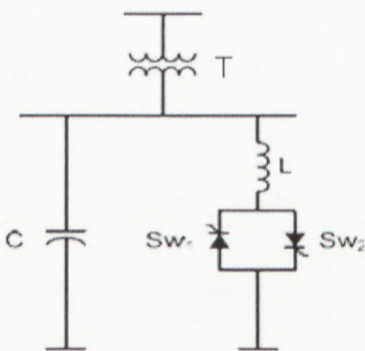
$$i_{TCR} = \frac{\sqrt{2V}}{X_L} (\cos\alpha - \cos\omega t); \alpha \leq \omega t \leq \alpha + \sigma \quad \dots\dots\dots 7.8$$

$$i_{TCR} = 0; \alpha + \sigma \leq \omega t \leq \alpha + \pi$$

Where  $V$  is the rms voltage applied,  $X_L$  is the fundamental reactance of the reactor and  $\sigma$  is the conduction angle. Hence full conduction is achieved with a gating angle ( $\alpha$ ) of  $90^\circ$ .

The compensation is characterized by the ability to perform continuous control, maximum delay of one half cycle and practically no transients. The disadvantages of this configuration are the generation of low frequency harmonic current components and higher losses when working in the inductive region. Low frequency current are eliminated by delta configurations for zero sequence harmonics. The relationship between the fundamental component of the reactor current and the phase-shift angle is given by:

$$I_1 = \frac{V_{rms}}{\pi\omega L} (2\pi - 2\alpha + \sin(2\alpha)) \quad \dots\dots\dots 7.9$$



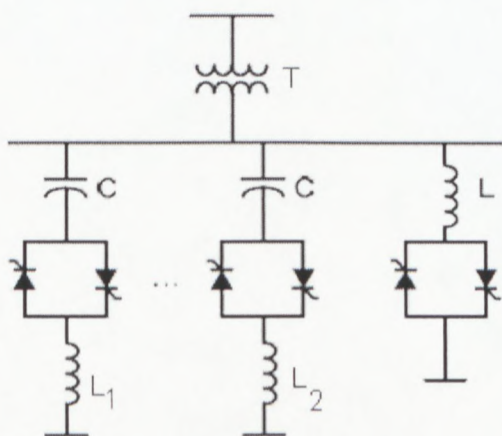
**Figure 7.8:** The Thyristor-Controlled Reactor Configuration.

Parallel combination of fixed capacitors and controlled reactors provides a smooth current-control range from capacitive to inductive values by switching the capacitor and controlling the current in the reactor. Shunt combinations of thyristor-controlled reactors (TCRs) and thyristor-switched capacitors (TSCs) yield static var compensators (SVCs).

### 7.3.3.3 Combined TSC and TCR

The thyristor switched capacitor, thyristor-controlled reactor (TSC-TCR) type compensator was developed for dynamic compensation of power transmission systems with the intention of minimizing standby losses and providing increased operating flexibility. It provides greater flexibility and better performance under system fault condition. The connection diagram is given in Figure 7.9. In case the plant loads are varied from lagging to leading, the combined switch TSC -TCR may be used.

In case there is a need to absorb reactive power, the entire capacitor bank is disconnected and the equalizing reactor becomes responsible for the absorption. By coordinating the reactor and the capacitor steps, it is possible to obtain full control. Static compensators of the combined TSC-TCR type are characterized by a continuous control, practically no transients, low generation of harmonics due to the small controlled reactor rating compared to the total reactive power and flexibility in control and operation. The main disadvantage of the system is its relatively high cost. The combined Static Var compensator is given in Figure 7.9



**Figure 7.9:** Combined TSC and TCR

To reduce transient phenomena, harmonic distortion and improve dynamics of compensators, some researchers have introduced self-commutation, Var generator (STATCOM) (proposed in chapter 8) to replace TSC and TCR whereby a voltage source converter is used. The technical advantage of this technique is given in Table 8.1. Although the STATCOM seems to be more expensive than the shunt capacitor, this high cost is overcome by the advantage acquired by installing the STATCOM in the system. The cost comparison of the reactive power compensation is given by (Sode-Yome & Mithulanathan, 2004; Kirby & Hirst, 1997) as presented in Table 7.1

**Table 7.1:** Cost Comparison of Shunt Compensator

Shunt compensator	Estimated cost (\$/ kVar)
Shunt capacitor	8-30
Synchronous condenser	30-35
SVC	40-50
STATCOM	50-55

By using STATCOM in the demand side (industry), flexible power factor correction is achieved, hence reducing electric bills.

**7.3.4 Advantages of Power Factor Correction**

IEEE (1993) mentioned the advantages of power factor improvement as:

**7.3.4.1 Low Utility Charge;** this is because low power factor cause the utility to over load its distribution system, increasing system capacity can be achieved by improving the power factor and this allows additional load to be added to the system.

**7.3.4.2 Increase System Capacity;** power factor improvement can reduce the kVar demand; this allows the increase of system capacity. Equation 7.4 gives the relationship between the increase in system capacity and power factor.

$$\% KVA = 100 \left( 1 - \frac{Pf_{old}}{Pf_{new}} \right) \dots\dots\dots 7.10$$

**7.3.4.3 Improving Voltage;** High kVar load demand increase the voltage drops (Vd) across transformers, cables and other system components resulting in decreased equipment utilization voltage. ANSI. C84.1- 1982 establishes limit for minimum equipment utilization voltage. Less Vd, improve equipment performance, Equation 7.11 shows how the reactive power component of current contributes to voltage drop.

$$\Delta V \equiv RI \cos \phi \pm XI \sin \phi \dots\dots\dots 7.11$$

Where  $\Delta V$  is the voltage change which may cause a drop or rise in voltage  $\Delta V$ , R, X, and I ; may be in absolutes value

**7.3.4.4 Reducing Circuit Loss;** Equation 7.12 shows the relationship between power factor and loss.

$$\% \Delta P_{loss} = 100 \left[ 1 - \left( \frac{Pf_{old}}{Pf_{new}} \right)^2 \right] \dots\dots\dots 7.12$$

**7.3.5 Disadvantages of Power Factor Correction Capacitor**

- Capacitors consume energy at the rate of 0.5 - 1.0 W/kVar. This value might look small but depending on the rating of the capacitor and at how many hours it is connected to the supply and it gives a clear picture of the power consumption.
- Blown fuses due to resonance occurring with rectifier circuit in the system.
- Harmonic distortion produced by variable speed drives or other equipment which alters the normal A/C wave can be magnified when capacitors are used.

**7.4 Selection of an Appropriate Range of Power Factor Capacitor**

The size of capacitor is determined by the size of kVar required to be compensated. The value of kVar required can be expressed as:

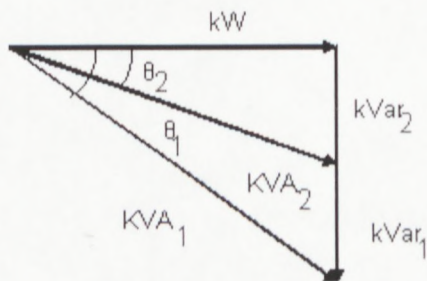
$$kVar = M \times Kw_{load} \dots\dots\dots 7.13$$

Where:  $M = \tan(\arccos Pf_{old}) - \tan(\arccos Pf_{new})$  or

M can be calculated as:

$$M = \left\{ \sqrt{\frac{1}{Pf_{old}} - 1} \right\} - \left\{ \sqrt{\frac{1}{Pf_{new}} - 1} \right\} \dots\dots\dots 7.14$$

The value of M can be easily calculated by using the power triangle shown in Figure 7.10. The cosine rule and Pythagoras theorem are applied in the calculation.



**Figure 7.10: Power Triangle**

Equation 7.14 is used to calculate factors improvement of any value of PFC which have been already simplified in many literatures and given in form of a table. That table is known as power factor improvement table (IEEE.1993).

### 7.5 Influence of Harmonic Distortion in Industrial Power Factor

Harmonics are steady state distortion of the electrical sine wave of voltage and current. Most often called the total harmonic distortion (THD). THD is categorised as ITHD (for current) and VTHD (for voltage). They are generated by non-linear loads such as variable frequency or speed drives, Arc welders, DC rectifiers and soft start motors when they are connected to the electrical distribution network. If non-linear loads in an electrical system exceed 15% of the total load, the system is likely to suffer from a harmonic contaminated network (Wayne & Fink, 2007).

Harmonic wave has a multi sharing characteristics that is the nonlinear loads of one system cause harmonics to its own system and to the power system network. In many industries the issue of power factor does not consider the influence of harmonic content caused by nonlinear loads although they draw the current with fundamental harmonics frequencies and inject back to the system with multiple harmonic frequencies. The impact of harmonic contaminated network includes shortening of the life expectancy of the connected equipment and appliances.

During data collection in some industries, it was observed that, there are few nonlinear loads in most visited industries; but the power quality study is not considered in many industries. The presence of harmonics was measured by indicating harmonic content in the wave form and is evaluated as the THD:

$$THD = \frac{\sqrt{\sum_{h>1}^{h_{max}} M_h^2}}{M_1} \dots\dots\dots 7.15$$

Where  $M_h$  is the rms magnitude of harmonic component  $h$ .  $M_1$  is the magnitude of the fundamental value. THD is related to the rms value of the wave form as:

$$rms = \sqrt{\sum_{h>1}^{h_{max}} M_h^2} = M_1 \times \sqrt{1 + THD^2} \dots\dots\dots 7.16$$

The active and reactive power content is given by

$$P = \sum V_h I_h \cos \theta_h \dots\dots\dots 7.17$$

$$Q = \sum V_h I_h \sin \theta_h \dots\dots\dots 7.18$$

$$S = V_{rms} I_{rms} = \sqrt{\sum_{h=1}^n V_h^2} \times \sqrt{\sum_h I_h^2} \dots\dots\dots 7.19$$

Where:  $\theta_h$  is the angle between the voltage and current sinusoid at harmonics h and  $V_h$  and  $I_h$  are the rms sinusoid harmonic voltage and current respectively.

### 7.5.1 Effect of Harmonic to the Capacitor Bank Circuit

The presence of harmonics in the supply voltage imposes high current levels to the capacitors and increases the possibility of resonance which may decrease the capacitor life. The installation of capacitors in a power system (in which the impedances are predominantly inductive) can however, result in total or partial resonance occurring at one of the harmonic frequencies.

Harmonics in the power supply can be controlled by limiting the injection of nonlinear loads or other sources of harmonics (Wayne & Fink, 2007). In most cases, in nonlinear systems the power factor correction is achieved by applying line reactors directly to the sources of harmonic current or by using kVAr capacitor networks with series inductors to limit harmonic current in the capacitors. Shunt filter is also commonly used for harmonic mitigation.

### 7.6 Economic Evaluation of PFC

The economic evaluation is normally done to identify the economical viability of power factor correction capacitor compared to the alternative technical solution. The cost of capacitor, switch, installation, operation and maintenance, power factor penalty, cost of loss and study cost are involved.

For the plant which does not have power factor correction, the base case for comparison is generally the existing case with a high power factor penalty. Then alternative capacitor applications are developed and the costs estimated. Then it is simply a matter of determining the least cost solution considering the cost in terms of money over time.

The economic evaluation for supply and demand side is called value based. Some companies use present value analysis which refers to overall costs to the present year and the lowest cost, has the lowest option and has the lowest present value. The present value (PV) of an arbitrary cost series  $x_0, x_1, x_2, \dots, x_n$  is given by:

$$P = \sum_{k=0}^n \frac{x_k}{(1+i)^k} \dots\dots\dots 7.20$$

Where,  $i$  is the interest rate corresponding to the time period and "n" is the total number of periods.

Cash flow series appear as a single purchase made at the present time. Another type of analysis is called annual levelized cost (Bonneville, Power administration, 1995). In this method the cost is converted into equivalent annual cost that is the entire period of evaluation. This has similar concept as present value analysis, except that the costs are converted to an equivalent annual cost that is the same for the entire period of the evaluation.

Benefit / Cost Analysis; this compares the benefit and a cost, if benefits exceed the costs, the method is economical. Benefit is the cash saving for the improvement while the cost is the cash for purchasing items.

Payback Analysis; this is the method preferred by many facilities and is calculated as simple payback as:

$$\text{Simplepayback} = \frac{\text{Investment}}{\text{annual saving}} \dots\dots\dots 7.21$$

Industrial consumers are typically looking for 1 to 3 years payback. For the correct analysis the annual saving should be levelized over the expected life.

**7.6.1 Economics Analysis of Power Factor Improvement: Case Study**

There are three principal methods by which utilities charge industrial customers for poor power factor. These are direct kVA charges, billing demand adjustments for low power factor and charges for excess kVAr. Economic analysis for power factor correction cost savings was done based on penalty charged for poor power factor.

The rate of penalty varies significantly depending on the particular utility rate structure. Billing on kVA has the most severe penalty and offers the most incentive

for correcting facility power factors.

In order to undertake economical comparison, the utility bills was analysed aimed at obtaining information necessary for determining the total amount of capacitance needed and the saving possible. For the analysis of electricity consumption trend, it is advised to consider the long term trend of the utility bills, maximum demand, power factor and typical energy usage and the power factor penalty if any or demand charge. There are also taxes and other miscellaneous charge, but these do not have a significant impact on the economic justification of power factor correction capacitors. Hence the billed demand was calculated as:

$$kW \text{ Billed} = kW \text{ Actual} \times \left( \frac{0.95}{pf} \right) \dots\dots\dots 7.22$$

or

$$kW \text{ Billed} = kW \text{ Actual} \times (1 + 0.95 - pf) \dots\dots\dots 7.23$$

The difference between the amount paid for billed demand and that, which would be paid for the actual demand is often termed the power factor penalty and expressed as:

$$penalty = \left( kW_{billed} - kW_{actual} \right) \times \$ / kW \dots\dots\dots 7.24$$

Two important comparisons were made in order to find the economic viability of the capacitor bank, that is:

- Power factor correction of the plant/system and individual loads (motors) compared with when the system is not corrected and
- Power factor correction of the system compared with the replacement of energy efficient motor.

### 7.6.2 Case Study – Cement Factory

In this section, the economical analysis of the plant with power factor correction is presented. We first considered the plant with normal /initial (low) power factor and corrected, the economics of correcting the power factor was analysed. The analysis was grouped into two parts: High voltage load of which power factor correcting capacitor is installed across the load (static correction). In the cement industry (case study), five loads have capacitor power factor correction connected across each of the load and there are many loads which are supplied by 3 phase, 440V of which bulk

correction is applied. As per types of loads, power factor of the plant without compensation range from 0.7 to 0.8. To avoid the penalty imposed by the utility due to poor power factor, it was to be corrected to at least 0.97.

This analysis case study used the real data of Mbeya Cement Company. The capacity of the plant loads is given in Appendix 6.1, the incoming voltage is 33KV and the operating voltage of HV machines is 6.3 KV, the plant has 5 loads which have static correction and other small motors and loads. Using the capacitor work sheet, the first step was to determine the approximate value of the capacitance needed to correct the pf from 0.75-0.95. The analysis was performed using different scenarios.

### Scenario 1: Bulky Correction

Assumed average power factor of the plant is 0.75

The kVar required is computed by equation 7.13,

Where, the monthly bill (maximum value) is taken from the history of plant bills of 12 months that is 5448.57 kW. Therefore the kVar required is 3432.5 kVar

The cost of capacitor bank power factor correction per kVar is \$ 8-30 (Guide to pfc, 1993). Therefore the capacitor bank cost is: \$ 99,542.5, for the price of (\$ 29/kVar)

Before implementing the power factor correction the study has to be undertaken to identify the viability of the capacitor. The cost of the study is an estimated value and ranges from \$ 2500-12000. For this research, the proposed study cost is taken \$4000. The total capacitor cost for compensating 3,432.5 kVar is \$103,542.5.

#### 7.6.2.1 Calculation of Power Factor Penalty

Billed demand and actual demand that are the demand after and before correction and are calculated by:

$$kW_{Billed} = kW_{Actual} \times \left( \frac{0.95}{pf} \right) = 5448.57 \times 0.95 / 0.75 = 7,046.8 \text{ kW}$$

Therefore the monthly power factor penalty is calculated as:

$$penalty = (kW_{billed} - kW_{actual}) \times \$ / kW = (7,046.8 - 5448.57) \times 5.9 = \$ 9,429.65$$

##### 7.6.2.1.1 Economic Evaluation

Monthly power factor penalty saving is \$ 9,429.65.

The annual saving is \$ 9,429.65x12= \$113,155.90.

Present worth factor is selected from the Table given in (Guide to capacitor, 1993) for the first year with 7% interest is 0.935.

The present worth savings is \$ 105,800.8.

For the good result, present worth of saving- cost of capacitor should be greater than \$ 0 in this case it is equal to \$ 2,258.

The benefit / cost ratio= 1.021.

The simple payback = 0.98 year.

Therefore the simple payback period is 1year.

From this economic analysis it was shown that, using power factor correction is viable and the simple payback period is only 1 year.

#### **7.6.2.1.2 Scenario 2: Static Correction**

The steps used to calculate economic viability are the same as in scenario one, the only difference is that; here, the capacitor banks involve individual loads. Hence to calculate capacitor rating is required to consider the power factor of the individual load and the remaining calculation can follow the same procedure as in scenario 1.

#### **7.6.2.1.3 Scenario 3: Improve Motor Power Factor**

This study compared low power factor standard motor with the same rating motors when power factor correction capacitor bank is connected across them. The study considered motors of different ratings starting from 1hp to 90hp. The study evaluated the power factor cost savings for a typical motor. The cost-effectiveness measure used is the simple payback period (SPP).

The example was conducted by 90kW motor, whereby the numerical analysis was computed. The overall results of the study are given in Figure 7.11. Excel program was used to analyse the system. Power factor correction technique was required to correct the power factor from 0.75 (motor pf) to at least 0.95 desired power factor.

By using power factor improvement table, the power factor improvement factor is 0.526; therefore the kVar required is calculated by equation 7.13 and is given as 47.34kVar. The value of capacitor cost is calculated as:

- The cost of capacitor is estimated to be \$1420.2
- Installation and maintenance cost = 10% the capacitor cost =142.02

The total capacitor cost = a+b= \$ 1562.22

The billed kW=112.5

Therefore the power factor penalty is calculated and is equal to 22.5kW.

Monthly demand saving is 22,5kW and annual saving = 270kW.

Annual monetary saving = \$1593.

The present worth for 7% interest is in the second year is selected =1.808

The present worth savings is \$ 2,880.

For the good result, present worth of saving- cost of capacitor should be greater than \$ 0 in this case it is equal to \$ 1317.9.

Current IUSD = 7.5 R (South African Rand)

Benefit /cost ratio= 1.84 and the simple payback period=0.98

The results of the economic evaluation of different motors of V= 400V of different ratings and different power factor if the power factor is improved to 0.95 is given in Figure 7.11. Figure 7.12 shows increase of penalty when the motor rating is reduced.

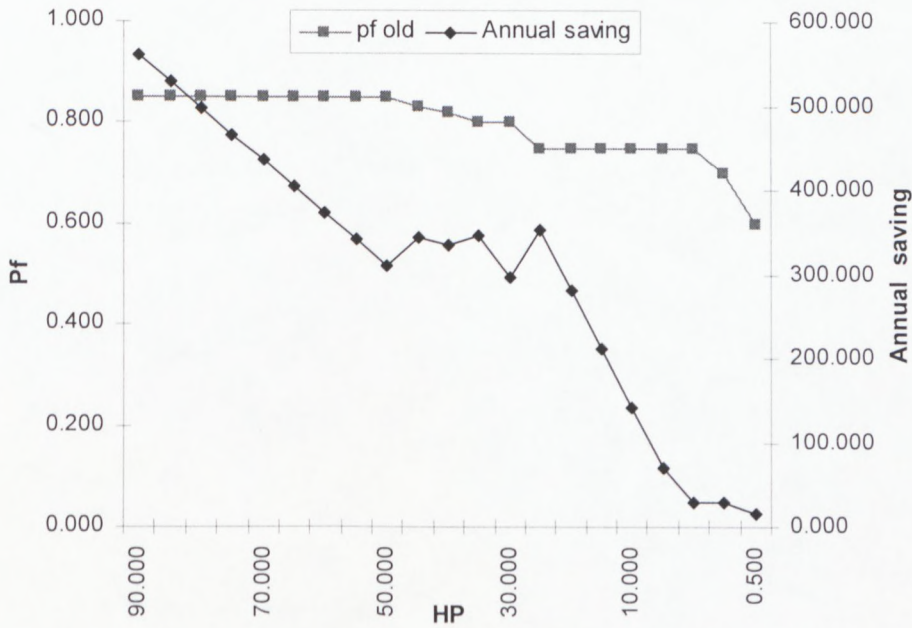


Figure 7.11: Relationship between the Ratings of Motor with its Annual Saving

**7.6.2.1.4 Scenario 4: Comparison; Standard with Energy Efficient Motors in Relation to the Power Factor.**

In this analysis, the power factor of energy efficiency motor was compared with standard efficient motor. This example considered 30Hp motor. The motors ratings of EE motor and standard motors were assumed to be the same. In this analysis, International Motor Master Software was used for the analysis of the motors.

The general equation used for annual energy saving is given by:

$$S = kW \times C \times H \left( \frac{1}{\eta_1} - \frac{1}{\eta_2} \right) \dots\dots\dots 7.25$$

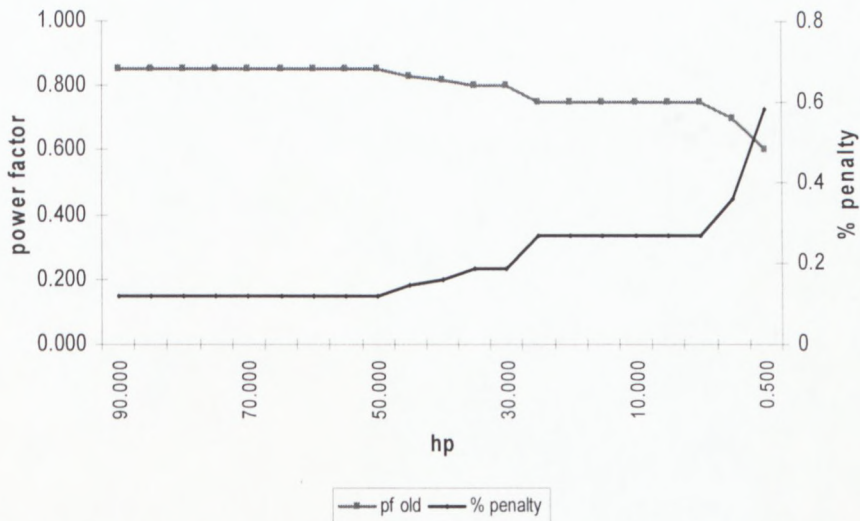


Figure 7.12: The Relationship between Motor Size, Power Factor and Penalty

The data collection information shows that, the industry is operating 641 Hours /month. If C is an energy cost (\$), in this case study, C is taken as \$ 0. 13/kWh and the demand charge is \$ 5.9/ kVA. The motor prices are obtained from the motor master software data base and are varying depending on the size and manufacture of motor. Installation and maintenance cost is 15% of the motor price. The motor analysis was done by the Motor master software whereby the efficiency and economic viability was analysed and is given in Figure 7. 13 and payback analysis is in given in Figure 7.14.

Figure 7.13: Motor Efficient Analysis

## 7.7 Proposed Modification

The proposed modifications include emphasis on measurement so as to identify the variation of power factor in industries; whereby self commutated static VAR Compensator (STATCOM) is proposed. The detailed analyses and development is given in Chapter 8.

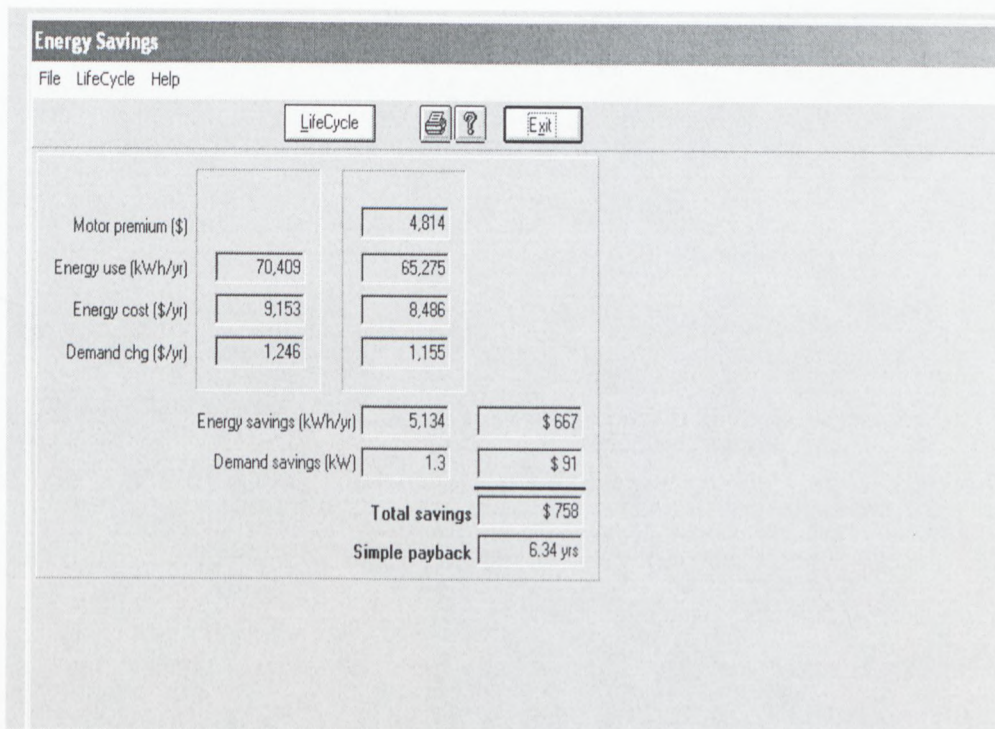


Figure 7.14: Payback Period Analysis

## 7.8 Conclusion

For a long time power factor correction has been used as a tool for energy conservation (supply and demand side) because of its ability to increase system capacity and to reduce electricity costs to the end user. For the utility that have power factor penalty charges (for low power factor), the economic benefit of improving power factor is achieved by installing the capacitor banks across the loads.

This chapter presented commonly existing power factor correction methods used in power supply and demand side. The economic evaluation have been undertaken to test the viability and adaptability of the technique. The algorithm used to evaluate the overall capacitor application was developed. The result of analysis showed that, the viability of using capacitor bank for power factor correction in the industrial sector is

still high for certain condition loads (linear and fixed load). It is cheap, but in the variable loads conditions, and where subjected to harmonics, this technique is not a viable option due to the resonance caused by nonlinear loads.

Replacing standard-efficiency motors with carefully selected high-efficiency, high power factor motors is another alternative to power factor correction for certain smaller-sized motors. Plant engineers and managers of the facility may use high-efficiency motors to improve the power factor especially for small motors and use capacitors to correct the power factor of large motors. Var comparator was also analysed and it has shown the possibility of switching on and off the capacitor bank but it is still subjected to the problem of resonance and is not faster compared to the proposed method (STATCOM).

## CHAPTER EIGHT: Proposed Power Factor Correction and Control Techniques

### 8.1 Introduction

Power factor of the system has a relationship with the apparent power which is obtained from the combination of active and reactive power. Currently capacitor banks power factor correction method is widely used in many industries in SSA. In many situations, in the industrial sector, the installation of the capacitor banks, considers the plants with high inductive loads, therefore the compensation always involves the addition of the capacitive component.

This chapter proposes an alternative method of power factor correction that can suite the variable load situation existing in many industries. The proposed technique is synchronous static Var compensator (STATCOM). The proposed STATCOM is to operate in the industrial sector for power factor correction. Their principle of operation is like the static synchronous generator working at different excitation so as to produce varying power factor (lagging, leading and unity). It is capable of varying the power factor of the system to suite the requirement of the supply.

The results show that, there is a possibility of obtaining variable power factor correction at variable load. The aim of the proposed STATCOM was to correct the power factor of the case study industry (cement industry) at any industrial loads. The proposed power factor should be between 0.95- 0.999, which was verified by the simulation results. During the compensation of the load, voltage sag that might appear during the starting of large loads, for example cement mill were mitigated.

### 8.2 Power Factor Compensation Principles

Loads with large reactive power requirements draw a lot of reactive current from the supply network and they lead to poor voltage regulation, high losses and limit the controllability of the amount of real power that can be delivered.

The major cement industrial loads have inductive load characteristic. This characteristic of loads tends to draw reactive energy from the main supply for the production of magnetic field which is used in the operation of all reactive loads. In addition, increase in the use of nonlinear loads like power electronic converters results into the generation of harmonics which in turn lowers the over all power factor of the plant.

When the reactive loads are connected to the supply system, it draws real and reactive power component as:

$$S = P + jQ \dots\dots\dots 8.1$$

Where  $P$  is the active power required for the accomplishment of work and  
 $Q$  is the reactive power

In order to avoid injection of low power factor in the system and reduction of high energy bills, industries are normally compensating the reactive power (depending on the size of reactive energy). The application of reactive power compensation focuses on two main aspects namely load compensation and voltage regulation. In load compensation, the main objective is to increase the value of the system power factor so as to balance the real power drawn from the supply, to compensate voltage regulation and to eliminate current harmonic component produced by large fluctuating nonlinear industrial loads.

The shunt capacitors compensation techniques were employed since year 1914 for the aim of power factor correction (Frank & Ivner, 1981). The leading current drawn by the shunt capacitors compensates the lagging current drawn by the load at the point of connection or point of common coupling. The selection of shunt capacitors depends on the amount of lagging reactive power required for the compensated load. In the case of widely fluctuating loads, the reactive power delivered by the loads also varies over a wide range. Therefore, the variable power factor correction is of great importance in electrical energy management.

The proposed variable power factor correction will replace the fixed or the thyristor controlled capacitor (SVC) commonly used in the plant (chapter 7). The proposed system operates like rotating synchronous condenser or var generator. VAR generators are classified depending on the technology used, their implementation and the way they are connected to the power system or load (shunt or series).

### 8.3 Compensator Connection

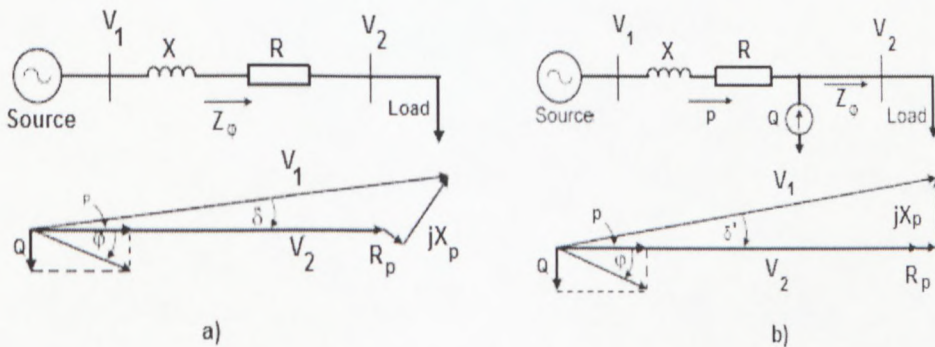
The compensator is connected to the supply system in either shunt or series mode.

### 8.3.1 Shunt Compensation

Historically, the shunt compensation was developed and connected to the supply system for the compensation of reactive power. Figure 8.1 shows the schematic and phasor diagram of shunt connected reactive power compensation, which comprises a source  $V_1$ , a power line and a typical inductive load. Figure 8.1 (a) is the system without compensation.

In the phasor diagram, the phase angle of the current has been related to the load side, which makes the active current  $IR$  out of phase with the load voltage  $V_2$  by angle  $\Phi$ . Since the load is assumed to be inductive, it draws reactive power; therefore, the supply source must supply more power to meet the load requirements. In turn, this leads to the increase of the current from the generator through the power lines. If reactive power is supplied or generated near the load, the line current can be reduced. In addition, it can reduce power losses and improve voltage regulation at the load terminals. This can be done in three ways:

- By a capacitor,
- By a voltage source inverter or
- By a current source inverter.



**Figure 8.1:** Principles of Shunt Compensation in a Radial AC System. a) Without Reactive Compensation and b) Shunt Compensation with a Current Source.

### 8.3.2 Series Compensation

Typical series compensation systems use the compensator to decrease the equivalent reactance of a power line at rated frequency. This type of compensation is commonly used in a transmission line. When it is connected to a transmission line, it results in improving the functionality of the power transmission system. Figure 8.2 shows the connection diagram of series compensation. Series compensation may also be implemented with current or voltage source. This compensation method is not a part of this study.

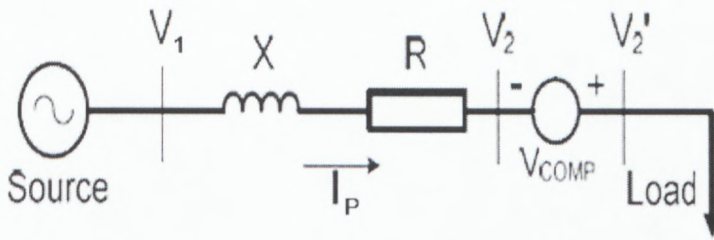


Figure 8.2: Principle of Series Compensation with Voltage Source

## 8.4 Types and Problem of Power Factor Compensation Control Systems

Industrial power factor compensation techniques use control systems to accomplish the compensation requirement. The types of compensation switch control used include:

### 8.4.1 Mechanical Switched Capacitors Compensation

The VAR compensation is achieved using switched capacitors. The capacitor banks are switched into or out of the system depending on the total reactive power requirement. The smoothness of control is solely dependent on the number of capacitors switching units. The switching is usually accomplished by relays and circuit breakers. However, the method is actuated by mechanical switches and relays. It has its own disadvantage as it is sluggish and unreliable. Also it generates high inrush currents and requires frequent maintenance (refer chapter 7).

### 8.4.2 Synchronous Condensers

Synchronous condensers have played a major role in voltage and reactive power control for more than 50 years. Functionally, a synchronous condenser is simply a synchronous machine connected to the power system. The connection and principle of operation was explained in chapter 7. In practice, this type of compensation is rarely used due to the requirement of substantial foundations and a significant amount of starting and protective equipment. These equipments cannot be fast enough to compensate for rapid load changes. Moreover, their losses are much higher than those associated with static compensators and their cost is much higher compared with static compensators.

### 8.4.3 Thyristor Controlled VAR Compensators

Static VAR compensators (SVC) consist of standard reactive power shunt elements (reactors and capacitors) which are controlled to provide rapid and variable reactive power. The thyristors are used as a switch to provide the control of the compensation. They are used to switch on or off the capacitor and or reactor according to the configuration. They are grouped into thyristor-switched capacitor and the thyristor-controlled reactor.

The presence of capacitor in SVC makes the configuration suffer from degradation in reactive capability as voltage drops, it usually requires harmonic filters to reduce harmonics and it has limited overload capabilities over the STATCOM (Taylor, 1994). STATCOM is proposed to overcome problems related to the switching control explained above.

The proposed load management technique is aimed at abolishing the problem of low power factor by introduction of STATCOM to the consumer side (industry) to replace capacitor banks. The application of STATCOM has been demonstrated as an effective solution to the reactive power compensation in many applications. The major advantages of STATCOM compared to a conventional static var compensator (SVC) include the ability to generate the rated current at virtually network voltage, a better dynamic response and the use of a relatively small capacitor on the dc side. Table 8.1 shows the advantage of STATCOM.

**Table 8.1:** Comparison of Basic Types of Compensator

Types	Synchronous Condenser	Static compensator		STATCOM
		TCR FC	TSC -TCR	
Accuracy of Compensation	Good	Very good	Very good	Excellent
Control flexibility	Good	Very good	Very good	Excellent
Reactive power capability	Leading/ lagging	Leading/ lagging indirect	Leading/ lagging indirect	Leading/ lagging
Control	Continuous	Continuous	Discontinuous with TCR	Continuous
Response time	slow	Fast, 0.5 to 2 cycles	Fast, 0.5 to 2 cycles	Very fast but depends on switching frequency
Harmonics	Very good	Very high (large size filters are needed)	Good, filter are necessary with TCR	Good but depends on switching pattern
Losses	Moderate	Good but increase in lagging mode	Good increase in leading mode	Very good
Phase balancing ability	Limited	Good	Limited	Very good with Single phase units, limited with 3 phase
Cost	High	Moderate	Moderate	Low to moderate

The size of the capacitor does not play an important role in steady-state reactive power generation, which results in a significant reduction of the overall compensator size and cost (Blaži & Papi, 2004).

## 8.5 Principle of Operation of STATCOM

STATCOM belongs to the family of power electronics controllers known as FACTS controller. The definition of STATCOM is given by the Gyugyi et al., (1976) and its main operation is to generate controllable reactive power directly without the use of capacitors or reactors. They further presented appropriate switching method of the converters (dc to ac or ac to ac), which operate as a voltage or current source to produce reactive power without reactive energy storage components.

The STATCOM is similar to the SVC in speed response, control capabilities and the use of power electronics switches. Instead of using conventional capacitors and inductors combined with fast switches, the STATCOM uses power electronics components to synthesize the reactive power output. Consequently, the output capability is generally symmetric, providing as much capability for production and absorption of reactive energy (El-Keib & Max, 1997; Taylor, 1994). It usually requires harmonics filters for harmonics reduction.

The solid-state nature of the STATCOM means that the controls can be designed to provide very fast and effective voltage control and reactive power control and in turn the power factor is controlled (Kirby, 1997; Purucker, 1997). They are comparable to synchronous condensers which can supply variable reactive power and regulate the voltage of the bus where it is connected (Padiyar, 2008).

STATCOM topology, control and operation are based on the voltage source converter principle. The principle of operation and the main characteristic of STATCOM are described as: The most basic configuration of STATCOM consists of two levels VSC with DC energy storage device (capacitor), a coupling transformer connected in shunt with the AC system and the associated control system. The AC output voltage of the converter is directly proportional to the dc voltage across the capacitor.

The DC side energy storage is a capacitor whose terminal voltage is raised or lowered by inverter control in such a way that its stored energy is either increased or decreased. In this research, the capacitor is charged by the converter itself. The VSC employs sinusoidal pulse-width modulation (PWM) with switching frequency for switching on or off of the inverter.

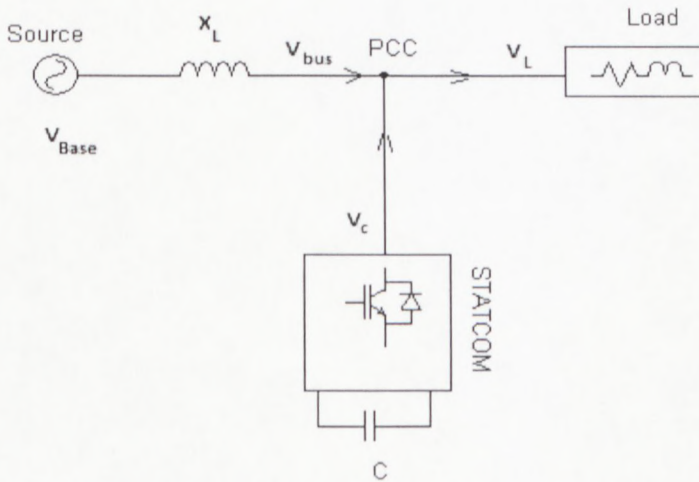
The output of the converter is coupled with AC system through the reactance of the coupling transformer. The active and reactive power exchanged between the converter and the AC system can be achieved by changing the phase angle at the point of common coupling. The basic configuration is shown in Figure 8.3 and the bus voltage can be calculated as:

$$V_{bus} = V_{drop} + V_L \dots\dots\dots 8.2$$

Where:  $V_{drop} = Z \times I_L$  Voltage drop across the reactance and  
 $V_{vsc} = V_L$  Voltage across bar at the point of common coupling

If the magnitude of  $V_C$  is greater than  $V_{bus}$  then the STATCOM supplies reactive power to the AC system and it absorbs reactive power if the magnitude of  $V_C$  is less than  $V_{bus}$  (Deepika et al., 2009) refer Figure 8.3. The quantity of reactive power flow is proportional to the difference of the two voltages.

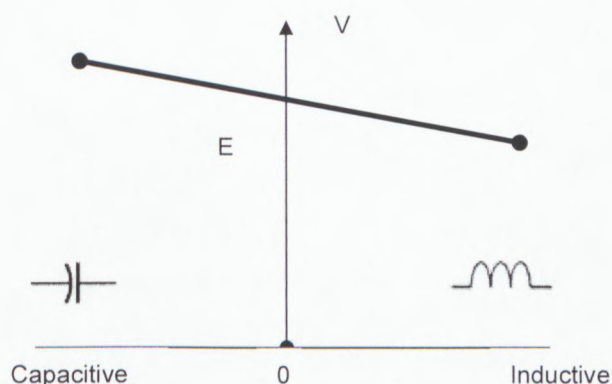
When the load draws current from the supply the terminal voltage  $V$  falls below  $E$  or  $V_{base}$ . The load line of the system is given in Figure 8.4. This figure represents the STATCOM characteristic.



**Figure 8.3:** The Basic Structure of STATCOM

For power factor correction mode, STATCOM provides power factor correction by acting as a current source connected in parallel with the load. Load current can be resolved into a direct axis component and quadrature axis component as presented

by (Sao et al., 2002). The direct axis is in phase with the supply voltage, while quadrature component is responsible for supplying the reactive power and it is  $90^\circ$  out of phase. Without the STATCOM, the Ac source supplies all of the current demand of the load. Therefore the quadrature component of the load is equal to the quadrature component of the supply.



**Figure.8.4:** The Overall Load Line of the System under Different Types of Compensation.

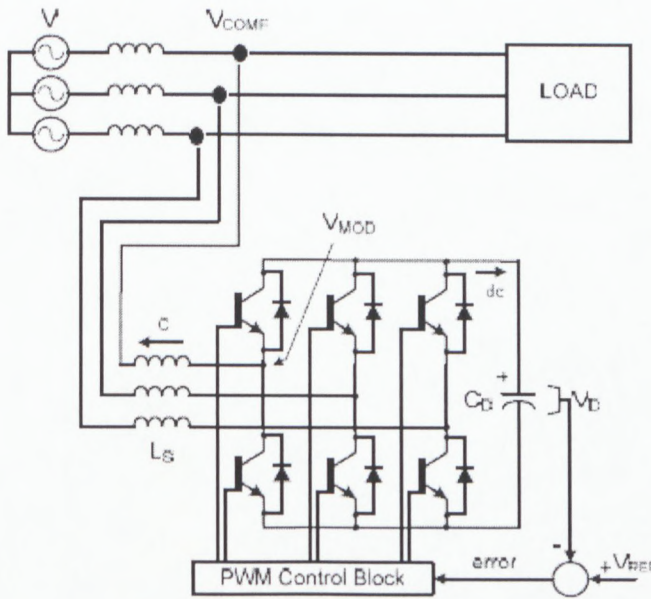
When STATCOM is connected for power factor correction mode, the current from the supply is eliminated because the STATCOM supplies the entire quadrature component to load current. In addition the voltage source converter draws a fundamental frequency current in phase with the supply voltage to maintain dc- side capacitor voltage at a set value despite the converter losses.

Figure 8.5 shows a shunt VAR compensator implemented with voltage source converter. Neglecting the internal power losses of the overall converter, the control of the reactive power is done by adjusting the amplitude of the fundamental component of the output voltage of the converter ( $V_{MOD}$ ), which can be modified with the PWM pattern. When  $V_{MOD}$  is greater than the voltage at the point of common coupling  $V_{cop}$ , the VAR compensator generates reactive power. When  $V_{MOD}$  is smaller than the ( $V_{cop}$ ), the compensator absorbs reactive power.

The voltage  $V_D$ , is developed by the capacitor connected in the dc link side of the converter. In the control mode, this voltage is kept constant and it acts as an input side of inverter and is considered equal to a reference value  $V_{REF}$ .

The amplitude of the compensator output voltage ( $V_{MOD}$ ) can be controlled by changing the switching pattern of the converter (modulation index) or by changing

the amplitude of the converter dc voltage  $V_D$ . The converter dc voltage  $V_D$  is charged by adjusting the small amount of active power absorbed by the converter.



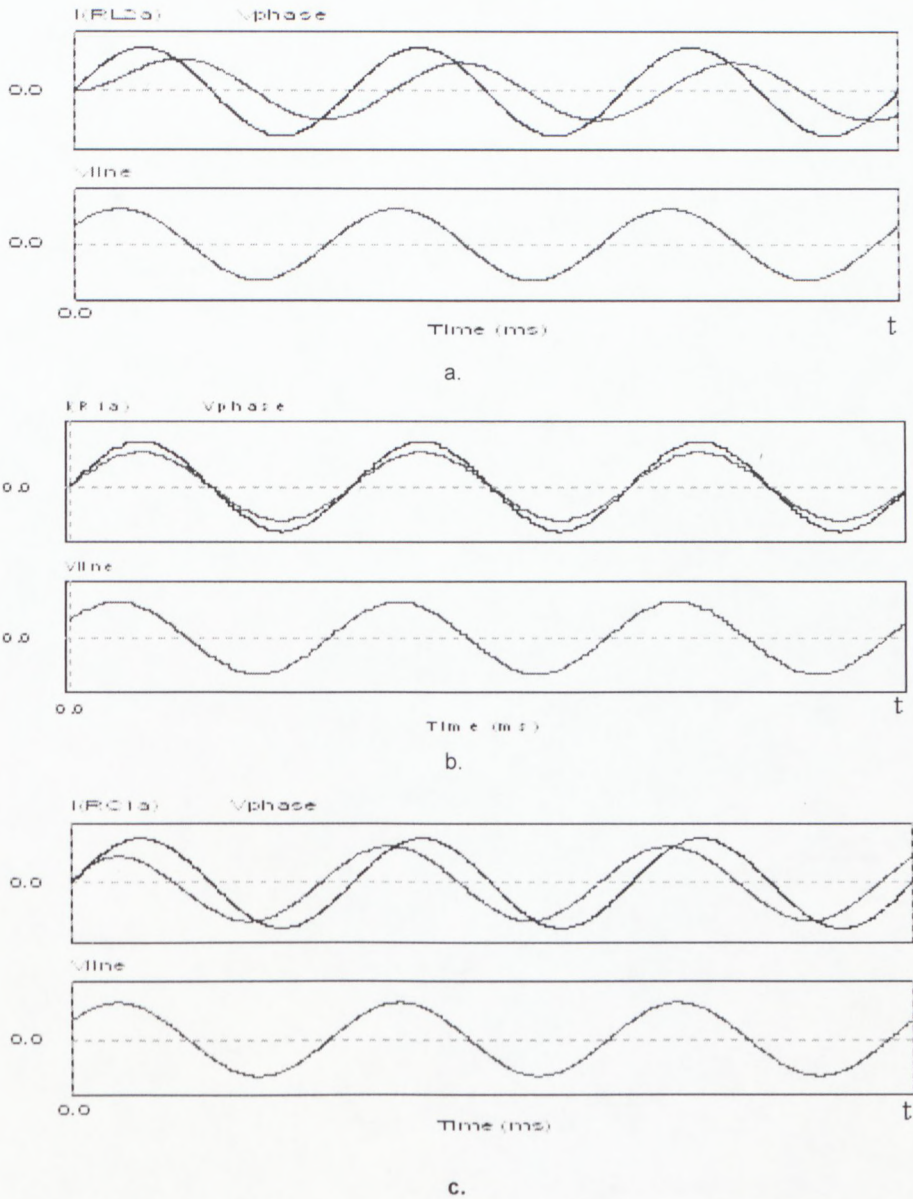
**Figure 8.5:** D-STATCOM Schematic Representation

The static synchronous compensator working on distribution system is called D-STATCOM. Suitable adjustment of the phase and magnitude of the D-STATCOM output voltages allows effective control of active and reactive power exchanges between the D-STATCOM and the ac system. Such configuration allows the device to absorb or generate controllable reactive power.

In this study STATCOM is used to replace capacitor banks. In normal situation, depending on the type of loads, the relationship between current and voltage of the industrial system provides either lagging, unity or leading power factor as shown in Figure 8.6. Hence the advantage of using the STATCOM in the industrial sector is to compensate the reactive power of the plant based on the types of load (leading, unity and lagging loads).

The transition from inductive to capacitive mode occurs by changing the angle  $\delta$  from 0 to negative value while the transition from capacitive to inductive mode takes place when  $\delta$  is changing from 0 to positive value respectively. Hence the active and reactive power exchange is given by:

$$P = \frac{V_{bus} \times V_{vsc}}{X_L} \sin\delta \dots\dots\dots 8.3$$



**Figure 8.6:** Voltage and Current Characteristic under Varying Load: a) Lagging, b) Unity and c) Leading

And reactive power is calculated as:

$$Q = \frac{V_{bus}^2}{X_L} - \frac{V_{bus} \times V_{svc} \cos\delta}{X_L} = Q = \frac{V_{bus}}{X_L} (V_{bus} - V_{svc} \cos\delta) \dots\dots\dots 8.4$$

Where:

- $V_{bus}$  The system / bus voltage
- $V_{svc}$  Compensator voltage
- $\delta$  The angle between compensator and system voltage

It is possible for the STATCOM to be controlled by only the phase angle between VSC output and the AC system voltage. The magnitude of VSC output voltage is proportional to the DC capacitor voltage.

The switching operation of the STATCOM depends on the control strategy. The control of STATCOM is done by using IGBT switch. It can be executed by using two different techniques:

- Fundamental frequency switching (FFS); where the switching of each semiconductor device is limited to one turn – on and one turn off per cycle. In this technique, the six pulses VSC produce a quasi-square wave output and it has high harmonic content. This is not the focus of this thesis.
- Pulse width modulation (PWM); the semiconductor switches are turned on and off at the rate considerably higher than the power frequency. The output waveform is chopped and the width of the resulting pulse is modulated. It shifts the undesirable harmonics in the output to higher frequencies. Although it suffers from high switching losses, it has faster response that adds to the advantage of the PWM.

In this thesis, the switching control is executed by using Pulse Width Modulation (PWM) techniques. The principal advantages attained include the significant reduction of the size and the potential reduction in cost achieved from the elimination of a large number of passive components and lower relative capacity requirement for the semiconductor switches.

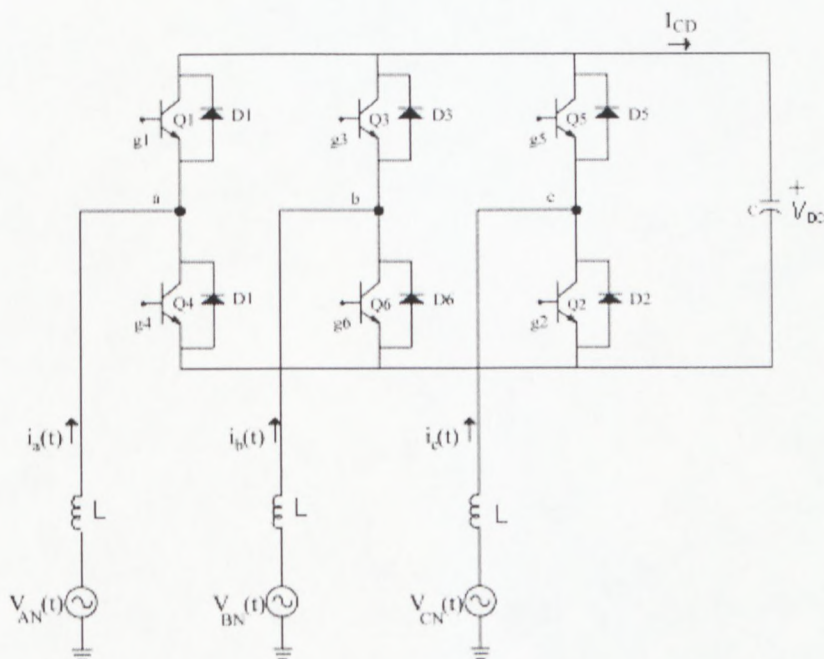
## **8.6 Voltage Source Inverter (VSI) Configuration for Reactive Power Compensation**

The inverter used in this work is a voltage source three phase type. It is preferred because of its small size, less heat dissipation and less cost of the capacitor compared to other methods for the same rating (Moran et al., 1995). It is connected in parallel to the main supply via a coupling transformer and is used for the generation of a sinusoidal voltage at any required magnitude, frequency and phase angle. The VSC is used to either completely replace the voltage or to inject the missing voltage.

The output voltage of the inverter was obtained by switching on or off of the inverter switches. It is in phase and coupled with the ac system through the reactance of the coupling transformer. The STATCOM is connected to the low voltage side of the transformer. The AC voltage difference across the leakage reactance produces

reactive power exchange between the STATCOM and the power line. The switching device used was IGBT selected based on the levels operating power of the converter. High power STATCOMs of this type essentially consist of a three phase PWM inverter. The inverter uses a DC side capacitor which provides the DC voltage required by the inverter, filter components to filter out the high frequency components of the inverter output voltage, a link inductor which links the inverter output to the a.c supply side, and interface with the related control blocks. The inverter generates a three-phase voltage, which is synchronized with the a.c supply. Figure 8.7 shows the two levels VSI circuit for power factor correction. The operation of the switches g1 to g6 is determined by comparing the modulating ( $V_{ma}$ ) signal with the carrier ( $V_{cr}$ ) signal which is applied to the gate of the switches. When  $V_{ma} \geq V_{cr}$ , the upper switch g1 in inverter leg a, is turned on. The lower switch g4 operates in a complimentary manner and thus is switched off. The resultant inverter terminal voltage  $V_{AN}$  which is the voltage at phase A terminal with respect to the negative dc bus N, is proportional to the dc voltage  $V_{dc}$ . When  $V_{ma} \leq V_{cr}$ , g4 is on and g1 is off, leading to  $V_{AN} = 0$

The inverter can be seen as a set up of three single-phase inverters, where each phase produces a voltage output phase-shifted by  $\pm 120^\circ$  with respect to the other two legs outputs. The firing control signals are shifted by  $60^\circ$  from each other. It is noticed that the phase-to-phase voltage has  $120^\circ$  pulse widths with peak voltage magnitude  $V_{DC}$  as shown in Figure 8. 8



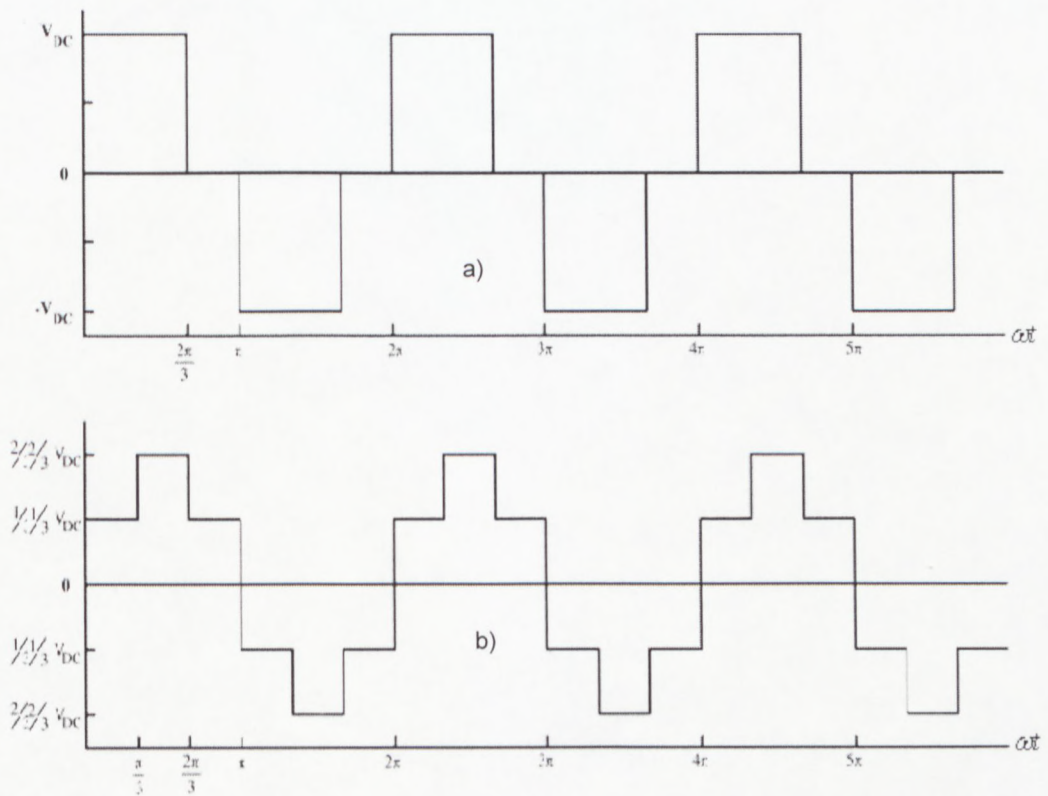
**Figure 8.7:** Six-Pulse VSI with Y-Connection.

When the voltage's fundamental component produced, the inverter is forced to lag or lead the AC system voltage by a few degrees. An active power may flow into or out of the inverter modifying the DC capacitor voltage value, otherwise, if the compensator supplies only reactive power, the active power provided by the capacitor is zero. Therefore the DC capacitor does not modify its voltage (Ricardo et al., 2005).

The current flow between the compensator and the AC system is determined by the voltage across the tie inductor L. Let the AC bus voltage be a pure sinusoidal signal, then the fundamental voltages of the compensator is calculated as the magnitude of the fundamental and harmonic current components. The instantaneous value of the line to line and phase voltage  $v_{ab}$  and  $v_{an}$  by 180 degree conduction is given by:

$$v_{ab} = \sum_{n=1,3,5,\dots}^{\infty} 4 \frac{V_{dc}}{n\pi} \sin \frac{n\pi}{3} \sin n(\omega t + \frac{\pi}{6}) \dots\dots\dots 8.5$$

Both  $v_{bc}$  and  $v_{ca}$  exhibit a similar pattern as in equation 8. 5, and phase shifting  $v_{bc}$  by  $120^\circ$  and  $v_{ca}$  by  $240^\circ$  respectively.



**Figure 8.8:** Voltage Waveform of the Inverter a) phase to phase  $v_{ab}(t)$  and b) phase to neutral  $v_{an}(t)$

$$v_{bc} = \sum_{n=1,3,5,\dots}^{\infty} 4 \frac{Vdc}{n\pi} \sin \frac{n\pi}{3} \sin n(\omega t - \frac{\pi}{2}) \dots\dots\dots 8.6$$

and

$$v_{ca} = \sum_{n=1,3,5,\dots}^{\infty} 4 \frac{Vdc}{n\pi} \sin \frac{n\pi}{3} \sin n(\omega t \frac{7\pi}{6}) \dots\dots\dots 8.7$$

In equations (8.5, 8.6, 8.7) the triplen harmonics is zero, hence the line to line rms voltage can be found from

$$V_L = \left[ \frac{2}{2\pi} \int_0^{2\pi/3} V_s^2 d(\omega t) \right]^{1/2} \dots\dots\dots 8.8$$

$$= \sqrt{\frac{2}{3}} Vdc = 0.8165Vdc \dots\dots\dots 8.9$$

The rms value of n<sup>th</sup> component of line the voltage can be found as:

$$V_{Ln} = \frac{4Vdc}{\sqrt{2} n\pi} \sin n \frac{\pi}{3} \dots\dots\dots 8.10$$

For n=1 it is a fundamental rms line value given as

$$V_{L1} = 0.779Vdc$$

The line to neutral value is calculated by taking the line value dividing by  $\sqrt{3}$

The intense principle operation is given in (Rashid, 2004)

When the phase value is calculated, it is necessary to consider the type of connection. For example, for Y connected load, the phase voltage is obtained by dividing line value by  $\sqrt{3}$  with a delay angle of 30° with respect to v<sub>ab</sub>. Hence the instantaneous phase voltage between phase aN, is given by:

$$v_{aN} = \sum_{n=1}^{\infty} \frac{4Vdc}{\sqrt{3}n\pi} \sin \frac{n\pi}{3} \sin n\omega t; \text{ for } n=1,3,5,\dots \dots\dots\dots 8.11$$

The voltage of phase bN, and cN are obtained by the same manner

The line current  $i_a$  is obtained by dividing the instantaneous phase voltage by the load impedance. The capacitor current is made up of segments of the three AC phase currents and is dependant on which semiconductor devices are conducting over each  $60^\circ$  period. The capacitor current  $I_c(t)$  can be described in the following pattern:

$$I_c(t) = i_a(t) + i_b(t), 0 \leq \omega t \leq \frac{\pi}{3} \dots\dots\dots 8.12$$

$$I_c(t) = i_a(t); \frac{\pi}{3} \leq \omega t \leq 2\frac{\pi}{3} \dots\dots\dots 8.13$$

and

$$I_c(t) = i_a(t) + i_b(t); \frac{2\pi}{3} \leq \omega t \leq \pi \dots\dots\dots 8.14$$

The capacitor current of the remaining sections can be calculated using the same principle.

### 8.6.1 Sinusoidal PWM Voltage Source Converter

In this technique, the width of the pulse is varied in proportion to the amplitude of the sine wave evaluated at the centre of the same pulse. Pulse-Width Modulation (PWM) is one of the most common modulation technique used due to a number of advantages including reduction of switching frequency, low DC side current ripple and reduction of PWM frequency which lowers the switching loss and reduction of low order harmonics. In order to obtain synchronous PWM, the carrier wave is synchronized with modulating waves.

The gating signal involves the sampling of an informational signal (reference wave); this sampled information content is then converted into a series of modulated pulses whose widths reflects the amplitude of the information signal (Jan, 2004). The PWM pattern is given in Figure 8.9. In this technique the frequency reference signal  $f_r$  determines the inverter output frequency  $f_o$ ; and the modulation index (MI) controls the rms output voltage which is calculated as:

$$MI = \frac{V_m}{V_{cr}} \dots\dots\dots 8.15$$

Where  $V_m$  and  $V_{cr}$  are the peak values of the modulating and carrier waves respectively.

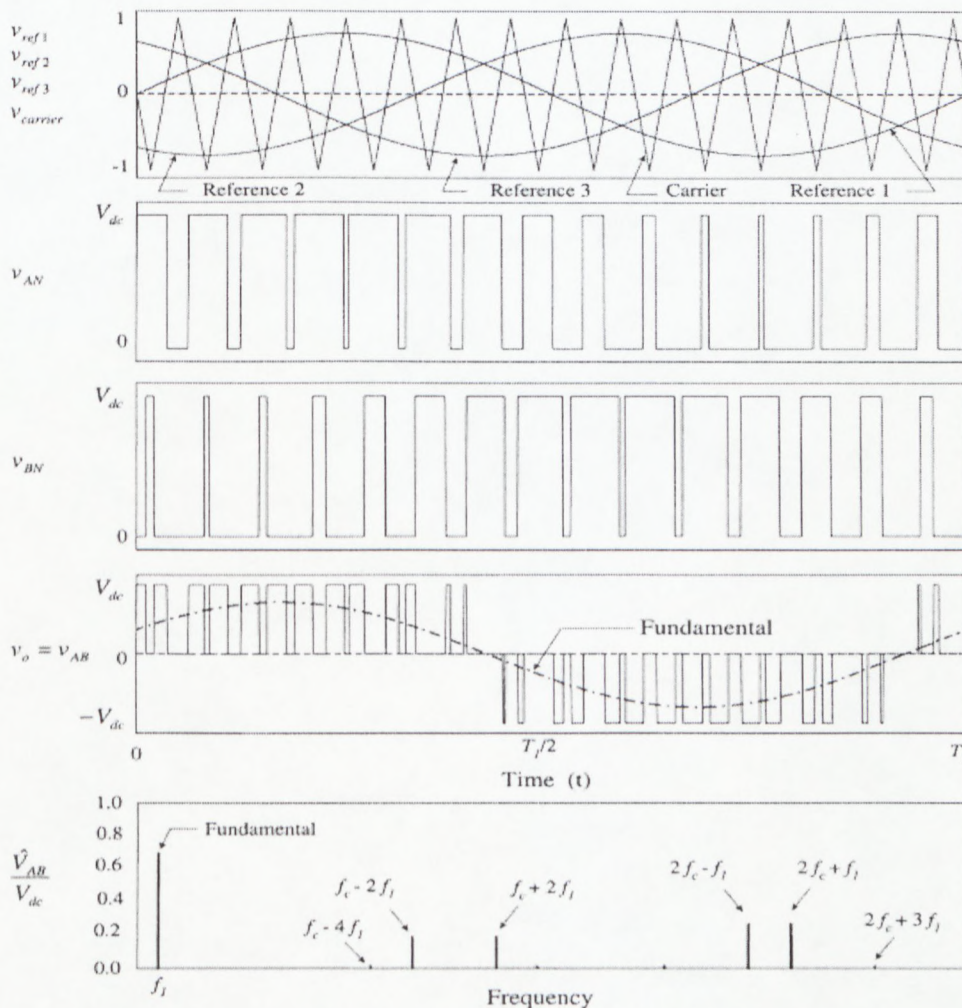
The amplitude modulation index is usually adjusted by varying  $V_m$  while keeping  $V_c$  fixed. The frequency of the modulation index is calculated as given by (Bose, 2002) as:

$$mf = \frac{f_{cr}}{f_m} \dots\dots\dots 8.16$$

Where;  $f_m$  and  $f_{cr}$  are the frequencies of the modulating and carrier waves respectively.

The switching frequency of the two levels inverter can be calculated by:

$$f_{sw} = f_{cr} = f_m \times mf \dots\dots\dots 8.17$$



**Figure 8.9:** Two Level Sinusoidal PWM, with A Single Phase Full Bridge

## 8.7 Modelling and Analysis of A STATCOM

The major part of the STATCOM system component is three phases PWM forced commutated voltage source inverter. The AC terminals of the inverter are connected to the supply mains through the low pass filter. The dc side of the inverter is connected to the capacitor. Figure 8.10 shows a simplified equivalent circuit of STATCOM. In order to achieve an easier modelling of the system, the circuit is subdivided in several basic sub-circuits A to E as shown in the Figure 8.10

Given:

$V_{sa}, V_{sb}, V_{sc}$ : Voltage at the Point of common coupling

$V_{oa}, V_{ob}, V_{oc}$ : Inverter output voltage

$\alpha$ : The phase angle differences between source voltage and inverter

$V_s$ : RMS value of the PCC voltage

$R_s$ : Equivalent filter resistance

$L_s$ : Inductance of the coupling circuit

$C$ : Dc link capacitor

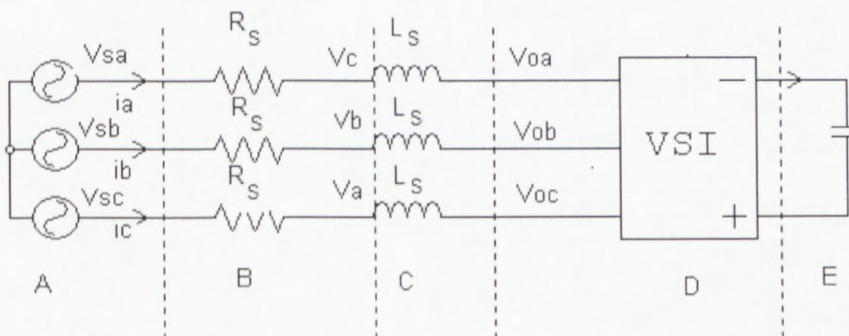


Figure 8.10: Equivalent Circuit of the system with STATCOM

### 8.7.1 Modelling of part A (Transformation of Part A)

The three phase supply voltage is given by:

$$v_{s,abc} = \begin{bmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{bmatrix} = \sqrt{\frac{2}{3}} V_s \begin{bmatrix} \sin(\omega t - \alpha) \\ \sin\left(\omega t - \frac{2\pi}{3} - \alpha\right) \\ \sin\left(\omega t + \frac{2\pi}{3} - \alpha\right) \end{bmatrix} \dots\dots\dots 8.18$$

In the d- q frame:

$$v_{s,dqo} = K v_{s,abc} \dots\dots\dots 8.19$$

Where K is the Parks transform

$$K = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\omega t) & \cos\left(\omega t - \frac{2\pi}{3}\right) & \cos\left(\omega t + \frac{2\pi}{3}\right) \\ \sin(\omega t) & \sin\left(\omega t - \frac{2\pi}{3}\right) & \sin\left(\omega t + \frac{2\pi}{3}\right) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \dots\dots\dots 8.20$$

### 8.7.2 Transformation of Part B

The relationship between the voltage and current in the resistance

$$v_{s,abc} = R_s i_{abc} + v_{abc} \dots\dots\dots 8.21$$

The d-q transform of the equation is:

$$v_{s,qdo} = R_s i_{qdo} + v_{qdo} \dots\dots\dots 8.22$$

### 8.7.3 Transformation of Part C

The relationship between the voltage and the current in the part of inductor Ls is:

$$L_s \frac{d}{dt}(i_{abc}) = v_{abc} - v_{o,abc} \dots\dots\dots 8.23$$

The d-q transform is written by:

$$L_s \frac{d}{dt}(i_{qdo}) = L_s \frac{d}{dt}(K) K^{-1} i_{qdo} + v_{qdo} - v_{o,qdo} \dots\dots\dots 8.24$$

This can be rewritten as:

$$L_s \frac{d}{dt}(i_q) = -\omega L_s i_q + v_q - v_{oq} \dots\dots\dots 8.25$$

$$L_s \frac{d}{dt}(i_d) = \omega L_s i_d + v_d - v_{od} \dots\dots\dots 8.26$$

Assembling part B and C by making  $v_{qdo}$  of equation 8.21 subject and substitution in equation 8.23 we obtain:

$$\frac{d}{dt} \begin{bmatrix} i_q \\ i_d \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L_s} & -\omega \\ \omega & -\frac{R_s}{L_s} \end{bmatrix} \begin{bmatrix} i_q \\ i_d \end{bmatrix} + \frac{1}{L_s} \begin{bmatrix} v_{sq} - v_{oq} \\ v_{sd} - v_{od} \end{bmatrix} \dots\dots\dots 8.27$$

Where  $\omega$  is the system frequency

**8.7.4 Transform of Parts D and E**

Under the assumption that harmonic components generated by the switching pattern are negligible, the switching function scan is defined as follows:

$$S = \begin{bmatrix} sa \\ sb \\ sc \end{bmatrix} = \sqrt{\frac{2}{3}} m \begin{bmatrix} \sin(\omega t) \\ \sin\left(\omega t - 2\frac{\pi}{3}\right) \\ \sin\left(\omega t + 2\frac{\pi}{3}\right) \end{bmatrix} \dots\dots\dots 8.28$$

Where  $m$  is the modulation index

$$IM = \frac{v_{o,peak}}{v_{dc}} = \sqrt{\frac{2}{3}} m \dots\dots\dots 8.29$$

The inverter output voltages are given by:

$$v_{o,abc} = sv_{dc} \dots\dots\dots 8.30$$

In the d-q axis:

$$v_{o,qdo} = Ksv_{dc} = m \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} v_{dc} \dots\dots\dots 8.31$$

Equation 8.27 can be re-written as:

$$\frac{d}{dt} \begin{bmatrix} i_q \\ i_d \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L_s} & -\omega \\ \omega & -\frac{R_s}{L_s} \end{bmatrix} \begin{bmatrix} i_q \\ i_d \end{bmatrix} + \frac{1}{L_s} \begin{bmatrix} -V_s \sin \alpha \\ V_s \cos \alpha - m v_{dc} \end{bmatrix} \dots\dots\dots 8.32$$

Based on equation 8.30, the ideal case gives the relationship between power in DC and AC system as:

$$i_{dc} v_{dc} = p_{abc} \quad ; \text{Hence}$$

$$\dot{i}_{dc} = S^{-1} i_{abc} \dots\dots\dots 8.33$$

In the d-q axis

$$i_{dc} = S^{-1} K^{-1} i_{qdo} = m \begin{bmatrix} 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} i_q \\ i_d \\ i_o \end{bmatrix} \dots\dots\dots 8.34$$

$$i_{dc} = m i_d \dots\dots\dots 8.35$$

The relationship between the voltage and the current in the dc side is given by:

$$i_{dc} = C \frac{dv_{dc}}{dt} \dots\dots\dots 8.36$$

Thus replacing equation 8.27 in eq. 8.28 we will have:

$$\frac{dv_{dc}}{dt} = \frac{m}{C} i_d \dots\dots\dots 8.37$$

Considering all parts of the system, while introducing another equation (the model of the dc part in the system), the complete mathematical model of the STATCOM in the d-q axis is given in equation 8.38

$$\frac{d}{dt} \begin{bmatrix} i_q \\ i_d \\ v_{dc} \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L_s} & -\omega & 0 \\ \omega & -\frac{R_s}{L_s} & \frac{m}{L_s} \\ 0 & \frac{m}{C} & 0 \end{bmatrix} \begin{bmatrix} i_q \\ i_d \\ v_{dc} \end{bmatrix} + \frac{V_s}{L_s} \begin{bmatrix} -\sin \alpha \\ \cos \alpha \\ 0 \end{bmatrix} \dots\dots\dots 8.38$$

### 8.7.5 The STATCOM Behaviour in Steady State

Equations governing the steady state behaviour of the STATCOM can be obtained by equating the term of derivatives of the mathematical model given by equation 8.38 to zero, which is similar to short circuiting inductors and opening the capacitor as:

$$\begin{bmatrix} -\frac{R_s}{L_s} & -\omega & 0 \\ \omega & -\frac{R_s}{L_s} & \frac{m}{L_s} \\ 0 & \frac{m}{C} & 0 \end{bmatrix} \begin{bmatrix} i_q \\ i_d \\ v_{dc} \end{bmatrix} + \frac{V_s}{L_s} \begin{bmatrix} -\sin\alpha \\ \cos\alpha \\ 0 \end{bmatrix} = 0 \dots\dots\dots 8.39$$

$$\begin{bmatrix} i_q \\ i_d \\ v_{dc} \end{bmatrix} = -\frac{V_s}{L_s} \begin{bmatrix} -\sin\alpha \\ \cos\alpha \\ 0 \end{bmatrix} \begin{bmatrix} -\frac{R_s}{L_s} & -\omega & 0 \\ \omega & -\frac{R_s}{L_s} & \frac{m}{L_s} \\ 0 & \frac{m}{C} & 0 \end{bmatrix}^{-1} \dots\dots\dots 8.40$$

After transposition of matrix, the inverse matrix is obtained by solving equation 8.40, as:

$$\begin{bmatrix} \frac{L_s}{R_s} & 0 & \frac{\omega L_s C}{m R_s} \\ 0 & 0 & \frac{-C}{m} \\ -\frac{\omega L_s^2}{m R_s} & -\frac{L_s}{m} & \left(\frac{R_s^2 + L_s^2}{m^2 R_s}\right) C \end{bmatrix} \dots\dots\dots 8.41$$

Therefore

Solving this equation, the following were obtained

$$i_q = V_s \frac{\sin\alpha}{R_s} \dots\dots\dots 8.42$$

$$i_d = 0 \dots\dots\dots 8.43$$

$$v_{dc} = \frac{V_s}{m} \left( \cos\alpha + \frac{\omega L_s}{R_s} \sin\alpha \right) \dots\dots\dots 8.44$$

Hence

Using instantaneous reactive power theory, the expression for calculating p and q is obtained and it can be represented in matrix form as:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_d & v_q \\ -v_q & v_d \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} \dots\dots\dots 8.45$$

Hence

$$p = v_d i_d + v_q i_q \dots\dots\dots 8.46$$

$$q = -v_q i_d + v_d i_q \dots\dots\dots 8.47$$

Where

$$V_{sd} = V_s \cos\alpha \dots\dots\dots 8.48$$

$$V_{sq} = V_s \sin\alpha \dots\dots\dots 8.49$$

Hence combining equation 8.42 and equation 8.49, the active and reactive power flowing from or to the compensator can be calculated as:

$$P_c = \frac{V_s^2 \sin^2 \alpha}{R_s} \dots\dots\dots 8.50$$

$$Q_c = \frac{V_s^2 \sin\alpha \cos\alpha}{R_s} \dots\dots\dots 8.51$$

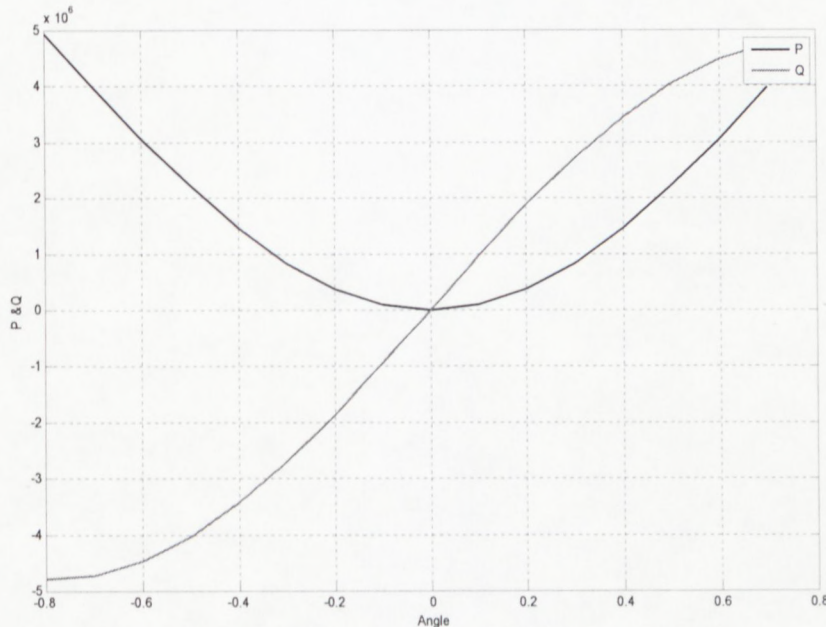


Figure 8.11: Real and Reactive Power in Steady State

We noted that the active and reactive power depends only on the square of the supply voltage and the resistor of the coupling inductance/transformer. It is independent of the other parameters of the circuits ( $L_s$  and  $C$ ). In addition, the dc side voltage depends on  $\alpha$ , the modulation index, resistance and inductance but independent of capacitance.

Analysing equation 8.50 and 8.51 for the small change of  $\alpha$  say from  $-0.8$  to  $0.8$  the result is as given in the Figure 8.11 and 8.12. MATLAB program has been used in the analysis of the steady state value.

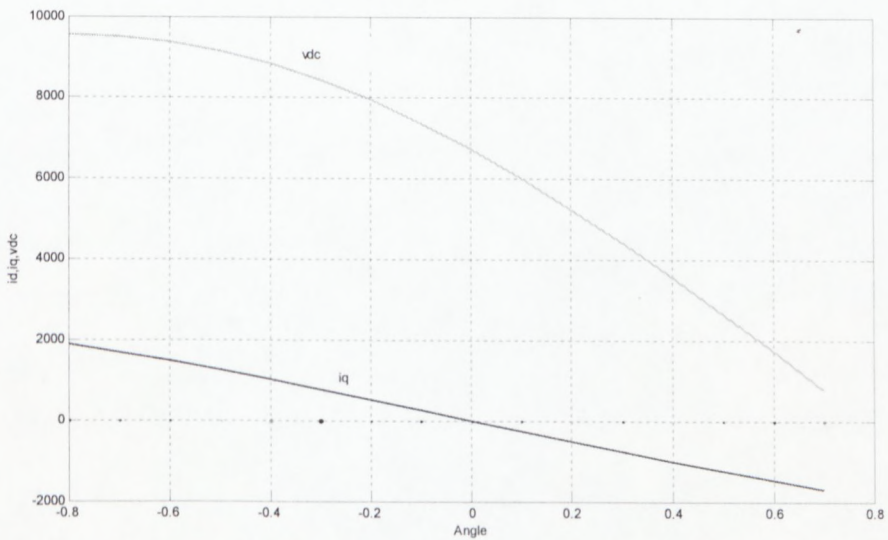


Figure 8.12: Steady-State iq, vdc

### 8.7.6 Controller Design

The controller design of the STATCOM is based on the linearized model of the system under the following assumptions:

- Disturbance  $\alpha_{\Delta}$  is small
- The second order terms are dropped
- The quiescent operating  $\alpha_0$  is zero

The trigonometric nonlinearities are treated considering the value obtained from equation 8.38.

The developed linearized model in state space is:

$$\begin{aligned} X_{\Delta} &= AX_{\Delta} + BU_{\Delta} \\ q_{c\Delta} &= C_{\Delta}X_{\Delta} \end{aligned} \dots\dots\dots 8.52$$

Where  $X_{\Delta} = \begin{bmatrix} i_{q\Delta} \\ i_{d\Delta} \\ v_{dc\Delta} \end{bmatrix}$ ,

$$A = \begin{bmatrix} -\frac{R_s}{L_s} & -\omega & 0 \\ \omega & -\frac{R_s}{L_s} & \frac{m}{L_s} \\ 0 & \frac{m}{C} & 0 \end{bmatrix},$$

$$B = \begin{bmatrix} -\frac{V_s}{L_s} \\ 0 \\ 0 \end{bmatrix},$$

$$U_{\Delta} = \alpha_{\Delta} \dots\dots\dots 8.53$$

$$C_{\Delta} = [-V_s \quad 0 \quad 0] \dots\dots\dots 8.54$$

Using the plant data the state space parameter model may be calculated.

### 8.8 Designed Parameters for the Developed STATCOM

The data used for designing the D STATCOM is the real plant data taken from a cement industry in Tanzania. Most of the influential loads are involved as shown in chapter 3.

The terminal input value of the plant is given as:

Line to line voltage (Vt) input = 6300V

Transformer rating: Two transformers are supplying the plant the rating of each transformer is 5MVA; other transformer specifications:

HV= 33kV

MV=11kV

LV=3.3kV

**Current**

HV=87.3A

MV=263A

LV=292A

**Impedance Z**

HV/MV=7.2%

HV/LV=12.03%

MV/LV=3.8% all are at 5 MVA base

Frequency= 50Hz

The transformer used is a variable transformer hence 6300V is obtained from the taping of the secondary side because there are some loads that need this type of supply. The energy and demand meters are connected on the 6300kV side. There are many loads which are connected to the 400V; hence 6.3/0.4kV transformer is connected to step down the voltage.

### 8.8.1 Total Plant Load Calculation

The calculation of the plant load is based on the per unit value. According to the plant voltage levels and the given MVA, the base value is selected as:

$$MVA_b = 5MVA$$

$$KV_{b1} = 6.3 \text{ kV}$$

The plant has 3 voltage levels, that is 6.3 kV, 0.4 kV and 0.24 kV in this research only two voltage levels were used, because most of the influential loads were connected to them. Therefore, the base voltage of the loads which is subjected to 400V is  $KV_{b2}$  and is given as:

$$KV_{b2} = 0.4 \text{ kV}$$

The base impedance is calculated by looking at the relationship between the  $MVA_b$  and  $KV_b$  and is given:

$$Z_b = \frac{(KV_b)^2}{MVA} \dots\dots\dots 8.55$$

Hence by using this base value, the per unit value of each component and each voltage level has been calculated and the results shown in Appendix 3.1. Finally the acquired per unit values is converted to the actual value to be used in different environments. The calculation of the total plant loads and the possibility of scheduling for demand reduction are presented in Appendix 3.1

The current flowing through the system is calculated as:

$$I = \frac{S}{\sqrt{3} \times V} \dots\dots\dots 8.56$$

**8.8.2 D-STATCOM Parameter Calculations**

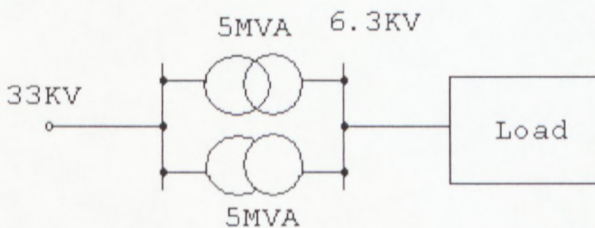
The 11kV level is used

Transformation ratio  $K = \frac{I_1}{I_2} = \frac{V_2}{V_1} \dots\dots\dots 8.57$

$$Z_b = \frac{(kV_b)^2}{MVA_b} = \frac{6.3}{5} = 7.93\Omega$$

$$X_{actual} = \frac{Z_b \times X\%}{100} \dots\dots\dots 8.58$$

Hence, the actual impedance of the supply calculated from the parallel circuit (each transformer has its own impedance) given in Figure 8.13 = 0.57/2 = 0.29 Ω  
 Therefore the reactance of the circuit is calculated and is obtained as = 0.9mH  
 This transformer is connected in parallel.



**Figure 8.13: Plant System Representation**

**8.8.2.1 Calculation of leakage reactance of FACTS transformer or coupling reactance**

Leakage reactance of FACTS components is given between 15-20%. In this research 17.5% is selected. The transformation ratio of the second level of voltage is calculated as per equation 8.57 which is = 0.0634

Taking  $V_b = 0.4$

$Z_b$  at the 400 V branch is calculated as per equation 8.55

$$Z_b = 0.032 \Omega$$

Hence Z actual as per equation 8.58 =  $5.6 \times 10^{-3}$

Transforming this Z to the high voltage side, Z is obtained as:

$$Z = 1.389 \Omega$$

Therefore, the coupling reactance is 4.42mH

### 8.8.2.2 Calculating value of R

It is assumed that, R is  $\ll X$  the ratio of  $X/R = 10$

$$\text{Therefore } R = 13.89 \Omega$$

### 8.8.2.3 DC Side Parameter Calculation

By neglecting losses the instantaneous power balance is given as:

$$v_s(t) i_s(t) = v_o(t) i_o(t) \dots\dots\dots 8.59$$

In the balanced 3-phase  $V_{ab} = V_{bc} = V_{ca}$ , these parameters are only phase shifted by  $120^\circ$  and  $240^\circ$  respectively and they are calculated by equation 8.5.

The alternative way of calculating line to line rms value of voltage is as given in (Rashid, 2004) and presented in equation 8.8 and 8.9. The rms value of the  $n^{\text{th}}$  component of line and phase voltage is given in equation 8.10 and 8.11.

Hence Vdc can be found by:

$$V_{LL} = \sqrt{\frac{2}{3}} V_{dc} \dots\dots\dots 8.60$$

$$V_{dc} = \sqrt{\frac{3}{2}} V_{LL} = 7,715.6V$$

The maximum value of DC voltage is obtained multiplying  $V_{ac}$  by  $\sqrt{2}$  which is equal = 10.912KV.

The load voltage can be also calculated as mentioned above. Assuming star connected loads, V line to neutral of phase A can be calculated by the use of equation 8.11, other voltage in other phases can be calculated in the same manner but they are phase shifted by  $120^\circ$  and  $240^\circ$  respectively.

The inverter output current is calculated by dividing the instantaneous phase voltage  $V_{an}$  by the load.

$$i_a = \sum_{n=1,3,5,\dots}^{\infty} \left[ \frac{4V_s}{\sqrt{3}(n\pi\sqrt{R^2 + nX_L^2})} \text{Sinn} \frac{\pi}{3} \right] \text{Sin}(n\omega t - \phi_n) \dots\dots\dots 8.61$$

Where  $\phi_n = \tan^{-1} n\omega \frac{L}{R} \dots\dots\dots 8.62$

In this case study, the  $\phi_n = 38.2^\circ$

**8.8.2.4 Calculation of DC Current**

In calculation of DC current the following balanced equation is considered

$$V_{dc}(t)I_{dc}(t) = V_{ab}(t)i_a(t) + V_{bc}(t)i_b(t) + V_{ca}(t)i_c(t) \dots\dots\dots 8.63$$

Where  $i_a(t), i_b(t)$  and  $i_b(t)$  are the phase currents

Assuming DC supply is constant and the ac output voltage are sinusoidal, using maximum value of load current, the DC current is calculated by the power balance equation and is given by:

$I_{dc} = 984.058A$

Hence the maximum switching current is calculated, that is  $I_{dc}/3 = 328.01A$

**8.8.2.5 Determination of Capacitor Size**

Capacitor size is calculated based on the reactive power delivered from the compensator. The reactive power delivered is calculated as:

$$Q = 3V_s I_c \dots\dots\dots 8.64$$

Where  $I_c$  is the compensator current

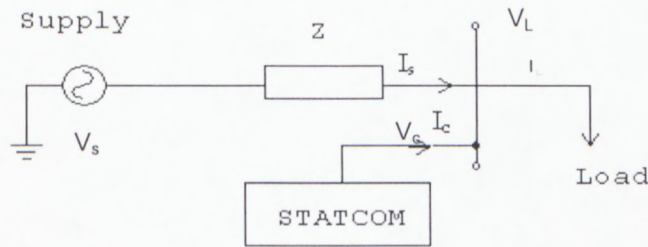
Or the capacitor size can also be calculated using the peak reactive power that might be delivered and using equation given in (Masanda et al., 2008).

$$C = \frac{2 \times Q_{\max} \times 20 \times 10^{-3}}{V^2 dc(1 - k_f^2)}$$

Where  $K_f = 0.6$  describes the minimum allowable dip in dc link voltage.

Hence the capacitor size is  $4852.8 \mu\text{F}$

Figure 8.14 shows the system representation and configuration of the system is given in Figure 8.15



**Figure 8.14:** STATCOM Configuration

From Figure, 8.14, it is seen that for the D STATCOM to be operated as a power factor correction,  $V_c > V_L$ , hence  $I_c + I_s = I_L$  .....8.65

The terminal voltage (V at the point of common coupling) of the system is calculated from:

$$E = V_L + IZ \text{ .....8.66}$$

Therefore

$$Q = 3V_s \times \frac{V_c}{\omega L_c} \left( 1 - \frac{V_s}{V_c} \right) \text{ .....8.67}$$

Considering Appendix 3.1, the actual Q of the group1 = 2699.59kVar and for group 2 is 2566.29kVar hence the maximum value is selected in the next calculations, that is 2699.59kVar. This reactive energy is responsible for the power factor of the plant of 0.7835, that is,  $\cos\phi = 0.7835$  and  $\phi = 38.2^\circ$

The active power (P) = 3435.732kW

If the power factor at any load is improved to 0.97, this is equivalent to  $\phi = 14.07^\circ$ , the STATCOM must compensate for the reactive power required to attain the targeted

value. The rating of STATCOM is selected based on the reactive power required to be delivered. Using the triangular method the reactive power to be compensated to attain the predetermined value is obtained as:

$$Q_{new} = kW \times \tan \theta \dots\dots\dots 8.68$$

$$Q_{new} = 861.08 \text{ kVar}$$

The amount of reactive power to be compensated can be calculated as:

$$Q_c = Q_T - Q_{new} \dots\dots\dots 8.69$$

$$Q_c = 1838.51 \text{ kVar}$$

Therefore the rating of the converter is selected according to the amount of reactive power to be compensated.

$$\text{The maximum reactive power to be compensated} = \sqrt{2} \times 1838.51 \text{ kVar} = 2,600.03 \text{ kVar}$$

**8.8.3 Compensator Rating**

The compensator used a voltage source inverter (VSI) IGBT is used as a switch.

The design of the STATCOM parameters include:

- Selection of DC link capacitor
- Selection of DC link voltage and
- Selection of coupling inductance

A selection of the parameters assumes a balanced AC supply and the voltage source converter operating in linear mode, which is  $0 \leq m \leq 1$ .

Where  $m$  is a modulation index

From the reactive power exchange, it is seen that, the reactive power can be compensated only if  $V_c \geq V_s$ .

Compensator voltage is calculated based on the plant data. At balanced load, current flowing in each branch of load is the same, that is:

$$I_{ca} = I_{cb} = I_{cc}, \text{ and the power flowing in each brunch is the same hence the current flowing through line A is calculated as:}$$

Where  $V_c$  is the converter output voltage can also calculated from the relationship with modulation index.

$$V_c = mV_{dc}$$

$$\text{The capacitor size} = 4852.8 \mu\text{F}$$

The compensator voltage to attain the maximum value of compensation can be calculated by equation 8.65:

The per phase  $V_c = 3968.26V$ , and the line value is obtained by multiplying by  $\sqrt{3}$  hence

$$V_{LL} = 6873.23V$$

The reactance of the supply side is calculated by using the circuit topology and the given % reactance. Two transformers are connected in supply side hence the actual inductive reactance (X) can be calculated as:

Leakage reactance of the FACTS devices- coupling transformer have been selected from percentage leakage reactance of FACTS device. It is selected from the standard value and it is normally higher than the value of power transformer by 15-20%.

Therefore the 17.5% of leakage reactance selected gave us  $X = 1.389\Omega$

## 8.9 Results of the Developed STATCOM

The designed STATCOM was validated by simulation results. Two software were used that is, MATLAB/ SIMULINK and PSIM. The developed circuit diagram is shown in Figure 8.15 and the control and measurement circuit is given in Figure 8.16 and the PSIM model is shown in Figure 8.17 respectively. The results obtained from both softwares were compared and they showed the capability of improving power factor at variable loads. The real plant data was used and many scenarios were considered during simulation. From this simulation, the possibility for STATCOM to operate as a variable power factor correction unit has been demonstrated. The detailed result and analysis are given in chapter 11.



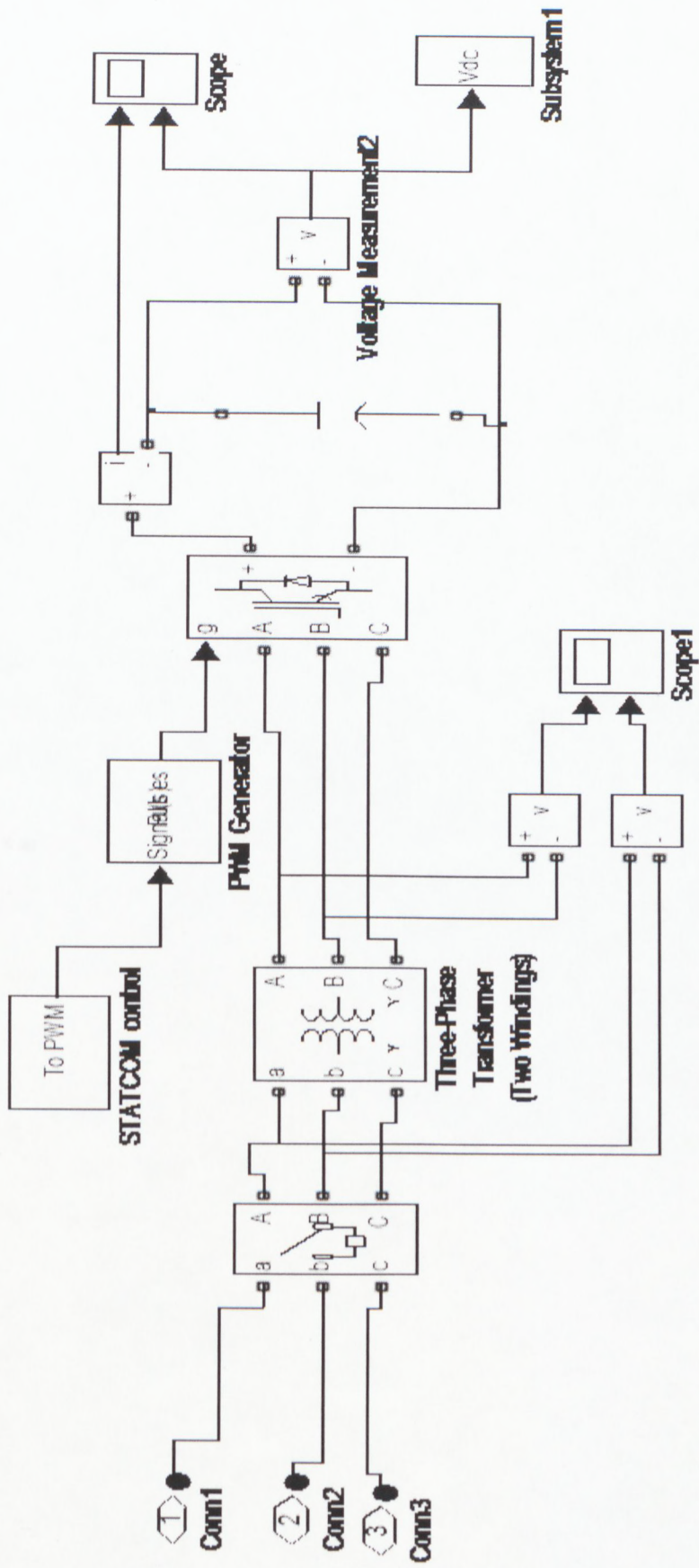


Figure 8.16: VSI Control Circuit

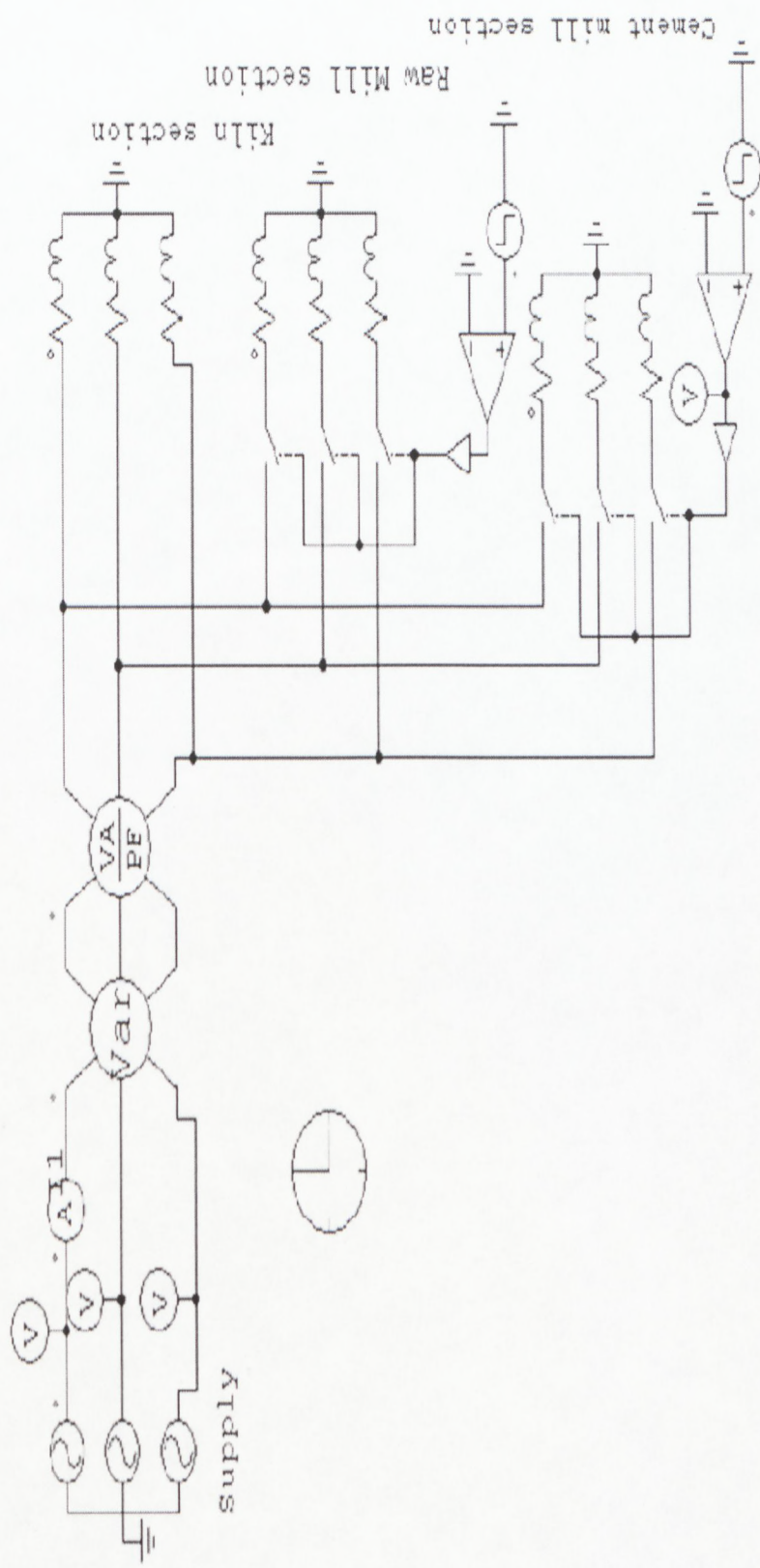


Figure 8.17 PSM Simulated Model

## 8.10 Conclusion

Electrical energy cost has a considerable contribution to the overall running cost of the manufacturing industries. Electricity demand charges in a plant plays a big role in contribution to the overall plant energy charge and contributes to the total running cost. Based on industrial production process, industrial loads may be inductive, resistive or capacitive. In cement industries the loads have inductive characteristics. In the process of operation, they draw both reactive and active energy from the supply resulting in phase angle difference between voltage and current. This increases demand and energy losses in the power system.

In most SSA industries, power factor is corrected by using capacitor banks. The controls of the capacitor banks depend on the modernity of the industry, the method used include; fixed mechanical switch or SVC controlled capacitor. This type of switching is not providing variation of capacitance to suite the variation of loads. In this case if load management method required is load scheduling, the profit can not be fully realized as the power factor may be reduced (depending on the types and size of load injected or reduced at a particular time). There is also an issue of harmonic caused by nonlinear loads, this can cause resonance that may lead to damage or decreases the life of the capacitor.

This chapter proposes STATCOM for power factor correction. This technique works successful in the fixed and variable load situations, which can be used for energy management techniques. In this case STATCOM can maintain the power factor level irrespective of the load level, type of load and variation. The technique has the ability to vary the power factor of the plant from lagging to leading and vice versa.

The developed STATCOM used the data from the cement industry (the case study) of which the circuit operation was tested and validated by the simulation results of two software. The first was executed with a MATLAB/SIMULINK environment and the second tested with a PSIM environment. The results were then compared with the real data of the plant. The computational simulation gave acceptable results, that is, when the loads varied, the power factor also varied (refer to the simulation result attached in chapter11).

## CHAPTER 9: Proposed Energy and Demand Management Strategies

### 9.1 Introduction

Electric Load Management (LM) is defined as any action taken by the customers and/or the electricity suppliers to change the load profile in order to reduce the total system peak load, increased load factor and conserve valuable resources for generation, transmission and distribution capacity.

Faster increasing energy costs combined with other energy related costs, most of the energy intensive industries are facing the challenge of overcoming the price war which consequently limits profits and economic future growth. This scenario creates an immense need for cost consciousness among industrial owners. Towards this endeavour, it has been observed that, energy management and energy conservation measures are indeed a major step to achieve reduction of energy cost. This can only be enhanced through specific energy management strategies. The institutionalization of strategic demand and energy management in industries ensures continuous monitoring and controlling of the amount of electric demand and energy utilized in industry and maintains production at the accepted level, quality and standard.

This chapter presents the strategies which have been developed for electrical energy management in cement industries. The aim of the developed strategies is to ensure a sustainable and continuous energy management program in cement industries. The survey results were analysed and used in the development of the strategies. Apart from load management techniques presented in the previous chapters, this chapter also introduces load scheduling technique as one of the powerful demand management strategy. Through this technique, load can be shifted from peak period to off peak period if pricing mechanism provides some incentive for cost reduction. The algorithms have been developed to provide step by step load management action.

### 9.2 Steps for the Strategic Energy Management Strategies

In the development of energy management strategies the accurate analysis of the load is required to identify how the electrical energy is consumed in any specific piece of equipment, system or the combined loads such as interlocked load. The analysis should also be done to identify the parameters or variables (including type of raw material, size of raw material, moisture content and kiln process) that have a big

impact in energy consumption and how its improvement might contribute to energy and demand management.

The initial control step for load management including studies of the individual load behaviour and control option mostly depends on the type of load, time and the duration for which it operates. In many countries the measured electricity demand drawn by large consumers is averaged at 15 or 30 minute period. During this period, it is possible to postpone some low-priority loads so as not to exceed the contractual threshold over the period.

Industries with storage production capacity can be used to modulate the load (that is to study the production environment and to switch off some machines during peak hours and to step up during off-peak time) without operational disruption and keeping the total production at its original size and standard. Therefore, the main element of strategic energy management are linked with energy planning and controlling of the organisation and the technology used for energy management.

### **9.2.1 Methods for Demand Control**

The methods for demand control start with the basic knowledge of the load being controlled. The demand control concepts require an understanding of utility rates, metering and manipulation of the demand drawn (load curve, maximum demand and load factor). The first steps towards achieving demand control is the analysis of loads which include:

- Definition of industrial loads, which is determined by measurements that are taken during the days or hours of operation. It identifies which time of day the maximum demands occur and which loads are connected at that particular time.
- Determination of the load curve and set the objectives to be achieved based on the pricing mechanisms.
- Checking monthly electricity bills to determine if load management opportunities exist and if so during which time periods (month).
- Technical analysis of the feasibility of load management so as to make sure that constraints are taken care off with respect to safety of operations, impacts on quality and quantity of production, preservation of the integrity of the equipment, and mutual interactions with other facilities in the factory. In this way, interruptible operations can be identified and the amount of load to be reduced can be established.

- Analysis of controllable operations that, for the value and timing of their consumption can be retained as the major contributors to the controlled load.

In generally, the demand of the plant can be controlled by the use of four basic techniques namely, manual, automatic controller, microcomputer system and computerised energy management.

#### 9.2.1.1 Manual Controller

This is performed by manual shutting down of nonessential loads during high demand period so as to limit high consumption at peak time. Under this circumstance, interlock system should be considered for the continuous process equipment.

Before control, energy audit should be performed to identify which machine/equipment and at what time the consumption of energy is higher and to identify if the machines are operating within the specified standard. Area of energy waste also needs to be identified (IEEE.std 739-1984).

#### 9.2.1.2 Automatic Controller

When more fine tuned operation is desired, an automatic demand controller is used. Most of the controllers require pulsating signal input developed from a demand pulse meter. These automatic controllers are categorised based on their operating principle as:

- 9.2.1.2.1 **Instantaneous Demand;** Action is taken when instantaneous demand exceeds the established prescribed set point value. Set point is determined for the demand interval. When one-fourth of the demand interval has transpired, accumulated demand should be no more than 25%. Load is switched in and out of service in accordance with this criterion. This mode of operation might result in short cycling of loads
- 9.2.1.2.2 **Ideal Rate;** Ultimate demand limit is prescribed and a slope is established to define when usage indicates that this limit is likely to be exceeded. The start of demand interval does not begin from zero, but it is established from offset point that takes into account nondiscretionary loads. The slope of the ideal rate curve is then defined by this offset point and a chosen maximum demand.
- 9.2.1.2.3 **Converging Rate;** it works like the ideal rate controller but it operates on an accumulated usage curve whose upper limit is defined by the specified maximum demand.

**9.2.1.2.4 Predicted Demand;** Average usage is observed periodically through the demand interval and compared with the instantaneous usage at that particular moment. This information is used to develop a curve of predicted usage for the remaining of the interval. If the projected curve indicates that the target set point might be exceeded, action is taken.

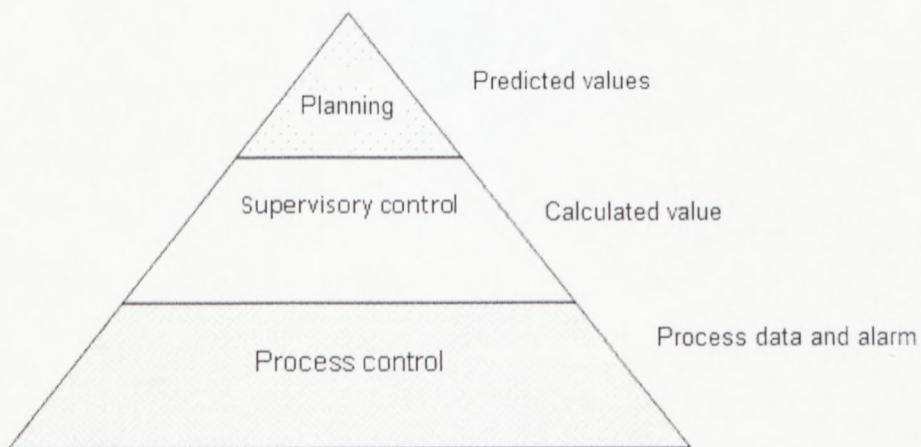
**9.2.1.2.5 Continuous Integral;** it monitors the power usage continuously rather than only when a time pulsating signal is transmitted by the utility company's demand meter.

### 9.2.1.3 Microcomputer System

Maximum demand can be specified in the microcomputer which can be tolerated based on previous experience. It continuously monitors the industrial electricity consumption and determines if the demand limit is exceeded. If the computer predicts that the demand may exceed the limit, the pre selected loads can be automatically turned off to reduce demand or an alarm can alert the operator.

### 9.2.1.4 Computerized Energy Management Control System

It consists of three hierarchical levels namely: operating, supervisory and management planning levels as shown in Figure 9.1. Data with the hierarchical require more manipulation. The uses for energy management systems are as diverse as the processes they serve.



**Figure 9.1:** Hierarchical Control Pyramid and Levels of Control

Source: IEEE std 739, 1984

### **9.2.2 Determining the Potential for Demand Control**

In the demand side, high irrelative demand cost at the billing period are the measure of inefficient use of electricity and it can be lowered only if the energy consuming loads or high power consumers operation is alternate in all billing period (that is some significant loads should be temporarily scheduled from peak to off peak period).

In order to find the potential for demand control, the following steps present the potential and the approximate size of the demand that can be saved in the whole production process.

First, the industrial loads study must be done in order to determine the potential for demand and energy reduction before the development or procurement of the controller. This potential might be obtained by considering analysis that includes: The development of a demand curve; this is obtained by the measurement of power for a period of time and interval of 15 or 30 minutes. In this study the load curve was drawn from the case study industry data. It is a daily curve taken within the interval of 15 min during week-days and week-ends as presented in chapter 3. This curve provides a picture on how the demand pattern looks like. From the load pattern it is easier to calculate the load factor of the industry for 6 months or a year. If demand factor vary significantly from billing and if less than 80% there might be a potential for maximum demand control.

Secondly, it is to identify the potential by analyzing the operational regime so as to identify which load can be shifted, which can be turned off first and for how long, and which load can be operated at reduced power or speed, for example fan, and pumps. In that priority the sequence of starting can be developed to avoid high inrush current that can lead to a maximum demand. There are also some loads which are known as nonessential loads. Nonessential loads are those independent of the process thus they can participate in load priority system because they are not affecting the production although it might affect the impact of comfort.

### **9.2.3 Operation of the Demand Control System**

The whole concept of LM is the use of different DSM technologies to achieve peak clipping, valley filling and strategic load conservation (Gelling, 1995). The aim of the demand / energy control techniques and strategies are to ensure that the demand does not exceed the targeted value. The objective of energy management is to achieve and maintain optimum energy procurement and utilization, throughout the

organization so as to minimize energy costs without affecting production. So far most of the demand controls operate as:

- The load control is performed by the use of devices that optimize power consumption on the basis of a pre-established limit regarding the maximum load required at a particular time and disconnecting some loads if the amount exceeds the pre-set value. The operation of the demand controller can either be triggered by a peak load or tariff structure. A load limit is set for each rate and each period. When the operating load conditions are approaching the set point, the controller sequentially switches off the loads according to a priority list.
- The control is usually performed through a forecasting algorithm; the difference is calculated between the total available energy in a given period of time (obtained by multiplying the maximum contractual power by the time period itself) and the energy consumed from the beginning of the period. The ratio between this difference and the remaining time to the end of the period represents the maximum power that can be absorbed without exceeding the contractual limits.

Moreover, the most sophisticated systems not only switch loads on and off according to their priority, but can also be programmed to take into account, both the power absorbed by the loads and the particular requirements of the loads themselves. The benefit of maximum demand controller is its ability to release electrical system capacity hence reduces operating cost.

### **9.3 Algorithm for Energy and Demand Control by Load Scheduling Technique**

In most SSA countries, traditional methods used to achieve valley filling and peak clipping are manually operated. The operator normally undertakes LM considering the referenced value of demand of the previous months' bill and control on/off switching as per the load curve requirement. The draw back of this method includes payment of penalty caused by abrupt raise of demand to the maximum value that is maximum demand consumption due to the reason that maximum demand occurs at any demand period (SSA 30min). This situation might appear once in the month but the reading pointer remains at the maximum point in all billing period (one month) until the meter reader reads and resets the meter. Hence demand detection and control must be formulated as to minimize the possibilities of maximum demand occurrence at the operating period.

**9.3.1 Formulation of Load Model in Cement Industries**

In order to formulate demand control strategies the physical plant load should be studied so as to identify the load management possibilities. The formulation starts by considering the physical load model which is used for the development of the demand control algorithm. Figure 9.2 presents the plant layout of the industry.

In this formulation, the cement industry under study is divided into different sections of operation as shown in Figure 9.2.  $R_2$ ,  $K_2$ , and  $T_2$ . They are the output of the storage system and are the input of the next process of different sections. The sections that have the influence on energy and the demand and the material flow are given as:

**9.3.1.1 Quarrying;** here, electrical energy is consumed for lighting and water pumping if the site is close to the plant. In the remaining part of the plant, electrical energy is used for production process. The produced tones of material in different sections of the plant is analysed and presented considering plant layout on Figure 9.2.

**9.3.1.2 In the Crusher,** the tones produced in the out put of the plant can be analyzed at any particular process taking into account the efficiency of each production process from the point of the production process to the final section. For example, at the crusher the tonnage can be calculated as given by (Tripathy et al., 1992) as:

$$Tonnes = C_2 \times \frac{R_1}{C_3} \times \frac{K_1}{R_2} \times \frac{T_1}{K_2} \dots\dots\dots 9.1$$

Where  $T_1$  is the cement produced by the cement mill

In the raw mill section, the production output (raw meal) is obtained as:

$$Tonnes = R_1 \times \frac{K_1}{R_2} \times \frac{T_1}{K_2}, \text{ and} \dots\dots\dots 9.2$$

The production output is considered from the kiln section is given as:

$$Tonnes = K_1 \times \frac{T_1}{K_2} \dots\dots\dots 9.3$$

The energy and hence electricity demand of any section (i) can be analysed as:

$$S_i = P_i + Q_i \dots\dots\dots 9.4$$

Where i represent the plant section

- C<sub>1</sub> - Crusher input
- C<sub>2</sub> - Material output from the crusher
- C<sub>3</sub> - Raw meal input
- R<sub>1</sub> - Raw mill output
- R<sub>2</sub> - Raw meal silo output
- K<sub>1</sub> - Kiln output (clinker)
- K<sub>2</sub> - Clinker silo output
- T<sub>1</sub> - Cement mill input
- T<sub>2</sub> - Cement silo output

The capacity of the section depends on the number and rating of the connected loads at the point of analysis and the percentage loading of each equipments/machines. There are also nonessential loads that are not considered in the cement production layout such as the lighting and ventilation at workshops, and office building of which its total energy demand can be calculated as in Equation 9.4.

The simplified version of the industrial operation is divided into 3 operating sections namely, material preparation which involve crusher section and raw mill section, Kiln section which involves coal mills section for thermal energy generation and cement mill section which also involves the parking plant. The end of each section is incorporated with a storage plant (silo) for storing materials. Hence the overall plant storage section is 3 (see Figure 9.3). The composition of the process of each block is shown in Figure 9.4. For enhancing load shifting energy management technology, the following main guiding equation is considered.

$$P = \sqrt{3}V \times I \cos\phi \dots\dots\dots 9.5$$

And the demand of the plant can be elaborated as:

$$S = \sqrt{3}V \times I \dots\dots\dots 9.6$$

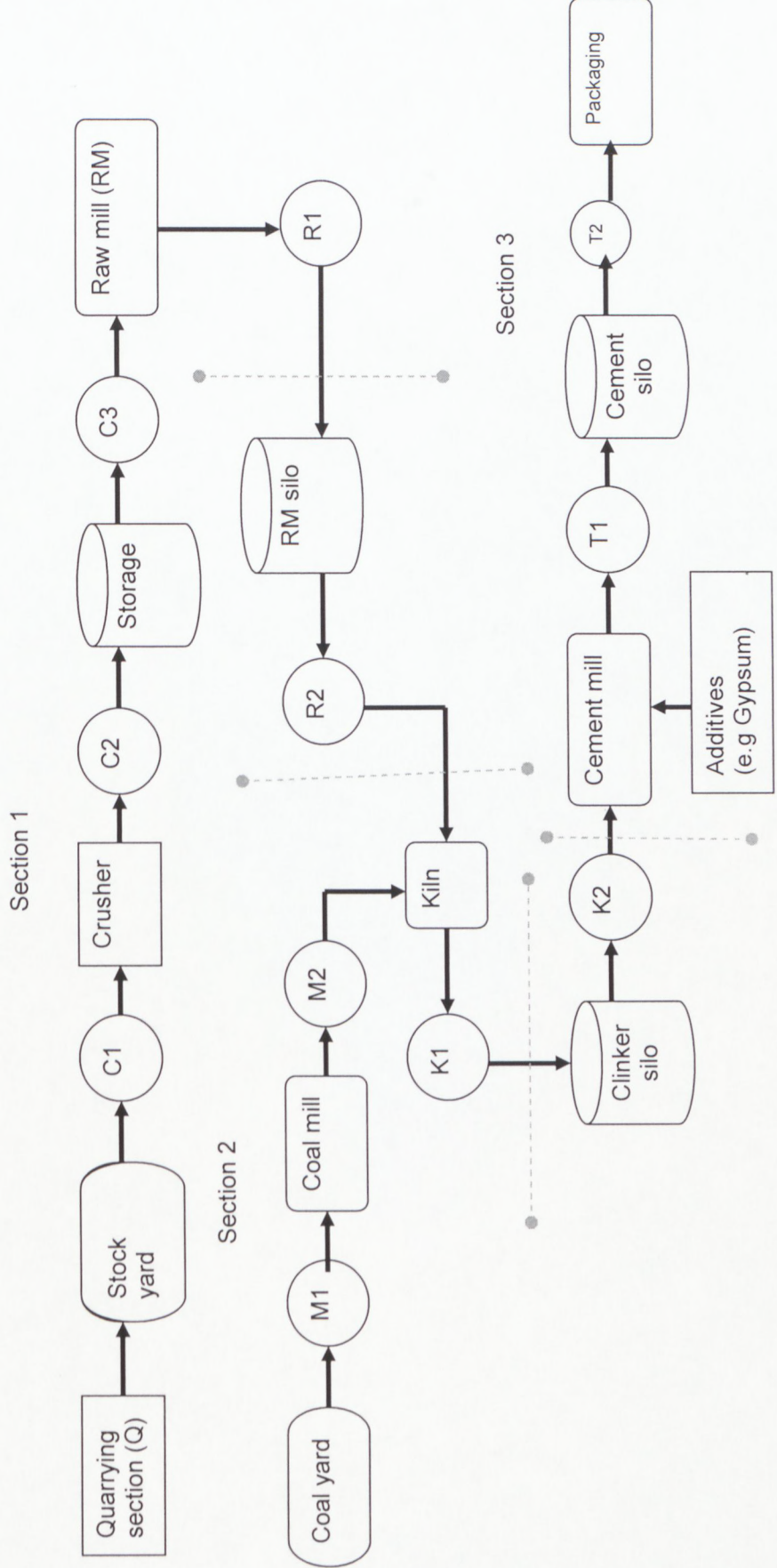


Figure 9.2: Cement Plant Layout

The maximum demand of the plant at any particular interval depends on the load connected in the system at a particular period while the total load at a particular time is taken as the sum of all connected loads.

The total energy consumed is calculated as:

$$E = \sum_{n=1}^M P \times t \dots\dots\dots 9.7$$

Where, M is a number of connected loads at a particular time n= 1, 2,....., M

From the physical model, a mathematical model was developed, so as to analyse the electrical energy use in the plant.

Cement production process is the batch process system and is a more appropriate process for load scheduling technology. This is because the individual section operation is independent of other sections. But it only depends on the previous section storage (for obtaining material input) hence there must be enough storage so that the production output can be constant.

In order to minimize the maximum demand, it is proposed that, only two sections of Figure 9.3 operate at the same period. This means the kiln condition is not stopped at any load management option. The packing section also has been given the priority to operate at all working conditions so as to allow the continuous out put of the product. The only alternative alteration remaining is the operation of kiln with raw mill section or the operation of kiln with the cement mill. The plant process model is designed in such a way that only two sections are operating together.

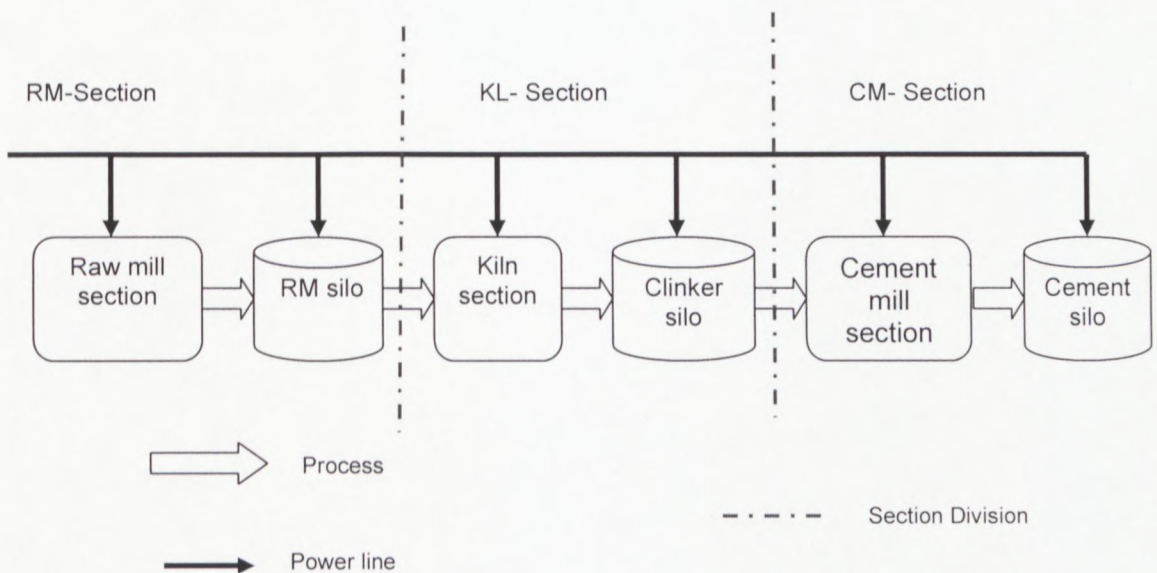
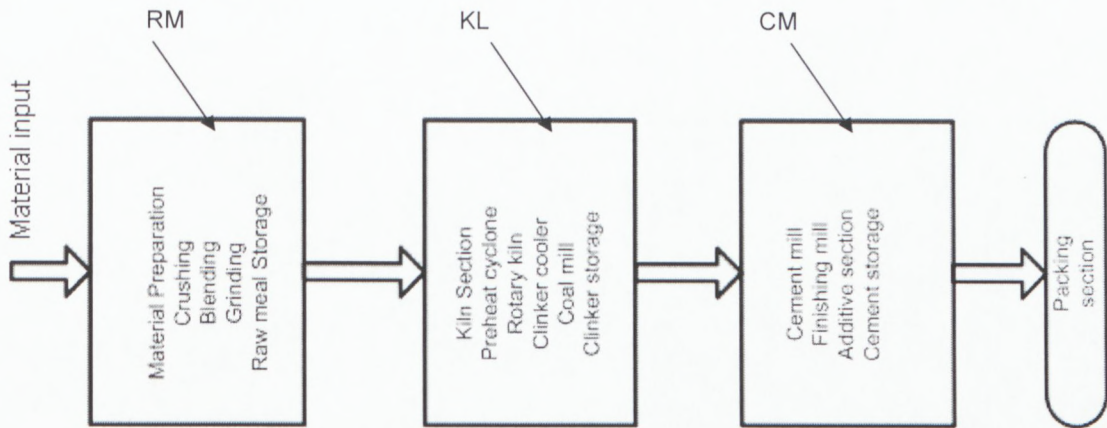


Figure 9.3: Simplified Plant Model



**Figure 9.4:** Cement Production Sections and Sub-section

From equation 9.4, the demand is calculated by summing the demand of the two sections.

$$S_1 = S_{RM} + S_{KL} \text{ and / or } \dots\dots\dots 9.8$$

$$S_2 = S_{KL} + S_{CM} \dots\dots\dots 9.9$$

Where: S1 and S2 are the power demand of each section (category)  
 $S_{RM}$  Electricity demand in the raw mill section  
 $S_{CM}$  Electricity demand in the cement mill section  
 $S_{KL}$  Electricity demand in the kiln section

The total demand in each group or category can be calculated as the sum of the aggregate number of loads connected to the system in any particular section and at any particular time. Hence the demand is obtained as:

$$S_{section} = \sum_i^N Si(t) \dots\dots\dots 9.10$$

For N number of load = 1, 2,.....N at a particular time

### 9.3.2 Load Management Method and Energy Management Model

Load shifting DSM objective is selected because it is a better and simpler method of load management. It is possible to practice without changing the total production output. In this technique some process loads are rescheduled to minimize peak demand and improve load factor. During load shifting, plant operating processes such as interlocked process and storage space limitations or constraints are considered as part of the study.

This method is offered through the level or amount of demand at the integrated demand period of the plant because most SSA countries are not implementing tariff structures such as time dependant and time of use tariffs. The process constraints is incorporated and studied. For example, there are some loads which are not possible to shift as a particular or single load alone; this is called the process interlocked.

Some processes are continuous. Thus loads having process interconnections or loads in continuous process chain can not be controlled independently. The cement industries have a number of storage spaces (as indicated in Figure 9.2 and 9.3) which allow the scheduling of one section while other sections operate and use material stored in the storage system. This is very useful for constant and continuous production output criteria.

In the formulation process, the kiln section energy consumption and the packing section are added together to make one unit because both are not considered in load scheduling. Considering this option, a more simplified model is obtained. Hence the total plant energy without load shedding action may be calculated as:

$$E_T = E_1 + E_2 + E_3 \dots\dots\dots 9.11$$

Where  $E = P \times t \dots\dots\dots 9.12$

$E_1, E_2$  and  $E_3$ , represent the energy of each of the section.

Energy consumption also depends on the number of connected machines at the measured period and the rating of the respective machine as given in equation 2.22

Page 44

And the total plant maximum demand was calculated as:

$$D = S_T = P_T + Q_T = I_T V_T \text{Cos}j + I_T V_T \text{Sin}j \dots\dots\dots 9.13$$

Let, C be the cost of electrical energy \$/kWh

Cd cost per maximum demand charge \$/KVA

Optimization formulation is aimed at minimizing the energy cost which is caused by the energy consumption and the industrial demand expressed as:

$$\text{Minimize } \sum_i^n (E_{it}) \times C + S \times Cd \dots\dots\dots 9.14$$

Where the power on an individual load mostly depends on the rating of the equipment or machine, efficiency and the utilization factor or percentage loading as given by:

$$Pin = \frac{X_n \times U_{nj}(t)}{\eta_{nj}(t)} \dots\dots\dots 9.15$$

The constraint when energy is managed is as follows:

### 9.3.2.1 Production Constraints

In the development of the demand control system, it is required to specify the minimum production output ( $Q$ ) of the final product in the time horizon. This constraint is formulated for production limitations. A given constraint should be in such a way that the production output is not minimized because of the load management action. The governing equation is:

$$\sum_{i=1}^N \sum_{m=1}^M P_{mi} \times t_{mi} \times I_{mi} \geq Q \dots\dots\dots 9.16$$

Where:

- $M$  The total number of machines processing or producing the final output
- $p_{mi}$  Production rate of machine m, in the interval  $i$
- $N$  Interval,  $N=1 \dots\dots i$
- $q_{ri}$  Production consumption rate at interval  $i$
- $S_m$  maximum storage capacity

Using the variable  $P_{mi}$ , it is possible to incorporate the change in production rate of machines at different intervals considering the variation of utilization and efficiency of parameters.

- $I_m = 1$  when machine  $m$  is on in the interval  $i$
- $= 0$  when machine  $m$  is off in the interval  $i$
- $t_{im}$  = Time interval i.e start and end of the process

### 9.3.2.2 Storage Constraint

The process loads with storage facility and maximum capacity limitations were modelled as in equation 9.17. It is assumed that, the cement industries have a number of silos for storage of the material. Comparison is made between the sum of the production input and output or/and consumption rate. The mathematical formulation is given as:

$$\sum_{i=1}^T \left[ \sum_{m=1}^M P_{mi} \times t_{im} \times I_{mi} - \sum_{r=1}^R q_{ri} \times t_{ri} \times I_{ri} \right] \leq S_m \dots\dots\dots 9.17$$

for  $T=1$  to  $N$

### 9.3.2.3 Process Flow Constraint

This is modelled in order to predict the capacity of the storage in relation to the consumption rate. Hence the monitoring of material flow is given by:

$$\sum_i^T \left[ \sum_{m=1}^M P_{mi} * t_{mi} * I_{mi} + \sum_{l=1}^{L_s} S_l \right] \geq \sum_i^T \left[ \sum_{r=1}^R q_{ri} * t_{ri} * I_{ri} \right] \dots\dots\dots 9.18$$

for  $T = 1$  to  $N$

### 9.3.2.4 Sequential Constraint

Some processes operate in sequence. The condition for the start of machine  $m$  at an interval  $i$  after  $t$  interval from the start of the  $(m-1)^{th}$  is also modelled as:

$$t \times I_{mi} \leq \sum_{j=i-t}^i I_{(m-1)j} \dots\dots\dots 9.19$$

### 9.3.2.5 Maximum Demand Constraint

There should be a peak demand limitation. This is an important factor for load scheduling since many industries are subjected to maximum demand restriction for intervals  $i$

$$\sum_{m=1}^M \left( \frac{k_{mi}}{pf_{mi}} \right) \times I_{mi} \leq KVA_i \dots\dots\dots 9.20$$

Where  $KVA$  is the maximum demand limit  
 $K_{mi}$  is electrical power input and  $pf_{mi}$  power factor of the machine  $m$

The predetermined load of the industries was calculated using equation 9.15. Hence the electrical power input in kW to any machine  $m$  at any interval  $i$  is:

$$k_{mi} = Pin = \frac{X_m \times U_{mi}}{\eta_{mi}} \times I_{mi} \dots\dots\dots 9.21$$

Where  $X_m$ , is the rated capacity of device  $m$  in kW,  
 $U_{mi}$  utilization factor of the device  $m$  at the interval  $i$  and  
 $\eta_{mi}$  is the efficiency of the machine.

The given mathematical model can be solved using different methods to achieve valuable results.

The algorithm used for solving load scheduling as a demand management strategy is as given in Figure 9.5 and Figure 9.6 is the algorithm for checking out the constrains. The input to the algorithm is the information from the data bases which contain information of material flow, energy flow and control data of production of machines. The developed model is based mainly on the process itself and its behaviour. In the developed tool, the current flowing in the circuit is the control factor of high or low demand. The general expression of demand in a single phase system is:

$$S = IV \dots\dots\dots 9.22$$

Where,  $I$  and  $V$  are the per phase values of current and voltage respectively.

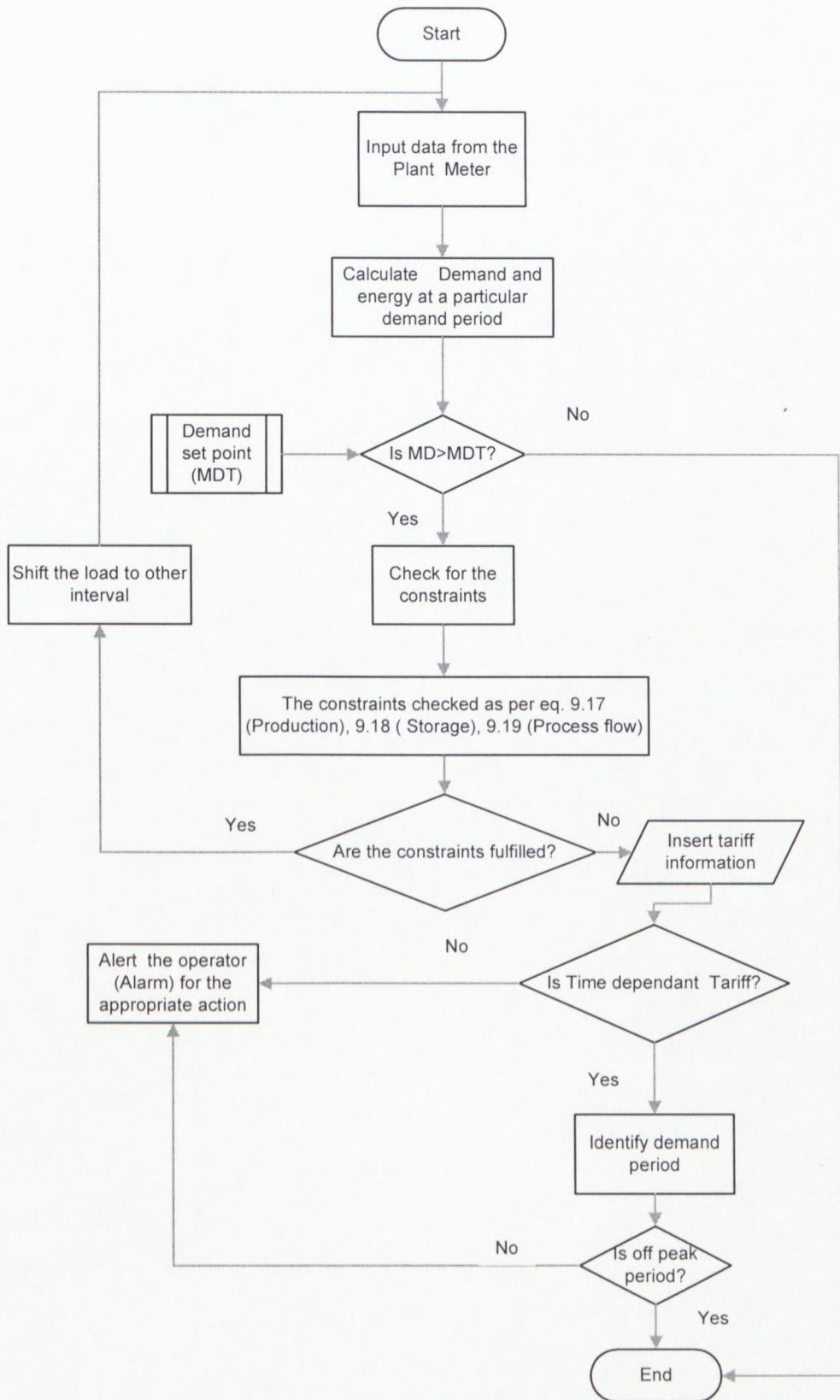


Figure 9.5: The Algorithm for Solving Optimal Load Scheduling Demand Management

In order to limit maximum demand, the preset value should be the predicted value of the current which might raise the maximum demand at a particular time but it is reduced before the raise of maximum demand. When the plant is in operation and if the predicted load is reached, the alarm should ring so as to alert the operator to minimize the load before it reached the maximum demand. This process should be designed such that, after few minutes of alarm and if no action has been taken, the system can shed non critical loads according to the priority.

The input data for the operation of the algorithm is measured by kWh, kW and KVA meter. The kWh meter measure the total energy consumed in the industry while the KVA meter measures the demand over the specified period of time. The demand period of many SSA countries industries is 30 min. The recording instruments read data that can be used to determine the load behaviour by plotting the load duration curves (LDC) of the plant. The LDC is used to provide the analysis which shows the insight of opportunity for load management where the next stage of the creation of the load management can be preceded.

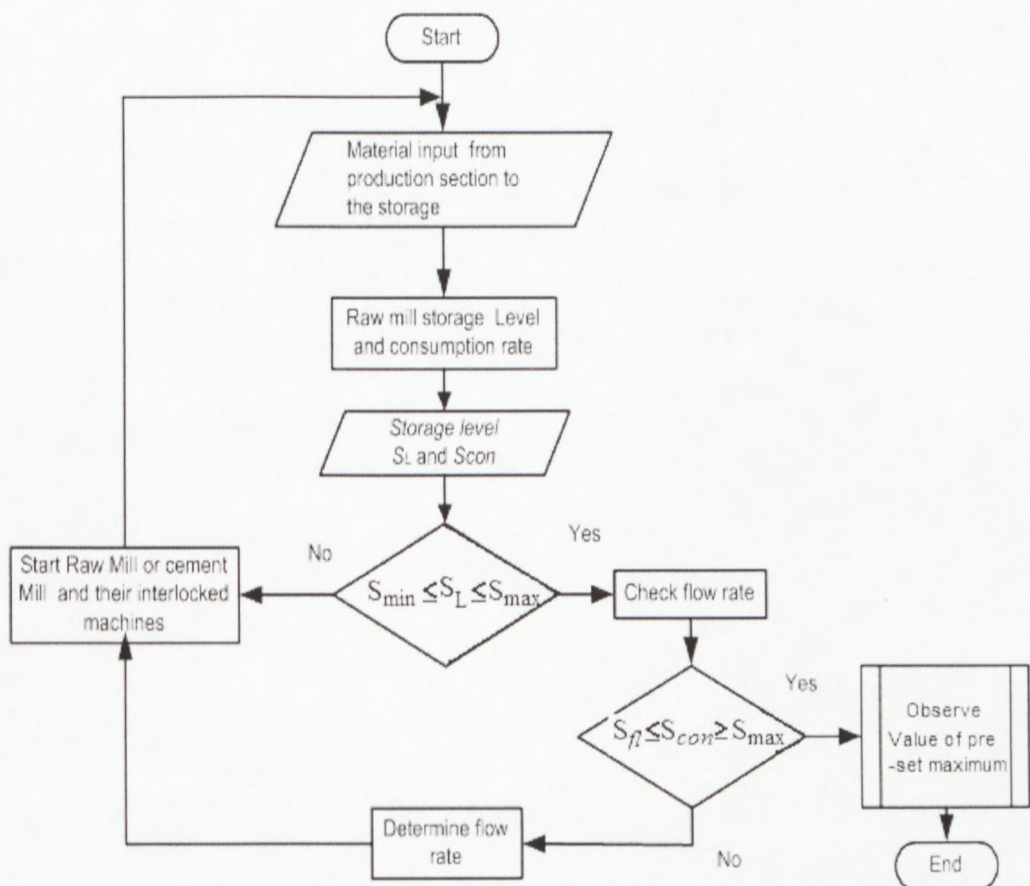


Figure 9.6: Solving Constraint

Where  $S_{min}$ ,  $S_{max}$  and  $S_L$  is minimum, maximum and the predetermined storage level

$S_{fl}$  and  $S_{con}$  is material input flow rate and consumption rate respectively

Figure 9.6 shows the algorithm for solving constraints of raw mill storage. The procedure is still valid for the algorithm of the remaining storage system of other departments or sections in the plant.

### 9.3.3 Analysis of Storage System

**Sections Storage Size:** The total capacity of the silo in the RM section is 7200 tonnes. The clinker silo has the capacity of 10550 tonnes and the cement mill section has a silo capacity of 8400 tonnes. The charging and discharging rate is as given below (equation 9.23 and 9.24).

The charging rate of the raw mill silo is 70t/ hour while discharging rate is 30 t/ hour.

The kiln charging rate is 30t/ hour and it discharges at the rate of 42t/ hour, and the cement mill charging rate is 42t/hour and discharged at 60t/hour.

Considering the storage capacities of each silo, the time required to fill the silo to full value if at particular period the material is not consumed is calculated as.

$$\text{Time for filling storage} = \frac{\text{Silo capacity}}{\text{Charging rate}} \dots\dots\dots 9.23$$

$$\text{Time for discharging the storage} = \frac{\text{Silo capacity}}{\text{Discharging rate}} \dots\dots\dots 9.24$$

Using equation 9.23, the time is calculated and obtained as:

- The time required to fill the RM to its full capacity = 103 hours.
- The time required to discharge the RM without filling = 240 hours.

By assuming the RM silo is discharged while RM section is off, the limiting factor is the minimum pre-set value of stored material. It should be designed in such a way that the minimum level of storage is 15% of the silo level. This analysis shows that, there is a potential possibility of scheduling or switching off the RM section for even a day while other sections are working.

Clinker storage discharging time is 352 hours if the initial condition of silo is full. The charging and discharging time of the cement mill storage is calculated as 140 hours

and 75 hours respectively. Hence, considering the storage analysis, it is possible to schedule each section for several hours without affecting other section or production output.

### 9.3.4 Formulation of Power Factor Monitoring and Control

An important parameter for quantifying the effectiveness of energy utilization is the power factor. Inductive loads such as electric motors and its drives and fluorescent light ballasts can cause the voltage and current to shift out of phase. To compensate for the phase shift of I and V, external reactive power is required. The STATCOM has been proposed in this thesis to provide flexible power factor correction. The proposed STATCOM vary the generated reactive power as the loads vary. This allows the flexibility of power factor correction at any load condition. The proposed reactive power compensation expression is given in Chapter 8. From the equation it is seen that, the developed STATCOM operates perfectly under the following constraints:

$$\cos\phi = \frac{P}{KVA} \dots\dots\dots 9.25$$

$$0.95 \leq \cos\phi \leq 1$$

$$V_c \geq V_s$$

Where  $V_2$  is the converter or STATCOM output voltage and  $V_1$  is the voltage at the point of common coupling.

The algorithm for power factor monitoring and control is given in Figure 9.7. It is developed based on the simulation and circuit design of chapter 8.

## 9.4 Strategies for Industrial Load Control

In order to assess the viability of managing the industrial electrical load, proper strategies should be followed. The proposed strategies are required to provide the savings opportunities and mainly categorised in to:

- Assessment of load characteristic
- Assessment of load control impact
- Implementation of load control
- Verification including monitoring and evaluation

In assessment of load control characteristics, many LM methods can be used provided they have benefit to the consumer. For example the load shape objectives discussed in Chapter 4 is considered as an energy management techniques. The analysis of the plant load characteristics starts from big load such as cement mill.

The motors used to drive these mills are characterized in terms of their rating, efficiency, power factor, percentage loading and types of control system.

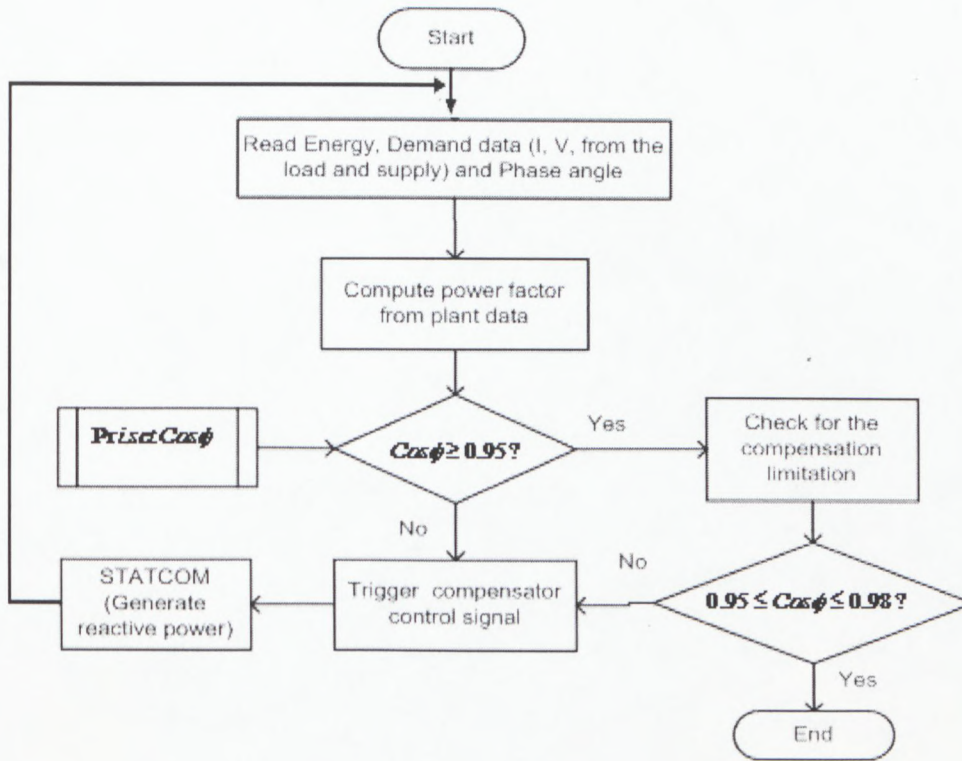


Figure 9.7: Power Factor Correction Control Algorithm

The baselines must be established, that is kWh/ton of output product as shown in Chapter 5. This may assist on the load control and hence demand or energy management. It will also assist in verifying the result. In addition it will easily identify the inefficiency or efficiency of the system. Load characteristics such as load shape, load duration curves, load factors, variance, peak and off peak time energy /demand consumption should be established by the use of measurement. These quantities show the possibility in which the saving opportunities are feasible. Hence, the first step to identify energy saving opportunity is the measurements.

In order to assess the impact of load control on the system, the information from the first step is used. The opportunities obtained in that step were used to decide which technologies and methods were appropriate to achieve load management. In the assessment of this step, the load model with production correlation may be developed. The actual plant production data was then employed to determine the load management decision via simulation. The input to the model was the measured data. This can generate the simulation of control of load shape which is compared

with the actual system. The end- use control strategies were thoroughly tested before any control took place. Then the control technology can take place, before and after the control/ load shape is analysed to get the indication of saving benefit (for the specific technology).

#### 9.4.1 Use of Energy Efficient Techniques in Energy Management Strategies

The use of energy efficient techniques, equipment and process in industry has been recognized for its greater support to energy management. The technique has been used in DSM to achieve strategic conservation. The strategic conservation will be achieved only if the strategic energy management is developed and implemented.

Energy efficiency is the cost-effective utilization of energy which is achieved by the use of efficient process and equipment. Figure 9.8, shows an example of different efficiency level in a single process. The efficiency of each part in the process has an impact to the output of the specific equipment, and consequently to the output of the section which is proportional to the energy consumption. Hence the strategy should be implemented for achieving continuous energy management in the system.

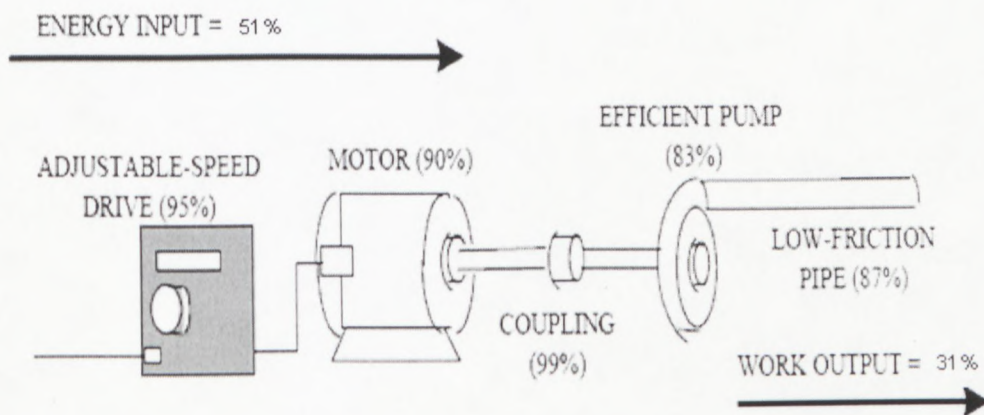


Figure 9.8: Plant Process with Efficiency

#### 9.5 Enhancing Energy Management Strategies

The electrical energy management techniques, methods and strategies presented in previous chapters and sections should be enhanced so as to make industrial energy management process a normal and continuous industrial activity.

Through the survey made in three cement industries, among the asked questions were; if the industries have an energy manager, the answer from all the industries was, there is no energy manager in any of the industry. All electrical matters were

managed in the engineering section (electrical department) and the thermal energy concern was handled by the mechanical department in the same section. This thesis focuses only on electrical energy management strategies and the responsible persons are known as technical personnel.

During industrial visits, apart from analysing the electrical loads behaviour given in Chapter 3, 4, 5 and 7, a number of questions were asked and the responses support the enhancement of EM strategies. The targeted group to the questionnaire was the technical personnel in charges of the industry. The number of questions was 18 as listed below. In questionnaire form, some questions have been expanded depending on the detailed information needed.

These investigative questions were based on load management strategies (step 1 to step 4). All three industries responded appropriately and each in charge represented the view of their industry. Most of the asked questions were trying to answer the research question which says "Does the use of electrical energy management techniques, tools and strategies in industries capable of minimizing electrical energy consumption and reduce the level of electricity demand in the industry?" The arrangement of the main questions is shown below and the summary of the response is given in Appendix 9.2.

- 1) Do you have an energy management program in your industry?
- 2) How flexible tariff structure is your utility system presents for load management
- 3) Are you aware about energy auditing?
- 4) How often energy auditing are performed?
- 5) Do you know the characteristics of your load?
- 6) How are you handling energy issues in your industry?
- 7) How are technical personnel involved in EM
- 8) How are you measuring efficient consumption of energy in your industry?
- 9) Do you have any energy consumption benchmark?
- 10) Which types of energy and demand management are implemented in your industry at the moment?
- 11) What is the potential saving?
- 12) Are there any energy saving opportunities you find in your industry?
- 13) What kind of barrier have you encountered for introducing and implementing EM
- 14) Are the top managers in support of the LM idea?
- 15) What is the internal and external factors affecting LM
- 16) Are all workers involved in the existing energy management strategy?
- 17) How do you value EM program in your company
- 18) Does your industry have any energy management policy?

### 9.5.1 Summary of the Survey Results

The arranged structure to respond to the questions was categorized into three groups. The first one is that, the responses are in form of ranking. The rank is between 0-4, that is 0- unknown or not applicable (NA), 1- poor, 2- satisfactory, 3- good and 4 is very good. The second group responses were yes or no and any of the responses can have explanations. The third is typical explanation. In this study the visited industry is presented as Ind.1, Ind.2 and Ind.3, where the response on the question above is given in Appendix 9.2. The summary and analysis of Appendix 9.2 are presented as:

There is no flexible tariff structure in all three industries. The meter reading method is manual, due to human error, the energy bills of all industries were found to have discrepancies either in recording or in billing itself.

Energy auditing seems to be known in all industries but 75 percent of the industries have not considered them as an initial stage for energy saving. The remaining percent have not stated the motivation of performing it. The electric motors and lighting have been mentioned to dominate the total industrial load of the industries.

In the case of who is in charge for energy management, all industries do not have energy managers and all matters regarding electrical energy are handled by the electrical department, in the engineering section.

Twenty five percent of the industries were shown to have been practicing EM in their industry and the involvement of technical personnel was good. The EM awareness was shown to have a satisfactory rank for the most of industries. The remaining percentage of industries has never attempted to practice EM but technical staff are aware of EM theory. This means that, many none technical staff are not aware or participating in energy management.

Energy benchmarking has been used in many industries worldwide. In this case study, 75 percent of the industries have set their value as indicated in appendix 9.2. 25 percent of industries did not provide a clear picture of the value. The given indicator mostly seems not to meet the target; hence special effort is needed to empower this area.

The barriers affecting industrial EM were mentioned as financial, lack of knowledge and technologies. The possibilities to overcome the barriers have been given 50 percent of the total rating. The contribution of EM technology has been rated between poor and satisfactory (refer Figure 9.9), because most of the industries do not implement any method.

It has been observed that, the top management of all industries have a positive thought on EM and they are likely to support it, but tariff, manpower, technology, peoples' perception and funds are the factors mentioned that would affect LM. Finally the survey showed that, none of the industries have an energy policy. Therefore, in order to enhance the developed EM strategies, observations from this survey result have to be overcome. The emphasis for the enhancement of energy management is given in the following section.

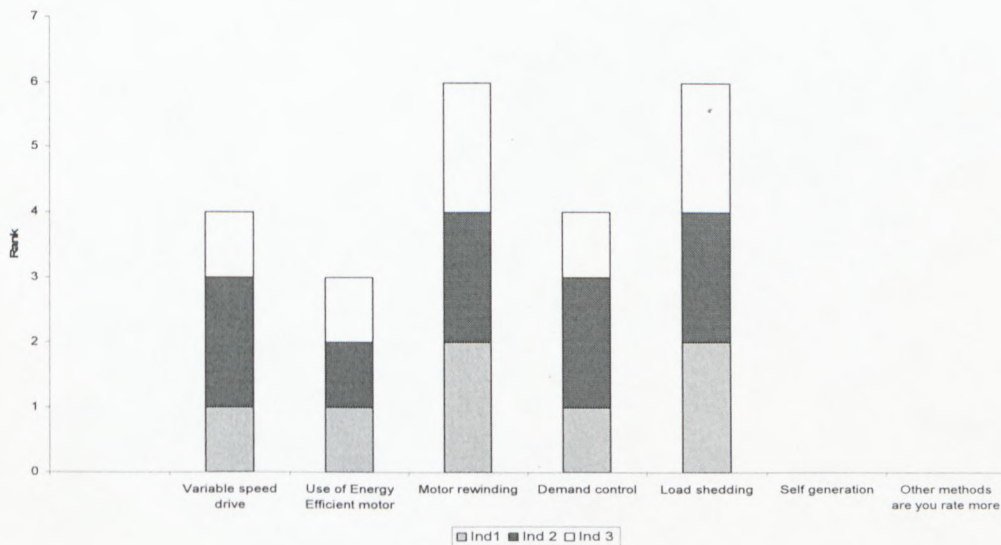


Fig 9.9: Evaluation of the Use of Energy Management Technology (in rank)

### 9.5.2 Establishment of Energy Auditing and Accounting

Energy Audit is the key to a systematic approach for decision-making in the area of energy management. Energy audit must be made mandatory to identify areas of waste and identify all the energy streams in a facility, and quantify energy usage according to discrete functions. Energy audit is verification, monitoring and analysis of the use of energy including submission of a technical report containing recommendations for improving energy efficiency with cost benefit analysis and an action plan to reduce energy consumption.

In general, energy audit is the translation of conservation ideas into realities. It provides a way to determine benchmark and the basis for planning a more effective use of energy throughout the organization. This information is frequently used to evaluate the customer's energy-savings opportunities due to changes in tariff structure, technology or equipment usage. It may also help gather information on consumer behaviour.

### 9.5.3 Energy Monitoring and Control

This is a powerful management technique for load management. It involves the analysis of the historical energy performance of the industrial facility, setting energy reduction target, controlling current energy performance and projecting future energy consumption and budget

It has been proven that, an active energy monitoring and control can save about 15% as a direct consequence of effective performance monitoring and creating management information needed to identify and implement energy efficiency measures (Barner et al., 2005). It further provides a framework for savings verification when measures are implemented. Monitoring, targeting and reporting (MT&R) are normally built by a statistical technique which is known as Cumulative Sum of differences (CUSUM). It is the analysis of the variance between energy consumption predicted by an energy performance model and the actual measured consumption.

The CUSUM analysis of the Mbeya cement plant of the case study is given in Figure 9.10. The function derived from CUSUM analysis are the target setting methodology which can be used in the development of energy benchmarking and the application of energy control charts for real time management performance. This chart was developed using plant data, which is the monthly energy consumption and production.

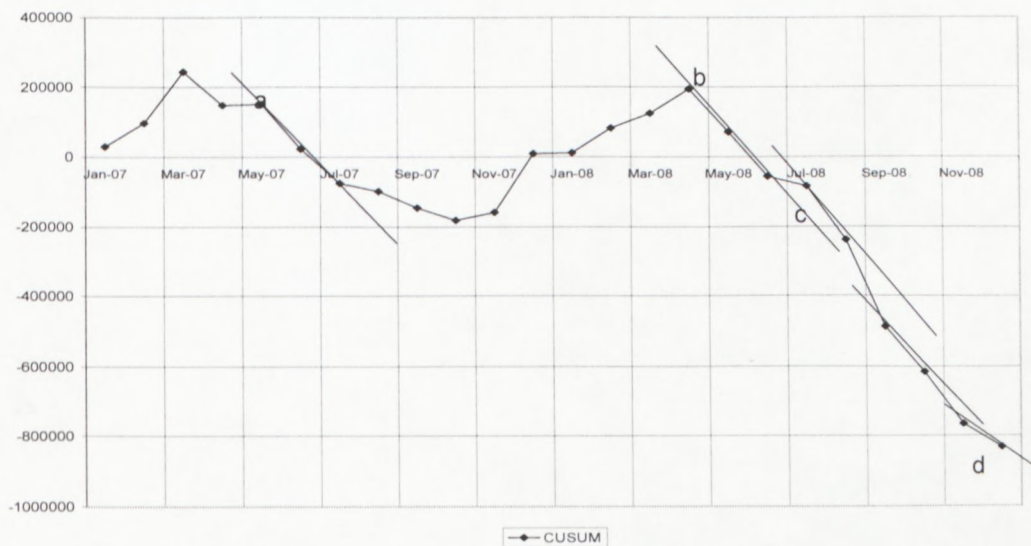


Figure 9.10: CUSUM analysis of the cement plant

The key function of energy monitoring, targeting and reporting process are to:

- Measure the energy consumption of the industry over the time
- Measure independent variable that influence energy consumption over the corresponding time interval
- Develop a relationship between energy and the independent variables
- Analyse historical energy use by CUSUM trend into the future
- Define and set the reduction targets
- Make frequent comparison of actual consumption and targets

Analysis of this curve shows that, there is a saving possibilities in some months as indicated in line a, b, c and d. This process allows the responsible person to take action if the target is not met. As the most monthly target indication of the case study industry has not been met, it is high time for industries to analyse their consumption by this way so as to find the gap and correct its implementation of this strategy and it will enhance primary energy saving. Some of these benefits are improved budgeting and forecasting, improved product or service costing, track verification of energy efficiency retrofits and opportunity for improving operational maintenance practice.

As a general rule, monitoring comes before the target setting so as to identify the starting point and identifies if the target has been achieved. MT& R with other continuous improvement techniques applied in organization should be an ongoing cyclical process as shown in Figure 9.11 and the general energy management process is given in Figure 9.12

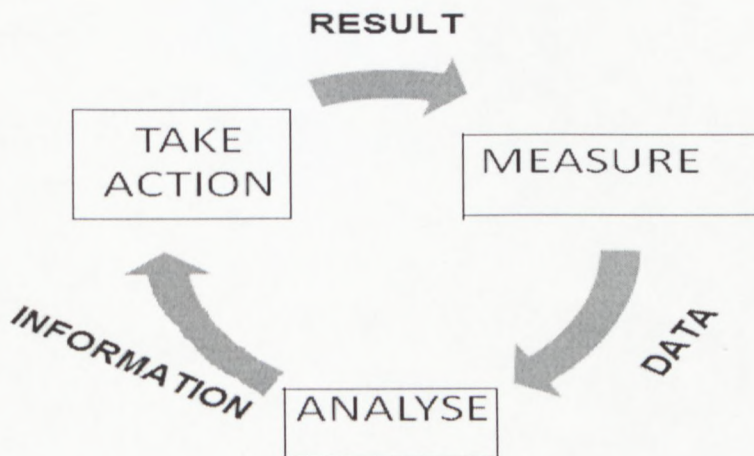
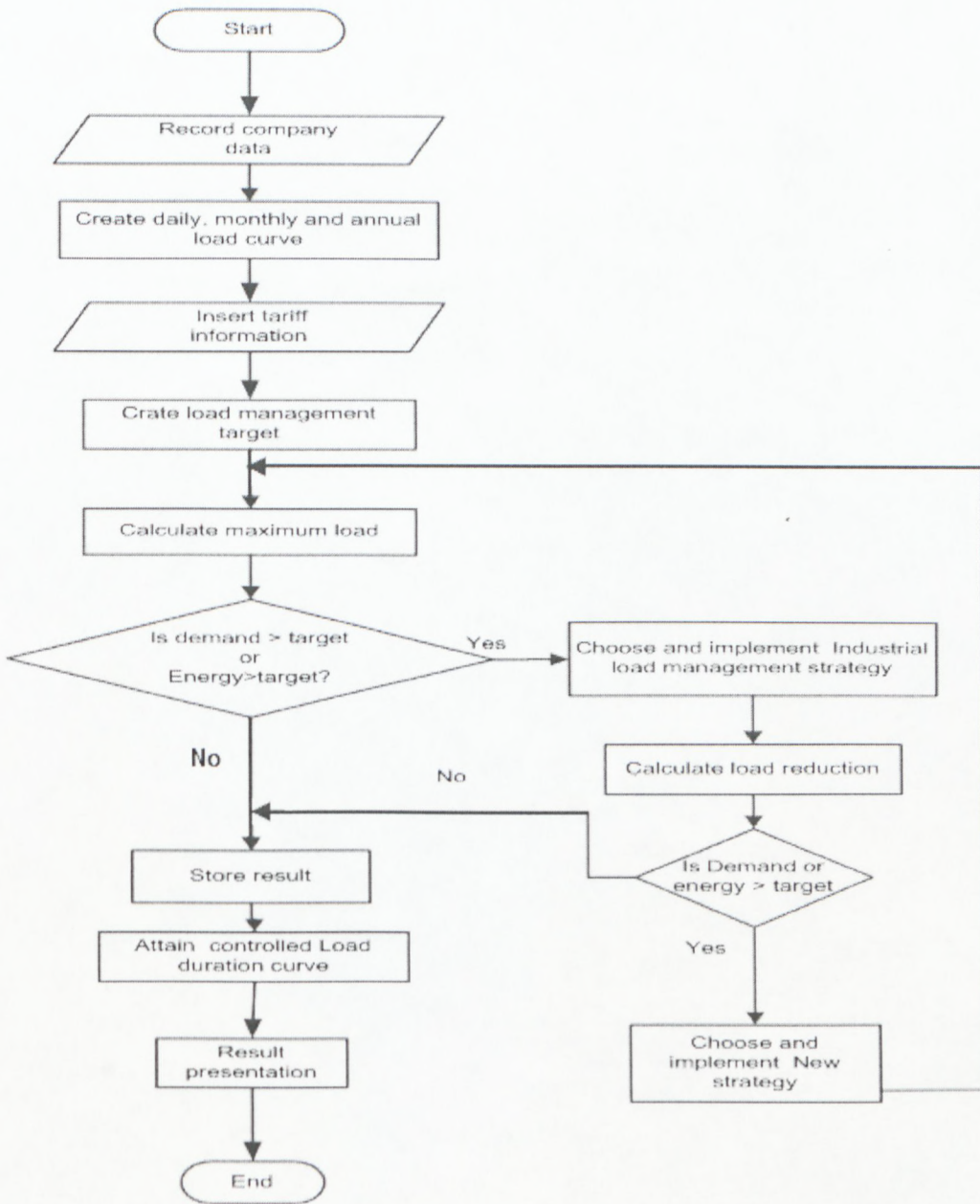


Figure 9.11: Cyclic Action of Energy Monitoring



**Figure 9.12:** The Overall Energy Management

The proposed algorithm for load management strategies in the plant considering various energy management techniques as depicted in previous chapters. Figure 9.13 shows the strategies for strategic electrical energy and demand management.

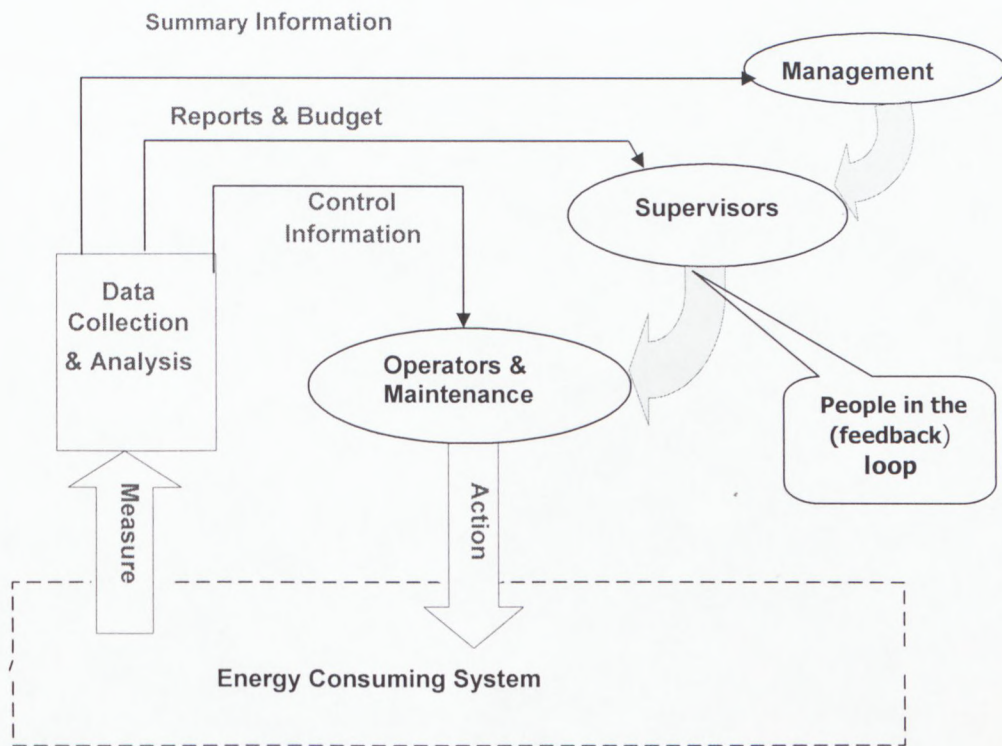


Figure 9.13: Strategies For Electrical and Demand Management

## 9.6 Proposed Strategic Energy / Demand Management

In this section, strategic energy management is proposed so as to accomplish and enhance EM which comprises of:

**9.6.1 Appointment of the Top Management Committee and Assignment of Energy Manager;** the top management is the most important for the success of energy conservation activities within companies or factories. The top management is required so as to provide a clear and official commitment either at the corporate top (senior) management or factory levels. The top (senior) management shall announce explicit commitment to the energy management and behave along this line, for example, by participating in Energy Conservation (EC) events and encourage the people for EC promotion.

They should also understand the issues including

- a) Grasping the current energy use
- b) Identifying management strength and weakness
- c) Anticipated barriers to implement
- d) Estimating the future trend

### 9.6.1.1 Planning and Organizing

- a) Developing policy statements
- b) Setting targets

- c) Making out a plan/program
- d) Implementation; the actual records of implementation should be closely monitored. If some problems arise, or some variance between the planned figures and the actual record is observed, the necessary actions should be taken immediately
- e) Management review
- f) Standardization and dissemination

Figure 9.14 shows the flow chart of strategic energy management

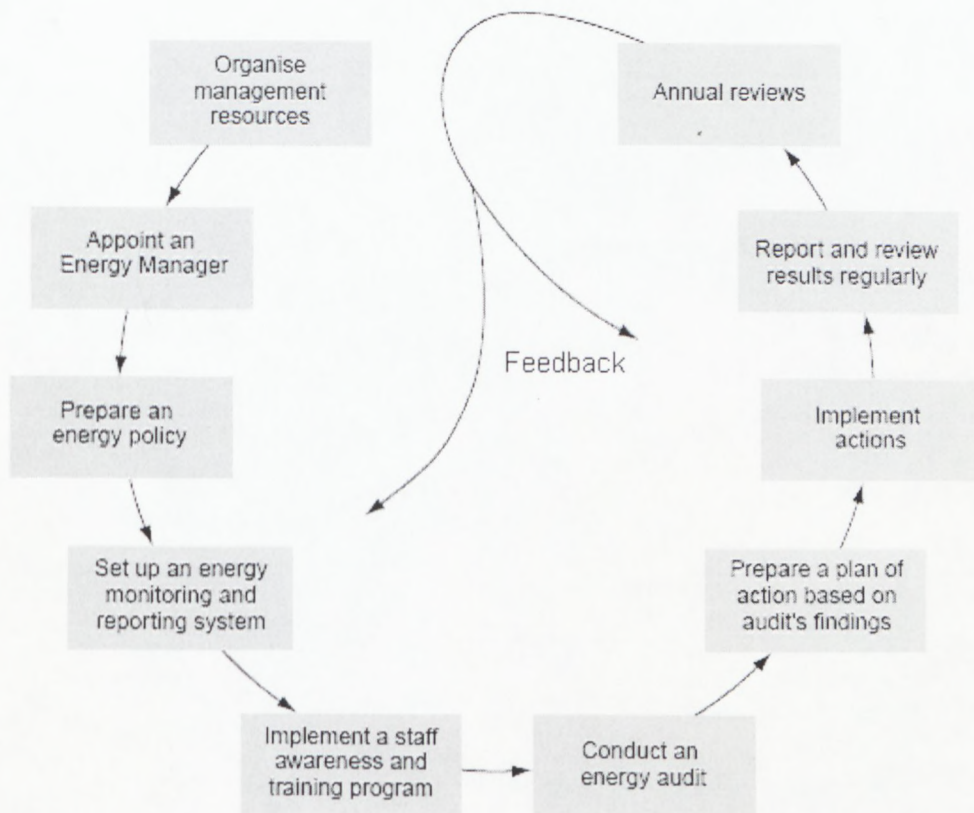


Figure 9.14: Flow Chart of Strategic Energy Management

## 9.6.2 Policy and Planning

### 9.6.2.1 Planning

Good planning is a basis and starting point for enhancing energy management strategies. It encompasses a setting up of strategic goals, focusing on action plans (starts by developing an energy policy), setting objectives and targets, preparing detailed action plans and allocating management resources.

### **9.6.2.2 Developing an Energy Policy**

To develop an energy policy, the top management shall convey their commitment clearly to others and the expected performance standards shall be set out. The effective energy policy may be of long term or medium term goals. The attributes of a successful energy policy include:

- Commitment; regular policy review.
- Thrust; a new and challenging dimension to energy and environment.
- Applicability.
- Implementation; guidance on how the policy objectives are to be met.
- Review; how an organization knows that the goals have been achieved.

### **9.6.3 Building Awareness and Motivation to Employees**

Energy managers have to find out how to motivate their employees so as to participate in energy conservation. He /she should also build moral encouragement to the staff by involving them in each stage of the energy management process.

### **9.6.4 Co-coordinating Load Management for Maximum Benefit**

Load management serves the efficient use of investments related to production and distribution of electricity. It has many benefits to the producers and distributors as well as customers. The focus of the action taken and the reasons for load management are somewhat different among the participants. However, through co-coordinated load management, unnecessary power production plants will be avoided.

The development of the strategies was based on drawbacks observed in the response of technical personnel through the questionnaire form (Appendix 9.2). The implementation of the proposed energy management techniques and strategies will highly contribute to sustainable energy management. This has answered research question 3 of this thesis.

## **9.7 Conclusion**

Strategies for electrical energy management in industries have been presented in this chapter. The need for the strategic energy management is important as it allows the sustainable energy management in industries and it leads to money saving and reliability of power supply on the demand and supply side respectively.

The techniques for accomplishing LM have been analysed and presented in this study. LM can be implemented on a daily, seasonal or periodical basis. If sustainable load management is required, a set of strategies has to be considered and put into

practice. The development of strategic energy management allows all involved parties to participate in LM. The general load management strategies involve planning and the implementation of the measures that can lead to energy and demand management.

The planning part involves the issue of assigning the managers and the tasks. However, this alone can not be much significant if LM actions are not implemented.

In this study, the load management techniques considered includes flexible power factor correction and energy efficient techniques. The load shedding is also imposed because it is the best method to easily and cheaply achieving demand control. The study showed that, there is a possibility of switching/altering the section or part of load for predetermined periods. This has been made possible by incorporating storage systems in the plant. The maintenance activities should be taken during the scheduling period.

The algorithm for each of the load management method has been developed to provide a specific step to perform the action. Energy accounting, monitoring and auditing has to be involved in initial steps of EM to identify the stream of energy waste. Finally, the chapter presents strategies that should be followed or implemented to achieve continuous and sustainable energy management in cement industries.

## **CHAPTER TEN: The Role of Electrical Energy Management in Mitigating Social, Economical and Environmental Impacts.**

### **10.1 Introduction**

During the last decades the electrical energy consumption in SSA industrial sector has been rapidly increasing and energy consumption behaviour of all sectors have been varying to a greater extent due to the increase in human activities. The increase of energy consumption has a direct relation to the electricity generation. The predominant method for electricity generation in SSA regions is by burning fossil fuel. The process of burning fuel has adverse effects including environmental, social and economical impacts. It has been realized that, the increase in industrial energy consumption has lead to the growth of environmental impact including global warming.

In SSA countries, cement industries are among the energy intensive industries. Reduction of energy consumption in these industries shall reduce burning fuel hence minimize environmental impact.

This chapter presents the role of electrical energy management on mitigating negative energy related impacts. It analyzes the different methods of electricity generation and related impacts on environmental, social and economic fields in SSA. It analyzes the process of electricity transmission and consumption and their related impacts. It also assesses and highlights the impacts of mostly used demand side electrical energy management techniques in social, economic and environmental aspects.

Finally, it has been observed that, the whole process of electricity production; from generation to the final user has in one way or the other energy related impacts. The only way by which this impact can be limited is by the institutionalization of an energy management program to the big users of electricity such as cement industries.

### **10.2 Environmental Effects of Electricity Generation and Consumption**

Worldwide, electricity demand is projected to grow at 2.7 percent per year between 2003 and 2030 (Myer, 2007). Most of the electricity is generated by the principle of energy conversion, the process through which, energy is converted from one form to electricity. This process has environmental as well as social and economic impacts because the predominant methods used for generation of electricity are by burning

fossil fuels. For the last decades the electrical energy consumption in SSA industrial sector has been increasing. This increase has a direct relation to the electricity generation and subsequently economic, social and environmental impact.

### **10.2.1 Electricity Production by Fuel Types**

Most commercialized electricity generation in SSA countries is generated by fossil fuels and hydro resources and few are generated by renewable energy (solar, wind, geothermal and biomass).

In the generation process; most of the fuels used to generate electricity in one way or another have environment impacts. Fossil fuel power plants release air pollutants, require large amounts of cooling water and can mar large tracts of land during the mining process of the fuel resources. Nuclear power plants are generating and accumulating copious quantities of radioactive waste that currently lack any reliable repository whereas renewable energy production has affected wildlife such as fish, birds and agricultural processes.

Electricity production is achieved by converting energy from one form to electricity. The process used is either a direct conversion process, where the energy source is converted directly to electricity or indirectly. An example of direct method is solar photovoltaic cells, which converts the energy found in solar radiation directly to electricity. In indirect methods, the energy source is first converted to an intermediate form before being converted to electricity. A Coal-fired generating plant is an example of the indirect process. In the process of generation, chemical energy is released as heat to burn the coal and then changed to rotating kinetic energy by the steam turbine and then the rotating kinetic energy is converted to electricity.

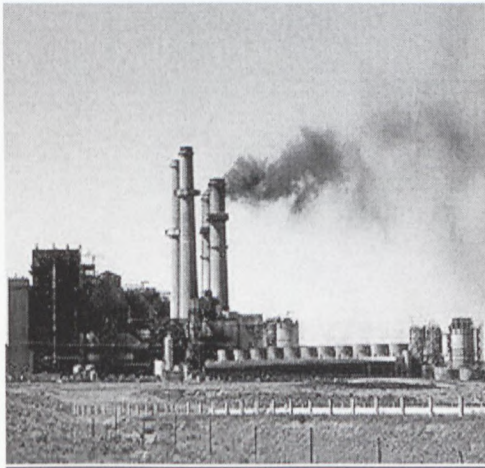
Most of the electricity generated world wide use indirect energy conversion processes through the use of thermo energy resources. In SSA, 66.6% of electricity generated is from coal.

#### **10.2.1.1 Fossil Fuels**

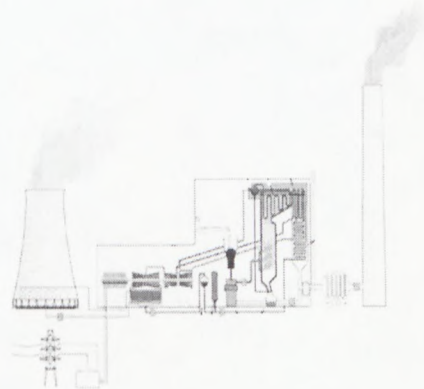
Fossil fuels used for generation of electricity include coal, oil and natural gas. As mentioned, the energy conversion process involves inefficient processes in each conversion stage of the system. For example, a Fossil fuel power plants efficiency is about 40%. Appendix 5.1 shows the most sources of the electricity consumed in SSA that is by burning fossil fuels.

The power production sector is among the industrial sectors that have a large contribution to emission. Combustion of fossil fuels produces carbon monoxide, carbon dioxide, sulfur dioxide ( $\text{SO}_2$ ) and nitrous oxides ( $\text{NO}_x$ ) gases. These greenhouse gases contribute to acid rain, smog and the formation of particulate matter which leads to global warming. It also disperses the fly ash, which is harmful to human health.

Figure 10.1 shows a simplified layout of a coal fired power plant. When considering the environmental impact caused by the industrial use of energy the whole cycle of electricity generation, including energy resource, transportation and consumption must be considered. This should include the production and transportation of fuel because fossil fuel and nuclear power plant use large quantities of fuel taken from the earth which have big impacts in water reservoir and land use.



(a) Oil-Fired Power Plant



(b) Coal-Fired Power Plant

Figure 10.1: Layout of Simplified Power Plants

### 10.2.1.2 Nuclear Energy

Nuclear energy like fossil fuels is a finite, non-renewable, energy source that uses an indirect conversion process to produce electricity. The two basic forms of nuclear energy commonly used are:

- 10.2.1.2.1 **Fusion**; the fusion reaction is a nuclear reaction in which nuclei combine to form more massive nuclei with the simultaneous release of energy.
- 10.2.1.2.2 **Fission**; the fission reaction is a nuclear reaction in which a heavy nucleus (such as uranium) splits into two lighter nuclei.

The fission reaction is the most widely used process for the nuclear generation of electricity. The heat output from the reaction, flows in a steam turbine, which drives a rotating electric generator.

Nuclear fission produces much greater energy content than fossil fuels. Uranium contains an energy content of approximately  $10^{10}$  Btu/kg, which is about one million times the energy content of fossil fuels. Africa generates only 0.4% of the electricity generated by the nuclei technology world wide. This amounts to 2% of the total electricity generated in Africa (Charles & Elias, 1999). Nuclear plants do not release any of the traditional power generation air pollutants as in the case of fossil fuel. Nevertheless, all stages of uranium fuel procurement process and handling can cause environmental impacts.

Uranium mining cause toxic contamination to the local land and water resources. Radioactive contamination is also hazardous to mine workers and the nearby populations. Abandoned mines contaminated with high-level radioactive waste can continue to pose radioactive risks which are harmful to humans and other living things for a long time (Litowitz & Brown, 2007).

In addition, during electricity generation, radioactive wastes are produced. This needs adequate storage and segregated to minimize the risk of radioactive release. The amount of solid wastes generated at nuclear plants pose health risks that exceed that of any other source of electricity. The issue of plant failures can lead to the release of radioactive steam into the atmosphere. In the worst scenarios it can lead to the release of more radioactive rays which is even more harmful to humans and the surrounding area. Also, most nuclear plants rely on water for their cooling systems. They require two and half times as much water as fossil fuel plants.

### **10.2.1.3 Solar Radiation**

Solar energy is defined as that radiant energy transmitted by the sun and intercepted by Earth. It is transmitted through space to earth by electromagnetic radiation with wavelengths ranging between 0.20 and 15  $\mu\text{m}$ . The availability of solar flux for terrestrial applications varies with season, time of day, location and collecting surface orientation. Solar radiation is a renewable energy source. Direct use of solar power includes:

- Active types involving photovoltaic cells, and
- Passive types using radiation to heat solar collectors.

The Photovoltaic cells (PV) directly convert sunlight into electricity. It is environmentally attractive because photovoltaic is emission-less, with minimal wasteful by-product, and an extraction-less energy conversion process. In addition, photovoltaic solar cells generate direct current, hence requiring inverting equipment to obtain the desired alternating current for most large-scale application. It can operate as a standalone system. When constructed for grid-interconnection systems, they require a significant land, which can impinge on the existing ecosystems. Nevertheless, most PV installations come in the form of distributed systems that use little or no land since the panels are installed on buildings.

Solar-thermal technologies generate zero air emissions. At present, several factors limit large-scale utilization of solar energy such as cost of solar cells, inverters and solar collector-heat exchanger systems and the requirement of an adequate energy storage system to smooth out the daily variation.

#### **10.2.1.4 Wind Energy**

Wind power is the world's fastest growing electricity generation technology. State-of-the-art of the wind power plants use large spinning blades to capture the kinetic energy in moving wind, which is then transferred to rotors that produce electricity. At the best wind fuel sites, state-of-the art wind plants today are nearly competitive with the conventional natural gas-fired combined-cycle plants. Regions where average wind speeds exceed 12 miles per hour are currently the best wind power plant sites.

Like other power-producing technologies, wind turbines are measured on their ability to provide low cost of electricity (COE) and high project net present value (NPV). Current costs of wind-generated electricity at prime sites approach the costs of a new coal-fired power plant. Wind power is the lowest-cost renewable energy technology available on the market today. Wind plants do not produce air pollution but it generates three types of environmental impacts, namely, visual; noise and wildlife:

- Wind farms occupy large natural landscape and comprise large numbers of turbines; each mounted at top tall towers in farm areas. These tall towers can often be seen from a long distance, hence develops visual impact.
- Wind turbines, particularly older designs, emit noise that can be heard in the vicinity of the wind farms.
- The most controversial significant negative environmental impact of early wind turbines is the impact on bird populations.

### 10.2.1.5 Hydropower

In hydropower plants, the potential energy of a mass of water in a reservoir is converted to kinetic energy by flowing through a hydraulic turbine. The resulting kinetic energy of the turbine drives an electric generator. Hydropower facilities intercept the water on its downward path and convert its mechanical energy into electricity.

Therefore, hydropower is obtained by conversion of falling water to useful work which run electric generator. Cassedy & Grossman, (2000) presented the principle of electromagnetic induction as the common principle used for the generation of electricity by using hydro power resource. Hydropower is a non-polluting renewable resource. However, the construction and exploitation of hydropower dams have an impact on natural river and the eco-systems.

The dams and powerhouse operations are the main cause of the primary environmental impacts. The changes in river conditions, the land and vegetation bordering the water bodies caused by dams and powerhouse turbines may impact fish populations and other wildlife significantly. By diverting water out of the river to the power generation, dams reduce water needed for the healthy in-stream ecosystems by disrupting the natural river flows; stretches below dams may completely be de-watered. By withholding and then releasing water to generate power during peak demand periods, dams may cause downstream stretches to alternate between no water and powerful surges that erode soil and vegetation and flood or strand wildlife. Hydropower may alter river and riverside habitat due to construction of dam that can flood riverside lands, destroying riparian and upland habitats.

### 10.2.1.6 Tidal Energy

Tidal energy uses the tidal flow of oceans to run a hydropower plant to produce electricity. In its construction, it is basically consists of a dam encloses a tidal pool. The tidal pool fills during periods of high tide and then empties during periods of low tide. The water flow into and out of the pool drives a reversible hydraulic turbine. Since the turbine is reversible, the flow of water into and out of the bay produces electricity. The major environmental concern associated with tidal energy is its disturbance to the surrounding ecological environment.

### 10.2.1.7 Geothermal

The heat from the earth's own molten core is converted to electricity. This resource is in the form of steam which can generate electricity and provide heat for thermal applications such as in industrial applications. Geothermal energy is a renewable energy source which has been harnessed as an energy source since the dawn of civilization, when natural hot springs were first used for cooking and bathing. At present, about 4 GWe of geothermal energy used for power generation and above 12 GW for thermal application.

Since the use of the geothermal energy involves interaction with a geologic system, the characteristics and quality of the resource involves some natural variability but, more importantly, the utilization of the geothermal resource can be affected profoundly by the way in which the resource is tapped (Myer, 2007). A variety of technologies are currently used to convert geothermal energy to useful forms. This is grouped into three basic categories: direct use, electric power generation and geothermal heat pumps. Each category utilizes the geothermal resource in a very different way.

Environmental impacts associated with geothermal energy conversion are generally modest and low compared with other alternatives; energy production is generally very reliable and available day and night. In addition, geothermal energy is not affected by weather. It takes little space and can be made unobtrusive even in areas of high scenic value, where many geothermal resources are located. The disposal of water and wastewater may cause significant pollution of surface waters and ground water supplies.

### 10.2.1.8 Natural Gas

Natural gas is the generic term used for the mixture of vapours that result from the decomposition of plant and animal materials over millions of years. The primary component of natural gas is methane, and hydrocarbon. Natural gas is the cleanest of all the fossil fuels. The stock of natural gas, like other fossil-based fuels is limited and is therefore not a renewable resource.

Natural gas can be used as a fuel in conventional steam boiler generators, like other fossil fuels. When the natural gas is burned, it creates superheated gas, which is then pressurized in pipes and used to drive the turbine. The combined cycle technology, which is basically the coupling of two electric generation technologies, boosts efficiency by using the same fuel to generate electricity.

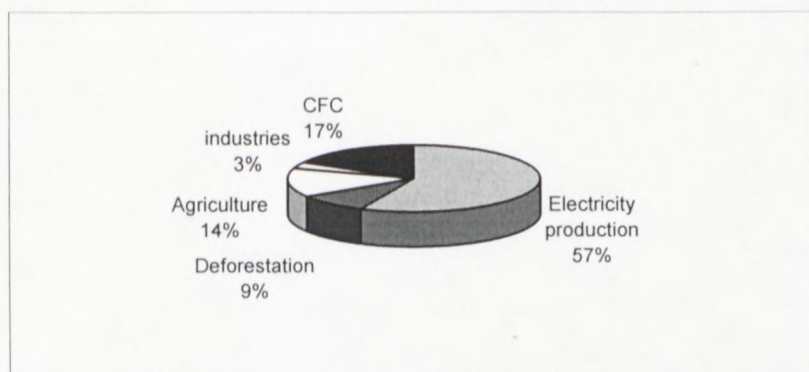
Natural gas creates significantly smaller environmental impacts than coal. On a Btu basis, natural gas combustion generates about half carbon dioxide as coal, less particulate matter and very little sulphur dioxide or toxic air emissions. Natural gas combustion may, however, produce nitrogen oxides and carbon monoxide in small quantities comparable to coal burning.

Natural gas drilling and exploration has impact wilderness habitat, wildlife and public open space. The potential negative land impacts associated with natural gas are erosion, loss of soil productivity, increased run-offs, landslides and flooding. Depending on the combustion technology and plant design, operations of gas plant may result on consumption of large water resources. For example, combustion turbines do not use significant quantities of water while combined cycle power plants use significant.

From the electricity generation resources it is seen that, all fossil fuel energy conversion methods used to produce electricity have some environmental impact. The impact may have direct effect like the emission of airborne pollutants or may have indirect effect like aesthetics. Hence the main energy related environment problems include:

- Urban and rural air pollution caused by use of energy
- Indoor air pollution for primary renewable energy for cooking
- Acid rain from fossil fuel burning
- Ozone depletion from industrial use of energy
- Greenhouse gases and climate change from fossil fuel burning and
- Desertification and deforestation

These are caused by the growth and changing patterns of industrial use of energy and energy transportation. The overall contribution to the greenhouse effect of energy production and consumption world wide is given in Figure10. 2.



**Figure 10.2:** Contribution of GHG Emission  
**Source:** Lashaf & Tirpak, 2000

The level of greenhouse emission caused by electricity production and industries appears to be about 60%, hence the introduction of electrical energy management to both supply and demand side is of great importance.

## **10.2.2 Energy Production; Social and Economic Impact in SSA**

Countries in SSA mostly suffer from unsustainable electrical energy, though it has many energy resources for power generation (Sokona, nd). This situation will continue to increase following SSA growing population (See Appendix 10.1, SSA population). Therefore, it is necessary to use these resources efficiently, so as to reduce the social, economical and other impacts associated to power generation and consumption. In other world electricity production may cause health impacts due to inhalation of air containing raised levels of sulphates in combination with certain other emissions (Bui Duy and Thierry, 2000; International Atomic Energy Agency, 1999).

The followings are the social and economic impacts caused by power production. They are categorized based on the type of fossil fuels used for electricity generation. The problems related to power generation include:

### **10.2.2.1 Coal Fired Power Plants**

- Accidents associated with production of raw materials, construction of the power plant, transportation of coal to the power plant and operation of the power plant ,
- Illnesses and health hazards such as lung disease caused by inhalation of pollutants released during power production,
- Somatic and genetic effects attributable to radiological impacts of the coal fuel cycle.

### **10.2.2.2 Oil or Natural Gas Fired Power Plants**

- Accidents occurred during the production of materials for plant construction and during power plant construction and operation,
- Illnesses caused by inhalation of pollutants released during production of materials needed for plant construction and oil or gas field development,
- Effects of inhalation of pollutants from oil combustion released during power plant operation,
- Fires and explosions of stored oil.

### 10.2.2.3 Nuclear Power Plants

- Accidents arising from uranium mine construction and operation; during construction of the power plant, transportation of fuel and operation of the power plant,
- Somatic and genetic effects of exposure to radioactive waste during power plant operation (including maintenance and accidents), radioactive waste handling and disposal and fuel reprocessing and to airborne, water-borne and food-chain-borne radio nuclides from uranium mining, fuel processing, plant operation and waste management,
- Health impact and effects of inhalation of pollutants released during production of materials needed for power plant and uranium mine construction.

### 10.2.2.4 Hydropower Plants

- Effects of inhalation of pollutants released during construction of the plant and reservoir and health problems in coastal waters due to growth of vegetation, muddy water and mosquitoes,
- Changes of local or regional climate,
- Influence of reservoir on fishing and negative influence on neighbouring land.

### 10.2.2.5 Biomass Power Plants

Accidents and illnesses connected with fuel processing and handling, transportation, plant construction, plant operation and waste handling.

## 10.2.3 Energy Consumption and Economic Activities in SSA

The increase of industrialization, combined with the modernization of some activities and rise in per capita income, has led to the rapid increase in energy consumption. The per capita electricity consumption of SSA has increased by 8.2-9% per year (2003-2004). Despite the increase of per capita electricity, it is far below the world per capita (Africapedia, 2007).

### 10.2.3.1 Environmental Impacts of Industrial Operations

Energy consumption has a significant impact on our natural environment. Most of climate changes caused by human activities are related to the use of energy. There is a strong relationship between energy consumption and CO<sub>2</sub>/ NO<sub>x</sub> emissions. Substantial reduction in CO<sub>2</sub> emissions can be achieved by improving energy efficiency, refer Chapter 5.

The commitments made at the international conferences in Rio de Janeiro in 1992 and in Kyoto in 1997 reflect the political importance attached to environmental policy (Jean-Guy, 2000). This includes the concern of reinforcement of law in regards to emission trading. In this regard, the global concern over the level of environmental degradation has increased.

The biggest environmental impacts in industries come from the use of fossil fuel, which is converted to useful energy through a combustion process. Electricity production consumes one third of the world's primary energy. Trends show the possibility of increase because the world energy strategy is towards increasing the accessibility of electrical energy considering that a large number of people worldwide do not have access to the electricity in general and especially in Sub-Saharan Africa. The number of population without electricity in SSA countries is shown in Appendix 1.2 and the carbon dioxide emission released is given in Appendix 10.2.

Industrial activities contribute indirectly to the damage caused by acid deposition of sulfate and nitrates. Furthermore, industries are the main source of highly toxic heavy metals emitted as particulates. Industrial operations also contribute to the destruction of the stratospheric ozone layer. Hence introduction of energy management in this sector will reduce the environmental impact.

Table 10.1 shows the percentage contribution of emission caused by the industrial use of energy including power generation. It has been realized that, in order to create 1GJ (277.8kWh) of electricity, the average primary energy of fossil fuels required is 2.57GJ (efficiency of the process is 38.9%). This production consumes 9.01 Kg of fuel oil, 6.92m<sup>3</sup> of natural gas, 0.13 Kg of coal and 34.64Kg of brown coal (Zoran & Dusan, 2006). The emission for such electricity generation is 0.1Kg of SO<sub>2</sub>, 116.71Kg of CO<sub>2</sub> and 0.16Kg of NO<sub>2</sub>.

Increasing energy efficiency is a direct way of increasing sustainability of the use of energy resources and decreasing environmental pollution. In an attempt to reduce the environmental impact many energy and environmental policies and conventions have been developed world wide, include:

- Integrated pollution prevention and control (IPPL)
- Energy market deregulation and linearization
- Consumer's choice in the liberalized energy market
- Emission trading
- Compulsory energy efficient programs

Environmental problems are the symptoms of inefficient use of energy. This implies wastage of resources. Energy management is the first logical step to introduce systematic environmental management.

**Table 10.1:** Percentage Value of Emission for Different Plants

Source category	Contribution to total emission (%)						
	SO <sub>2</sub>	NO <sub>x</sub>	CH <sub>4</sub>	CO	CO <sub>2</sub>	N <sub>2</sub> O	NH <sub>3</sub>
Combustion plants over 300MW	85.6	81.4	5.5	16.8	79.0	35.7	2.4
Combustion plants from 50-300MW	6.4	5.4	0.6	3.1	6.5	1.9	0.2
Combustion plants below 50MW	0.2	0.3	0.05	0.1	0.2	0.01	0
Gas turbine	0	0.39	0.06	0.05	0.35	0.02	0

### 10.2.3.2 The Relationship between Energy Consumption and Economic Growth in SSA

Energy consumption has a close relationship to the economic growth of the related country. The use of energy has a close relationship to the number of social indicators such as longevity, literacy and total fertility rate (Goldemberg, 1999). Human development index (HDI) is also designed to correlate some of the shortcoming of the use of per capital energy consumption and per capital income as a measure of development which is measured by GNP or GDP and is analysed by:

- Longevity; measured by life expectancy
- Knowledge; measured by the percentage of adult literacy
- Standard of living; measured by purchasing power

A plot of HDI as a function of energy consumption in various countries is given in Figure 10.3. The HDI in this curve rises sharply from 0.3 to 0.6 for the prospective countries. Most of these countries are poor whereby per capita GDP is between 714-1550 (2005). This means most of the SSA countries lie on that range of the energy life related index. There are some few countries whose HDI lie between 0.61 and 0.8. The correlation between HDI and electricity per capita consumption was observed by (Alan, 2000). Figure 10.4 shows the per capita electricity consumption of the SSA countries. The per capita electricity consumption seems to deviate among countries. Some countries have moderate per capita electricity consumption.

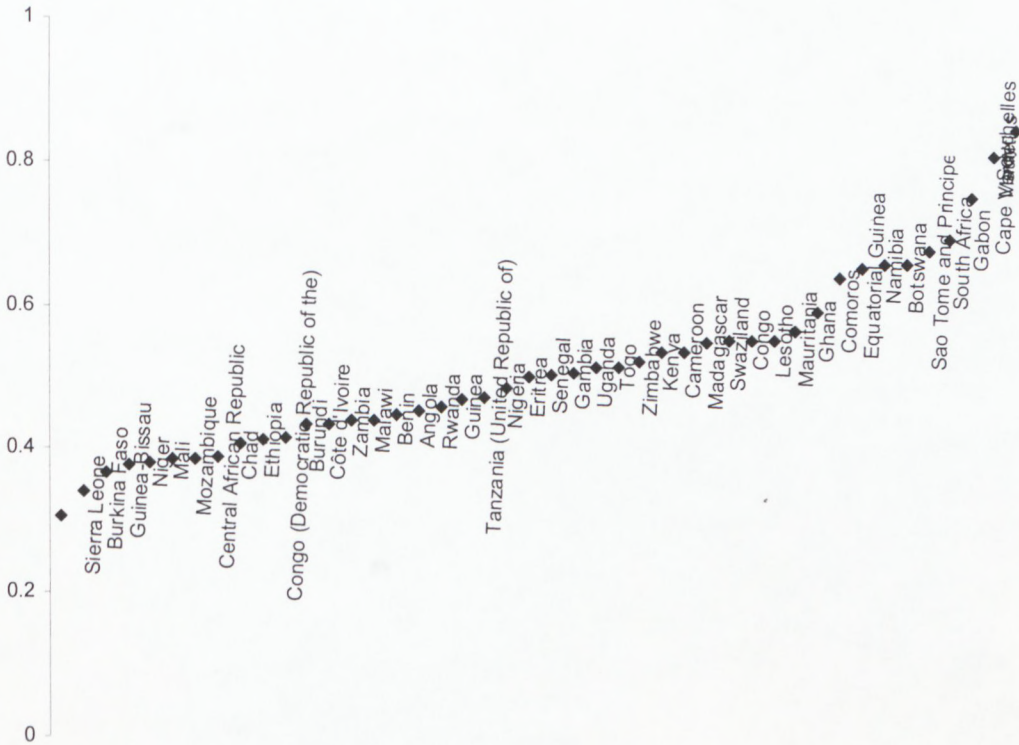


Figure 10.3: Human Development Index Vs SSA Country (2004 data)

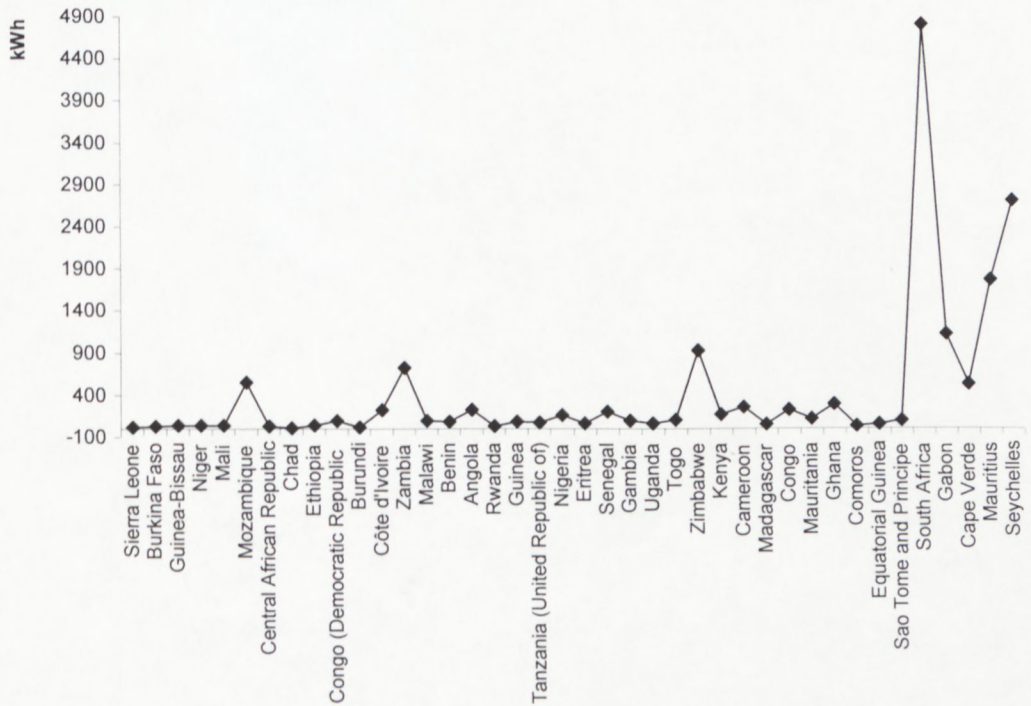


Figure 10.4: Per Capita Electricity Consumption for the SSA Countries

### 10.3 Environmental Impact Caused By Electricity Transmission and Distribution

Transmission and distribution of electric power is the process of transporting energy from the generation station to the distribution station and to the final user. Wires (transmission lines) are suspended on large towers for the transmission of electricity to the distribution station. This process involves energy losses associated with the length and diameter of the conductor as indicated in equation 10.1, as well as aging of equipment and the stability of the whole system.

$$R = \frac{\rho l}{a} \dots\dots\dots 10.1$$

Where  $\rho$  is the resistivity of the material,  $\mu\Omega\text{-cm}$   
L length of a conductor, cm  
a is a cross sectional area of wire,  $\text{cm}^2$

The loss in the line is proportional to the line resistance. The magnitude of the loss depends on the distance, diameter of wire and load which the transmission line carries at a particular time. This loss is relatively small in percentage but the sum of all system losses might be of considerable amount, if special reduction efforts have not been taken care of. This means that, the higher the losses, the greater the environmental impact.

Improvement of the existing technologies and application of new technologies, such as new conductors and high efficient transformers, high-voltage direct current (HVDC), Flexible AC Transmission System (FACTS), energy storage, improved communication system, and optimization helps reduce systems losses.

#### 10.3.1 Environmental Issues Associated with Transmission Lines

The following points describe the environmental and social impact caused by transmission lines:

**10.3.1.1 Aesthetic Impacts;** it include physical relationship of the viewer and the transmission line (distance and sight line), activity of the viewer (living in the area, driving through) and background or context of the transmission line.

**10.3.1.2 Agricultural Land;** transmission lines can affect farm operations and increase costs for the farm operator. Potential impacts depend on the transmission line design and the type of farming. Transmission lines can affect field operations, irrigation, aerial spraying, wind breaks and future land development. Pole placement in farm fields leads to compact soils and damage drain tiles.

**10.3.1.3 Electric and Magnetic Fields (EMF);** A common method used to reduce EMF is to bring the lines closer. This causes the fields created by each of the three conductors to interfere with each other and produce a reduced total magnetic field. EMF has potential impacts to implantable medical devices. These devices have been associated with problems arising from interference caused by EMF. This is called electromagnetic interference (EMI).

## **10.4 Energy Use and Global Climate Change**

### **10.4.1 Global Climate Change Definition**

The term global climate change usually refers to changes of the earth's climate brought by a wide array of human activities which cause a steady rise in a world-wide average temperature. This situation is somehow influenced by different methods of electricity generation.

There is a scientific evidence showing that human enterprises cause climate change by burning fossil fuels and releasing carbon that has previously been locked up in coal, oil and natural gas for millions of years. The carbon in these fossil fuels is transformed into carbon dioxide (CO<sub>2</sub>) which contributes to the greenhouse effect. Methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O) also contribute to global warming. The specific contributions of methane and nitrous oxide have been assessed respectively as 21 and 320 times that of CO<sub>2</sub> (Jean-Guy, 2000). These rates are referred to as the global warming potential. Although the warming potential of CO<sub>2</sub> is the lowest, its contribution remains predominant due to the size of the related emissions. The increase of emissions of CO<sub>2</sub> and other gases, (CH<sub>4</sub> and N<sub>2</sub>O) boost heat trapping processes in the atmosphere and gradually raising average world-wide temperatures.

The Intergovernmental Panel on Climate Change (IPCC), in the scientific advisory body, reported that, global temperatures projected to rise from 1.6 to 6.3 degrees Fahrenheit by the year 2100 if the world does not take immediate steps to reduce the emissions (David, nd).

Energy-related ventures account for a considerable percent of all greenhouse gas emissions linked to human activities. Therefore in order to reduce the amount of coal and oil burnt for production of electricity, the electrical energy management is of greater importance so as to provide opportunities of using electricity wisely and optimally so that the construction of new power plants can be deferred.

## 10.4.2 Effects of Global Climate Change

**10.4.2.1 Human Health Impacts;** Global warming poses a major threat to human health by increasing infectious diseases. Increasing temperatures nurture the spread of disease-carrying insects such as mosquitoes and rodents which in turn increase the spread of infectious diseases.

**10.4.2.2 Extreme Weather Impacts;** The ocean temperature shifts causes extreme weather impact such as El Nino and La Nina events.

**10.4.2.3 Coastal Zones and Small Island Flood;** As global temperatures rise, sea levels also rise. The sea water expands hence water previously bound to mountain and polar glaciers melt and flow into the world's seas. This raises a water table along coastlines.

**10.4.2.4 Forest Devastation;** Forest ecosystems evolve slowly in response to gradual natural climate cycles. The rapid pace of global climate change resulting from combustion of fossil fuels and other industrial and agricultural activities disrupts such gradual adjustments. Many tree species may be unable to survive at their present sites due to higher temperatures and drought.

**10.4.2.5 Agriculture;** Agriculture depends on rainfall, which has influence on how to manage crop production, the types of seeds planted and investments in irrigation systems. Changing weather patterns associated with changing global climate patterns pose major challenges for the farmers.

**10.4.2.6 Acid Rain;** The term acid rain is used to describe rain or snow that is unusually acidic. Rain and snow are naturally slightly acidic due to naturally occurring chemical reactions in the atmosphere. The burning of fossil fuels generates air pollution that scientists have determined as the major cause of acid rain.

SO<sub>2</sub> and NO<sub>x</sub> generated during the burning of fossil fuels combine with moisture in the atmosphere and are returned to the earth as acids. This process is known as deposition. It occurs when it rains or snows. It is linked to a range of negative impacts on the natural world as well as human environments. It also renders intense impacts on the health of forest ecosystems. Furthermore, Sulfur dioxide emissions content reduce visibility when they form sulfate particles in the atmosphere.

**10.4.2.7 Ozone Depletion;** Ozone depletion is one of the most critical concerns in the issue of globally sustainable development. Depleted ozone leads to increased ultraviolet radiation at the earth's surface, which may affect both aquatic and terrestrial environments, as well as human health.

## **10.5 Energy Efficiency Techniques**

Through improved energy efficiency technology, the economic growth and energy security of the countries as well as the region can be improved. The use of energy efficient techniques also reduces environmental impacts.

### **10.5.1 Lighting Systems**

The demands and preferences of people about lighting are strongly biased by economic, social and cultural factors. Although the use of energy efficient light, (for example CFL's) provide significant energy saving over incandescent lighting, many SSA countries have not set clear strategy for adopting this lighting fixture.

For a country like South Africa, CFL's are being promoted and used as part of its energy conservation program. Although energy efficient lighting has many advantages to the system, it also has disadvantages. These include harmonic generation and presence of mercury content in the lighting fixture. This raises the issue of disposal of the rejected light fittings.

#### **10.5.1.1 Impact of Large Number of Energy Efficient Lighting in Distribution System**

Compact fluorescent lights, like all discharge lights create harmonics on the supply system because of its control systems. These harmonic currents are injected into the distribution system. Most electrical systems were designed for linear voltage and current waveforms (nearly sinusoidal), thus excessive nonlinear loads can cause problems such as overheating conductors, transformer and capacitor failures as well as malfunction of electronic equipment. Nashandi and Atkinson, (2006) conducted a study on the impact of large number of CFL in distribution system whereby the result showed that the distortion level depends on the type of CFLs used and the distribution parameter. In order to minimize the influence of harmonics, the use of CFL with highly distorted current should be discouraged while those with low distorted current should be encouraged.

#### **10.5.1.2 Presence of Mercury in Energy Efficient Lighting and its Impacts**

Mercury (Hg) is an element found naturally in the environment. Mercury emissions in the air can come from both natural and man-made sources. Electricity use is the main source of mercury emissions. Coal-fired power plants are the largest man-made source because mercury that naturally exists in coal is released into the air when coal is burned (ENERGY STAR, 2008).

Although, the use of CFLs reduces power demand, which leads to reduction of mercury emissions generated from power plants, CFLs contain small amounts of mercury sealed within the glass tubing (Energy Star, 2008). Table 10.2 shows a 13-watt, 8,000- hour- lamp -life CFL (60-watt equivalent; incandescent light bulb), it saves 376 kWh from energy consumption over its lifetime, thus avoiding 4.6 mg of mercury. If the bulb goes to a landfill, overall emissions savings would drop to 4.0 mg.

**Table 10.2:** Mercury Emission from Electricity Use by Using Different Type of Lighting System

Light bulb type	Watts	Hours of use	kWh	National average mercury emission (mg/kWh)	Mercury from electricity use (mg)
CFL	13	8,000	104	0.012	1.2
Incandescent	60	8,000	480	0.012	5.8

**Source:** Energy Star, 2008

CFLs are the fragile accessories. When CFLs break the inner mercury can spread to the outer surface. To avoid the spread of mercury content, CFLs should be handled carefully so as to minimize incident of breakage; if it breaks, caution for handling the fragile parts and cleaning should be taken. The procedures for disposal and cleaning should be followed to avoid the risk of mercury contamination. The cleaning and disposal process are is given in (Energy Star, 2008)

The use of CFLs has considerable reduction of annual emission due to the minimization of electrical energy consumption. The estimates of reductions in emissions were calculated by multiplying emissions factors per kWh of electricity by the number of kWh of electricity produced by each generation facility.

### 10.5.2 Energy Efficient Motors

The motor driven system is important and it is the horse of industrial activities. It converts electrical energy to mechanical energy that is used to drive the connected loads. The amount of energy used depends on the type of motor, rating and the loads it drive. During its operation, it involves energy losses, thus it is important to understand the concept of energy efficiency in several dimensions including legal, environmental, social, economic, and financial; and technological (Sola et al., 2006).

Indirectly, the use of electric motors has impact on the social, economic and environmental aspects. Main social, economic and environmental impacts of motor result from high electricity consumption especially from low efficiency motors.

The higher electricity consumption indirectly leads to high electricity generation, which in turn results in air pollutants, particulate, ash, wastewater and heavy metals generation. The advantages achieved when implementing energy efficient motor include:

- Reduction of CO<sub>2</sub> equivalent emissions.
- Increasing productivity.
- Less maintenance due to improve motor design.
- Increased power factors,
- Improved lifetime of their bearings and windings.

## **10.6 Plant Power Factor: Environmental, Social and Economical Impact**

Power factor is the ratio of the active power over the apparent power. The advantages and methods of compensation are explained and analysed in chapter 7 and 8. The main source of poor industrial power factor is electric motors and any reactive loads connected in the system. The poor power factor causes undesirable effect to the whole supply system as well as causing the end use consumer to spend more money because of the penalty imposed for poor power factor.

With the power factor is less than unity, the amount of useful power that is supplied by the supply systems is less than its total power capacity due to the wasteful reactive power. In this case transmission and distribution losses increases, large voltage drop occurs in the generators and transmission lines. These lead to the requirement of large exciter which have high cost implications. Poor power factor also cause the voltage drop at the point of the end user which result in poor performance of the connected loads like induction motors and lighting.

In conclusion, Low power factor of the system / end user can have impact on the supply side and demand side. In that, the supply side is required to engage on more generation as to subsidize the loss caused by reactive energy drawn from the supply. More generation leads to more investment and more burning of fuel that contributes to the global warming. To minimize the impact of low power factor the industries normally correct power factor to the acceptable. Hence this research developed STATCOM for a more flexible power factor correction.

## **10.7 Deregulation and Energy Trading**

Deregulation is a reform that introduces competition in the generation or retail sale of electricity. Increased competition in wholesale electricity markets which results in more electricity generation and emissions production due to the decrease energy prices that may encourage customers to use more energy. In addition, competition in

wholesale electricity markets may lead to a greater proportion of generation from less expensive fuel sources with higher emissions output rates. Deregulation has also the potential to affect the regulatory mechanisms that are used to promote energy efficiency, renewable energy sources and emissions reductions through the use of control technology.

Regulatory mechanisms which are used to reduce emissions include introduction of standards for emission control technology, emission charges, emission trading and offset programs, programs to promote energy efficiency by consumers and requirements for the use of renewable energy sources. The regulatory framework and market conditions interact to produce outcomes that result in emissions reductions, including installation of control technology, shifts in fuel mix from coal to gas, demand management strategies and the use renewable energy sources.

The restructuring of the power sector changes the combination of regulations and market conditions that guide incentives for emissions reductions (Joel & Maria, 2006). The most significant impact of restructuring on environmental quality may be through its effect on total electricity demand (Ferguson, 1999). Changes in electricity prices to lower amounts can cause demand increase. Increases in electricity demand and generation lead to increases in emissions (Brennan & Palmer, 2002).

## **10.8 Conclusion**

Energy is an essential ingredient for every human activity. Electrical energy plays a central role in human development activities. The use of electrical energy has wide applications in every sector world wide. The percentage and per capita electrical energy consumption depends on the economic situation of the country. It also determines the lifestyle and income level of people and the overall economic status of the country.

The economy of any country has close relationship to the use of energy, especially electricity. This has been related to HDI, which associate indicators like longevity, knowledge and standard of living. High consumption of electricity calls for the need of high generation, that results in high environmental degradation due to the increase of carbon dioxide emission and other gases which results in global warming. This can also lead to undesired impacts to the social and economic spheres. Electrical energy management plays an important role on mitigating these energy related impacts.

The restructuring of the power system industry and energy market seems to be a modern concept, but depending on the regulatory systems in place, this move may

increase environmental impact following competition in the generation or retail sale of electricity. For example, reduction of energy price can be associated with high consumption of electrical energy.

It is concluded that, if electrical energy management is used, it minimizes the use of electrical energy and defer the construction of new power plants. This is typically answering the research question 'how inefficient consumption plays a role in environmental degradation'? The techniques for energy management have been analyzed and it was observed that, some techniques have inherent undesired effects. However, in comparison with the impacts caused by electricity generation, these effects are negligible. Hence, energy management is a better alternative for minimizing environmental impacts.

## **CHAPTER 11: Results and Discussion**

### **11.1 Introduction**

The study aimed at developing methods, tools and strategies that can be used in reducing electrical energy consumption in cement industries. The methods used in achieving the stated aim include: simulation using MATLAB/ Simulink, PSIM excel and motor master software. Obtained results were analysed and compared with the industrial data obtained through data collection. The results obtained from MATLAB/Simulink also compared with that of PSIM software and the results show similarities. The main circuit diagram used for simulation was designed to represent loads of a cement industry. The complete circuit diagrams are given in Figures 8.15 and 8.16 respectively. The simulations were carried out in the laboratory environment. MATLAB 7.1 was used in PC with the following specifications: RAM is 2 Gb, Processor speed is 2kHz. Data applied in the simulations are presented in Appendix 3.1.

This chapter presents the simulation analysis results and discussions of the developed power factor correction tool known as STATCOM to be used in cement industries. Other chapter's results and discussion have been presented on their respective chapters.

### **11.2 Simulation Using MATLAB /SIMULINK and Discussion**

Industrial loads were grouped into three main sections/ departments, namely, raw mill, kiln and cement mill section (refer Chapter 3 and Chapter 8). Each section is the sum of aggregate loads of the related section (refer Appendix 3.1).

Firstly, a simulation model was developed and simulations were carried out to validate the operation of the model. During simulation, several loads connection scenarios were considered including individual kiln loads; combined kiln and raw mill section loads; kiln with cement mill loads; the combination of all three loads; combination of cement mill, kiln loads and 5% of nonlinear loads and the combination of cement mill, kiln loads with 10 percent nonlinear loads. The performance of the model was analysed based on the connection or disconnection of the STATCOM. The simulation results were compared with the plant data and showed similarities among them. This demonstrated the perfection of the developed Simulink and STATCOM model that was operating within the expected condition. The simulation of the model was also carried out in PSIM software and compared with the Simulink results.

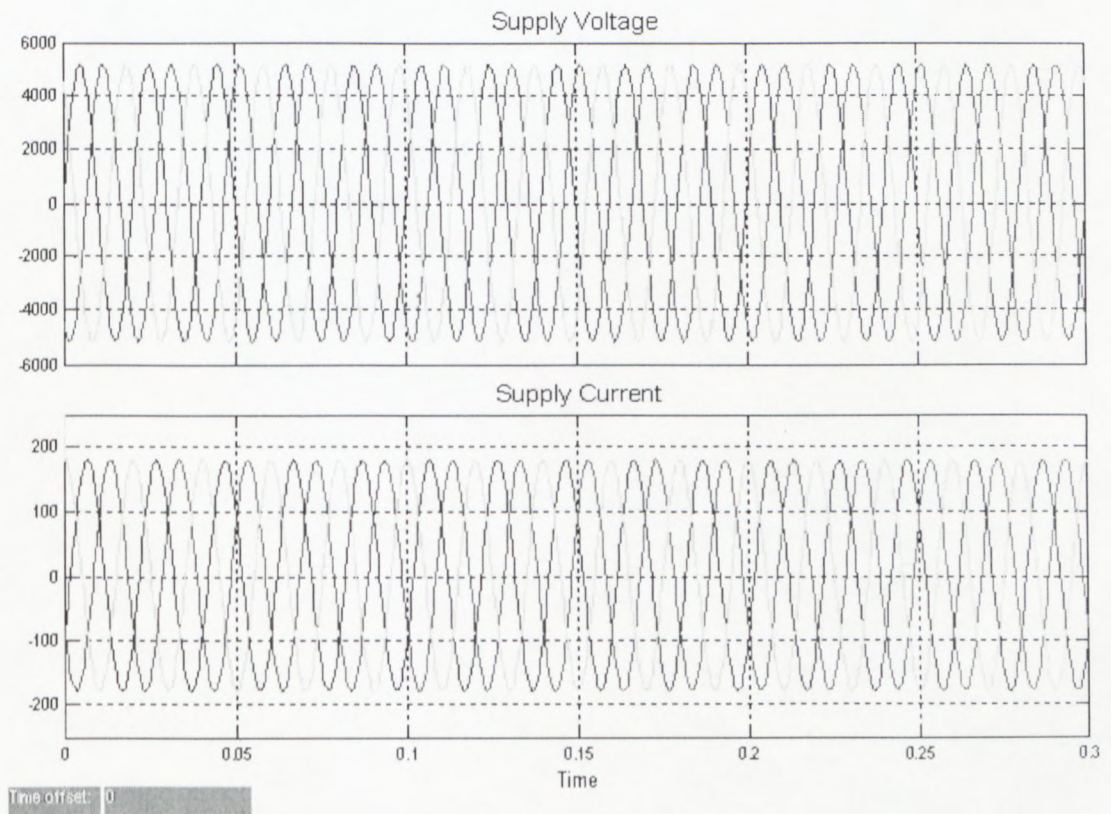
Section 11.2.1 shows the simulation results of industrial loads operation when STATCOM was not connected to the point of common coupling, while section 11.2.2 presents the simulation results of the industrial system when STATCOM was connected in the system.

## 11.2.1 Simulation Analysis without STATCOM

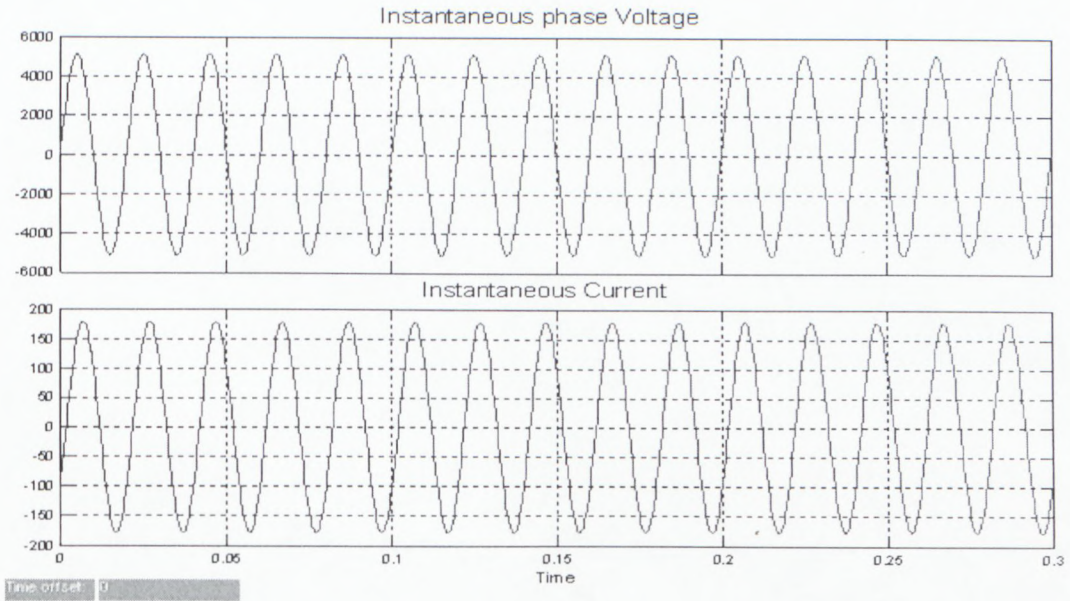
### 11.2.1.1 Kiln Section Loads Only

In this section, simulation analysis involved the connection of kiln load section to the industrial power system, while other loads were switched off. As explained in chapter 3, the kiln is not subjected to load scheduling due to its thermal characteristics.

Figure 11.1 shows the measurement of voltage and current of the kiln section loads, the supply input to the model was the peak value, hence the presented results are the per phase instantaneous voltage and current. The magnitude of these measurements is similar to that obtained in the real plant.

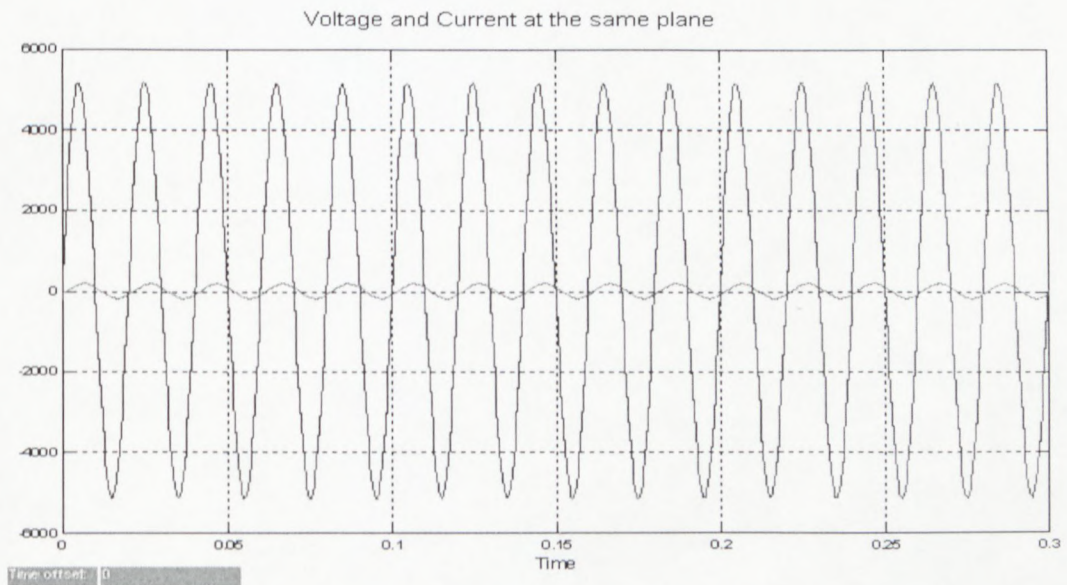


**Figure11.1:** 3 Phase Voltage and Current for Kiln Section Load



**Figure11.2:** Phase 'A' Instantaneous Value of Voltage and Current

Figure11.2 shows the phase voltage and phase current of the kiln load measured on phase 'A' terminal. They are displayed on different X -Y plot and they have the same X -axis scale. Figure11. 3 presents the voltage and current on the same X-Y plane while Figure11.4 exhibits figure three information in increased X - axis time scale. In these figures it has been noted that, the power factor of the kiln section is lagging (before STATCOM). This evidence can be obtained in the graph where the phase difference between voltage and current is observed.



**Figure11. 3:** Relationship between Voltage and Current

Figure 11.5 demonstrates the simulation of active, reactive power and power factor measured on the supply and the load side. The results show that, the value of the active, reactive power and the power factor presented in either side are the same because load and supply terminals are connected to the same power loop. Hence Kirchhoff's current Law is applied.

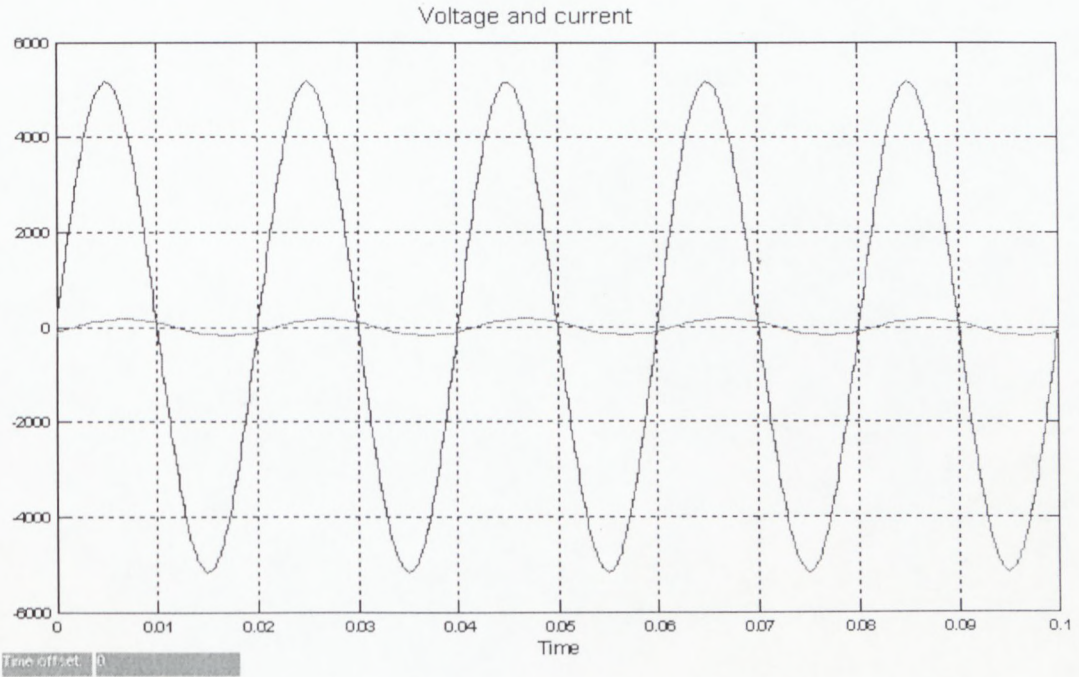


Figure 11.4: Extended Scale of Figure 3

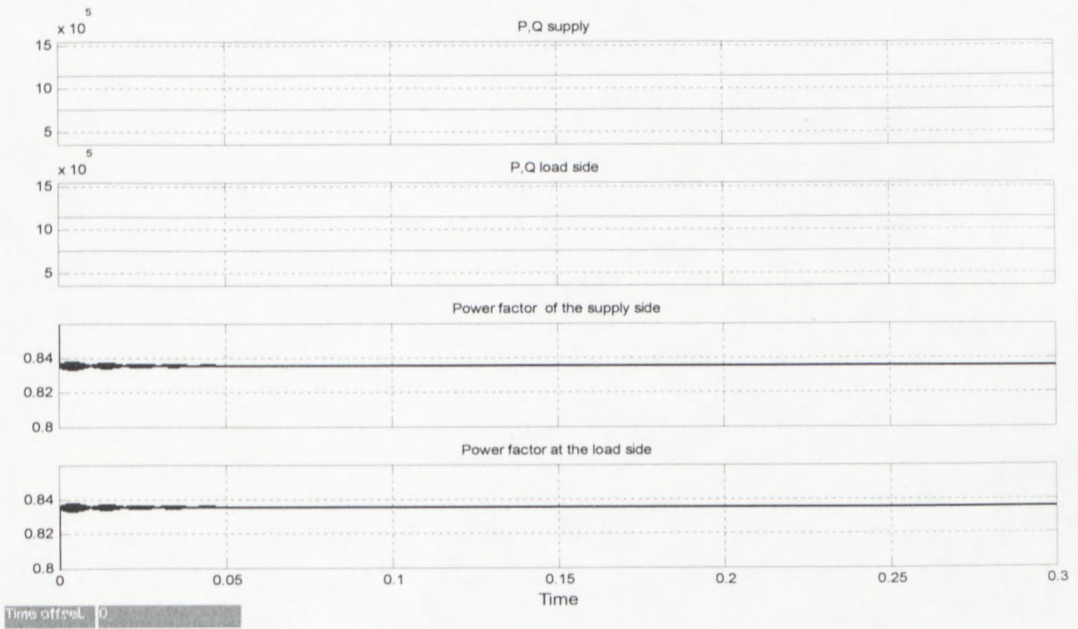
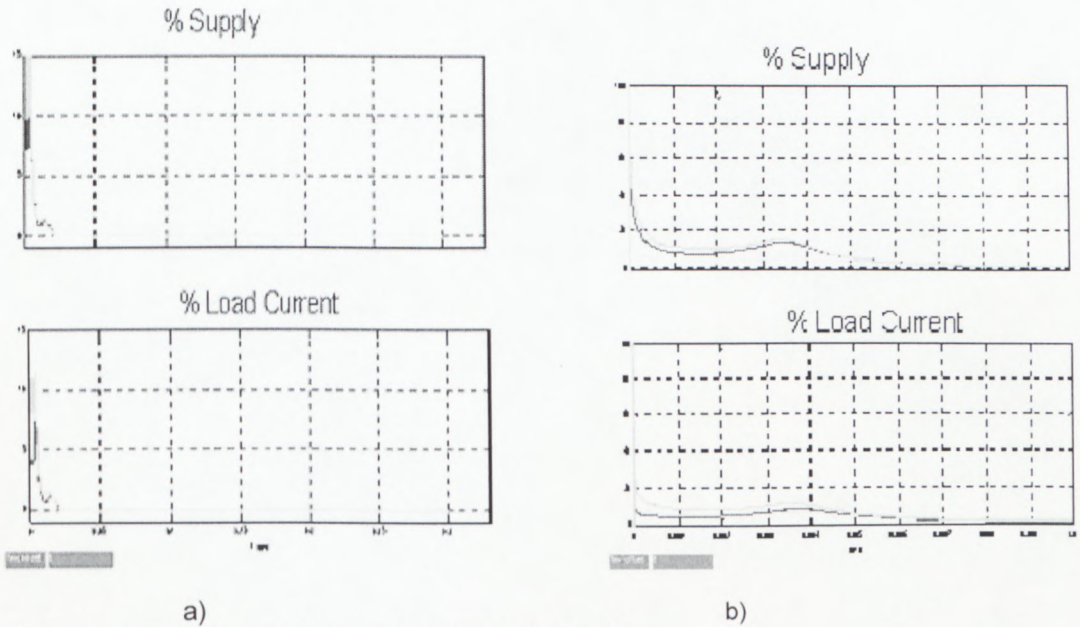


Figure 11.5: Measurement of Active Power, Reactive and Power Factor

Figure 11.6a, displays the total harmonic distortion measured on the supply /meter side. It was observed that, there is a considerable voltage and current distortion at the initial time of operation, that is, during the transient period which settled down after a short period as indicated in the Figure11. 6.a. Figure11. 6.b shows the extension of Figure11.6a, at a reduced the time scale. It has been demonstrated to analyse the transient's and decay period. In Figure 6.b it was observed that, the total transient period has ended at 6ms and the remaining simulation period is the steady state period.



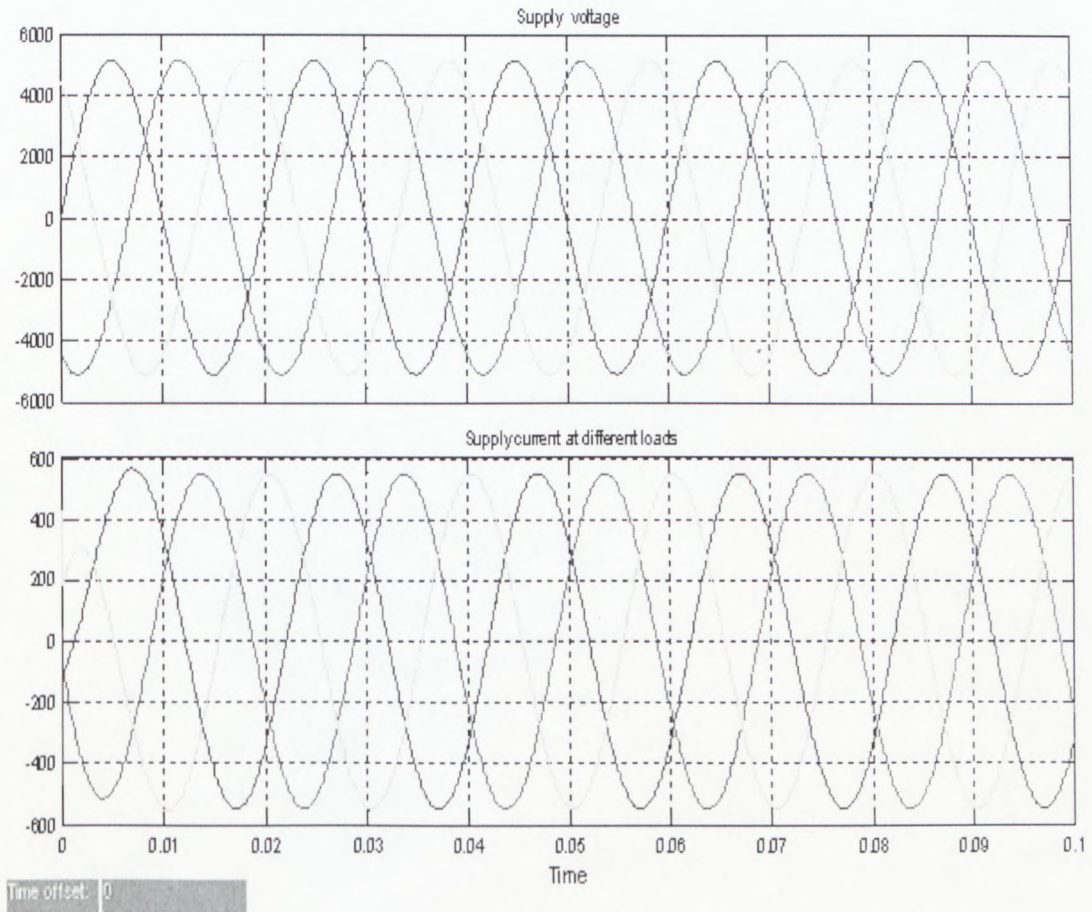
**Figure 11.6:** Total Harmonic Distortion of the Kiln Load

### 11.2.1.2 Kiln and Raw Mill Loads

This section presents the simulation analysis of the kiln and raw mill section loads. These loads are connected together and both are switched at the initial/ starting period [0s]. Assuming other loads have been switched off.

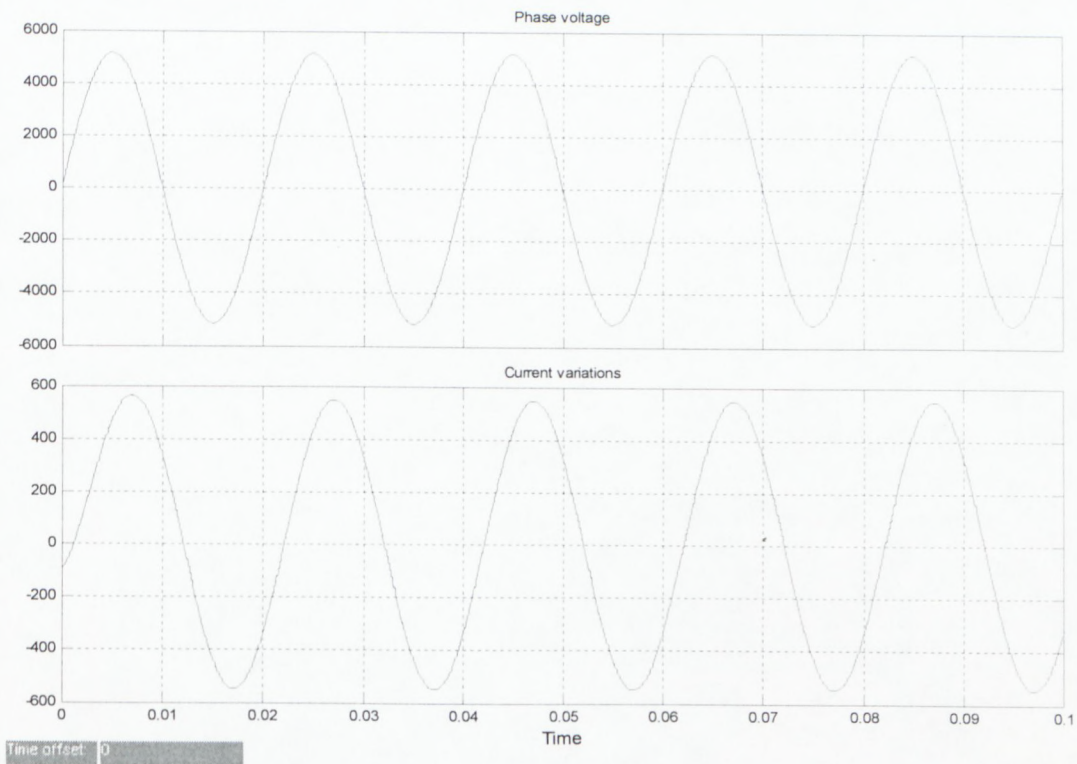
Figure 11.7 shows a 3phase voltage and current and Figure 11.8 gives a phase 'A' voltage and current measurements of the two (combined) sections loads respectively. Compared with the results obtained in section 11.2.1.1, the current has increased while the voltage is remaining the same. The increase of current was contributed from the additional raw mill section load to the system. The Ohms Law and Kirchhoff's Current Laws were applied. Hence the connection of raw mill section loads adds the current of kiln and raw mill section loads.

Figure 11.9 shows the phase relationship between voltage and current (lagging) while Figure 11.10 demonstrates the value of active and reactive power of the connected loads, measured on the supply side and the load side.

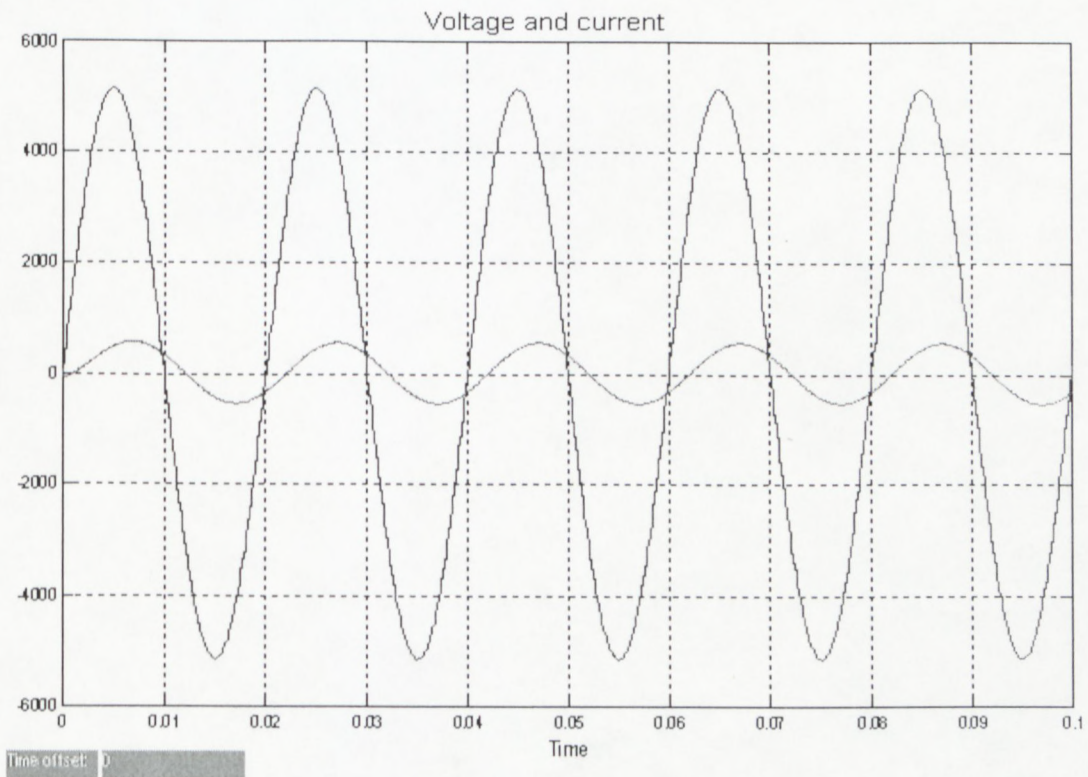


**Figure 11.7:** 3 Phase Voltage and Current of Kiln and Raw Mill Load

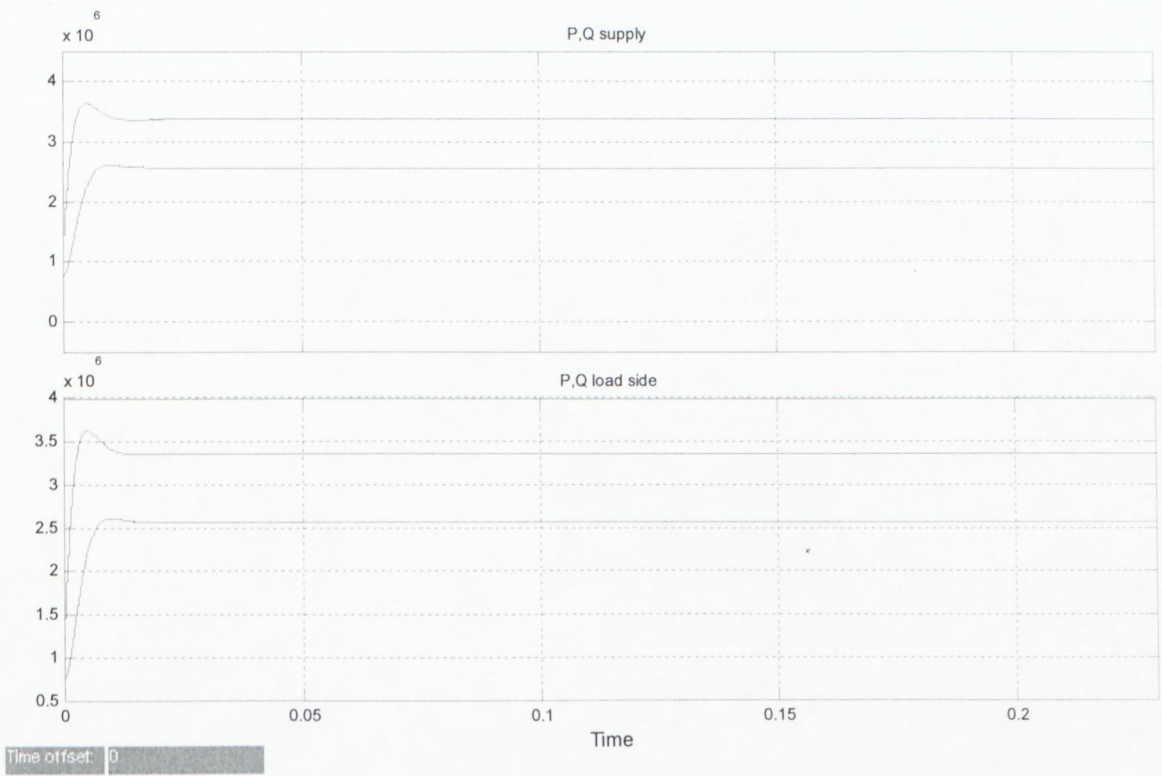
Figure 11.10 also shows that, the parameters measured on the supply side and the load side demonstrated similarity irrespective of the point of measurement because the load is assumed to be constant and they are connected at the same terminal as the supply. The power factor of the system is also given in Figure 11.11. After the transient period, the power and power factor were constant at all simulation periods. It was observed that, at transient period, the power factor rises abruptly and settles quickly. The results of measurement obtained in simulations are similar to that obtained from plant data or by numerical computation.



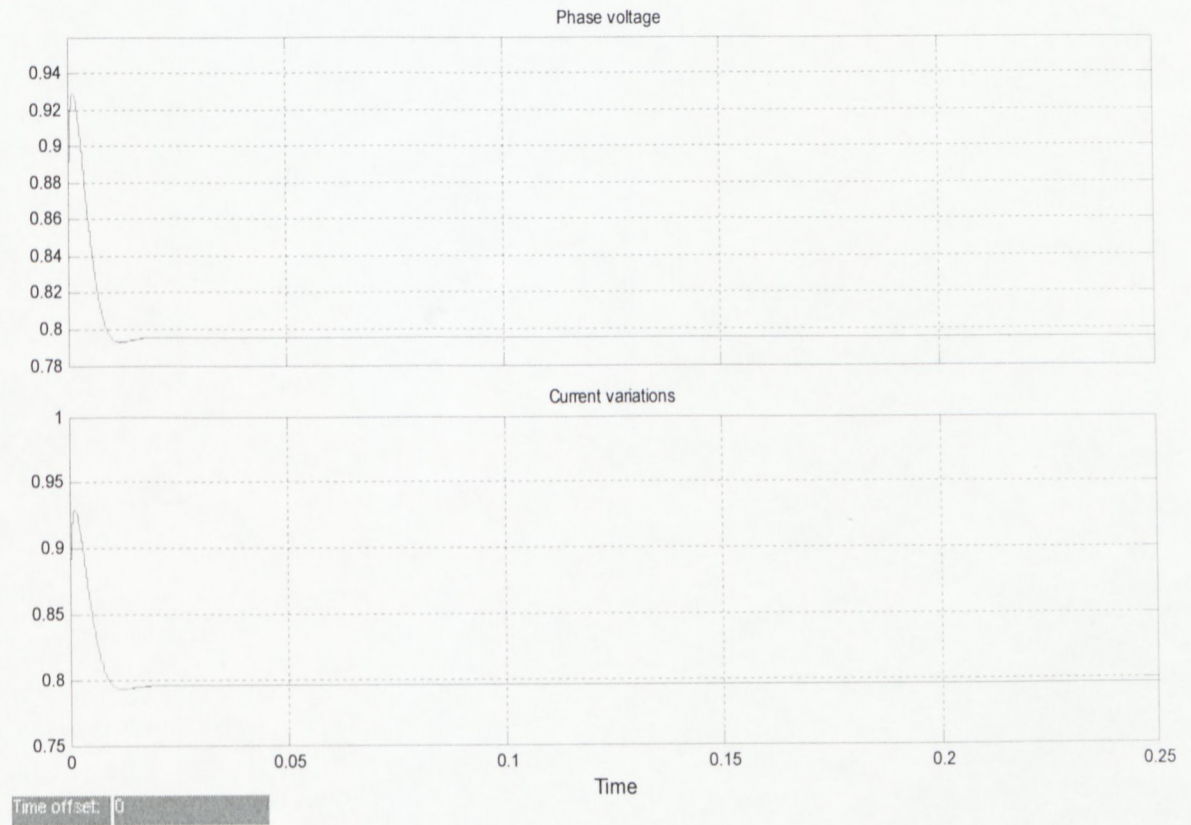
**Figure 11.8:** Phase 'A' Voltage and Current



**Figure 11.9:** Phase Voltage and Current on the Same X-Y Plane



**Figure 11.10:** Active and Reactive Power of the Connected Loads



**Figure 11.11:** Power Factor

Figure 11.12 presents total harmonic distortion (THD) of the supply and Figure 11.13 shows the same THD at the enlarged X-Y axis scale, hence only the transient period is analysed and presented the small value of transient period of  $4.5 \times 10^{-3}$  ms.

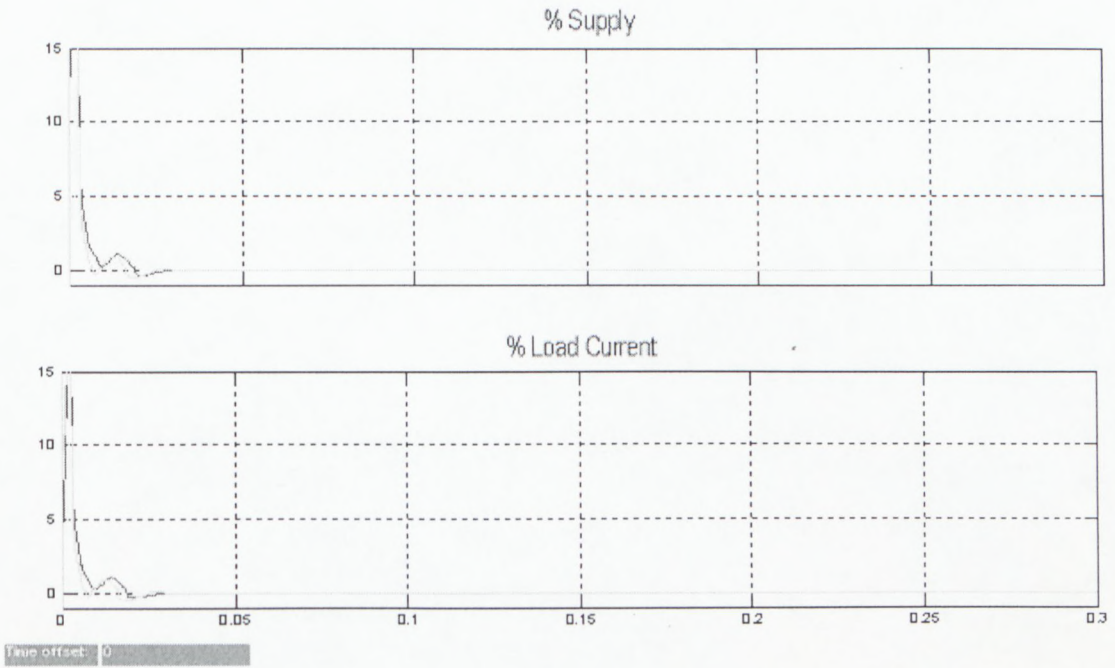


Figure 11. 12: THD of the System

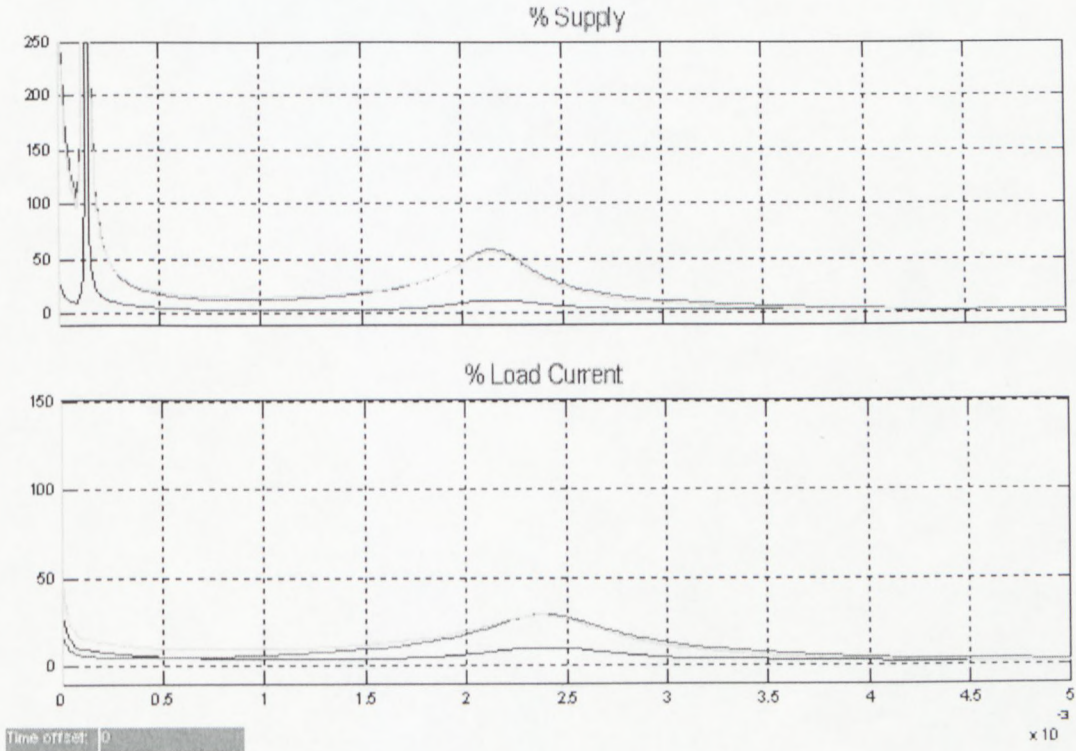


Figure 11.13: THD, Settling Time

### 11.2.1.3 Kiln and Cement Mills

This section presents the simulation results of the kiln and cement section loads, assuming other section loads have been switched off.

Figures 11.14-16 show the voltage and current measurements of the combination of kiln and cement mill section loads. 3-phase, V-I, phase 'A' V-I measurements on the different X-Y plane and the V-I characteristics displayed in the same X-Y plane are presented respectively. The current in these figures seems to increase compared with when only kiln load was connected; this is due to the addition of the cement mill load to the kiln load that sums the total current. The voltage remains the same irrespective of variation of the loads.

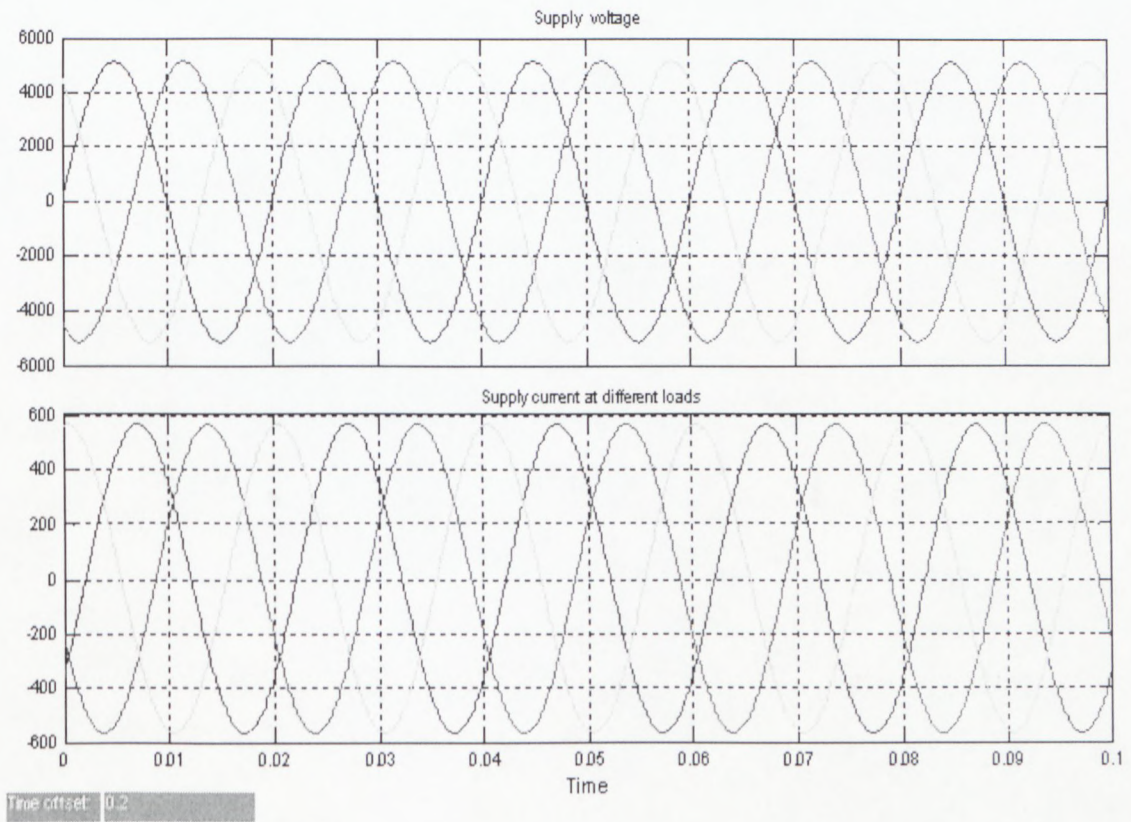


Figure 11.14: 3 Phase Voltage and Current of the Combination of Kiln and Cement Mills

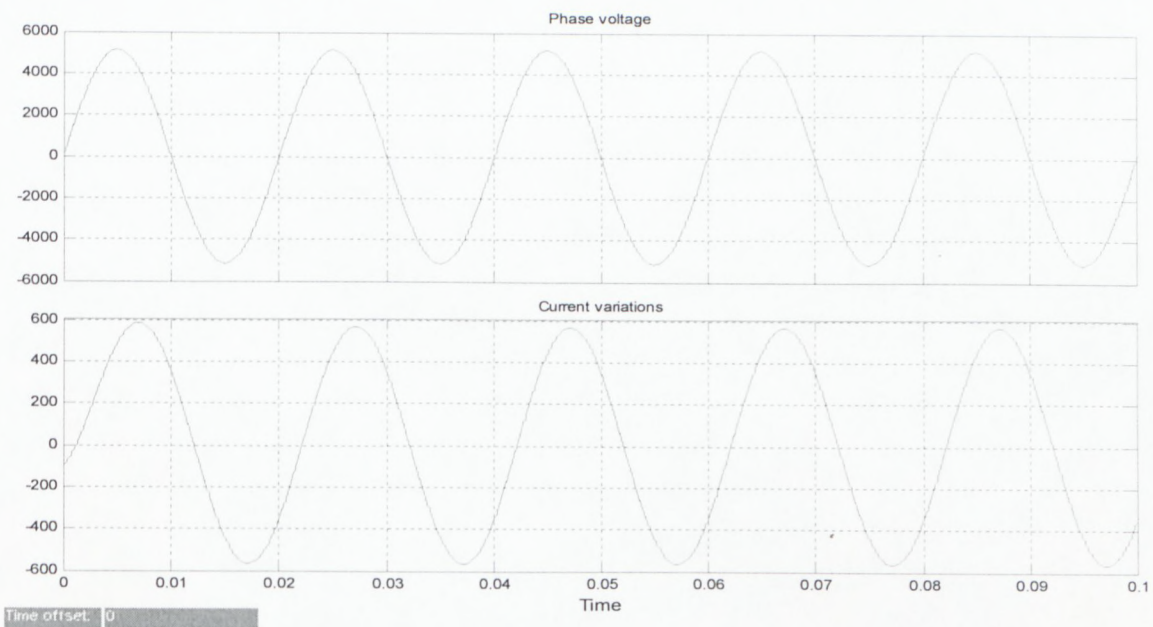


Figure 11.15: Phase 'A' Voltage and Current Measurement

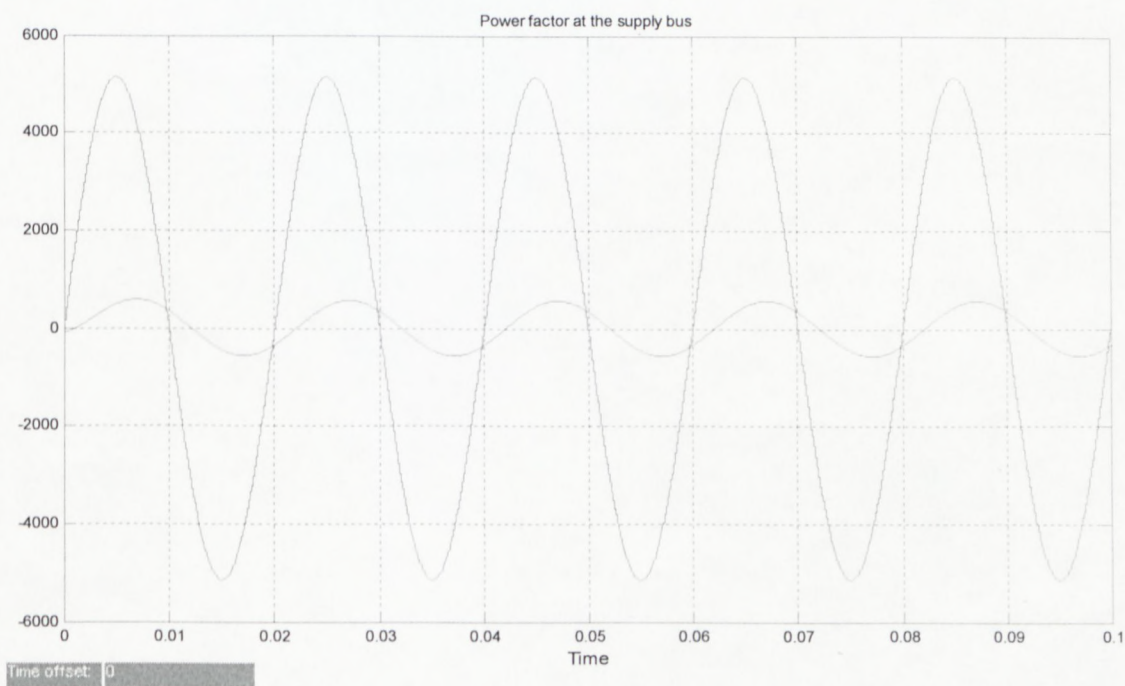
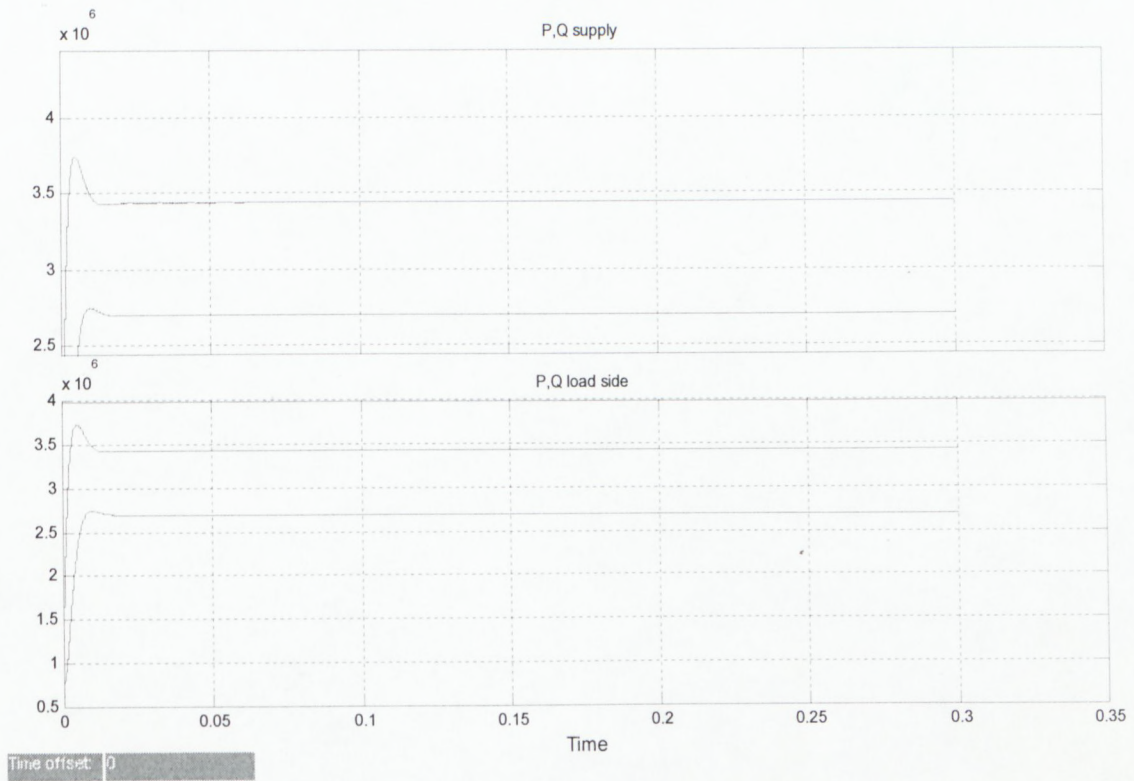
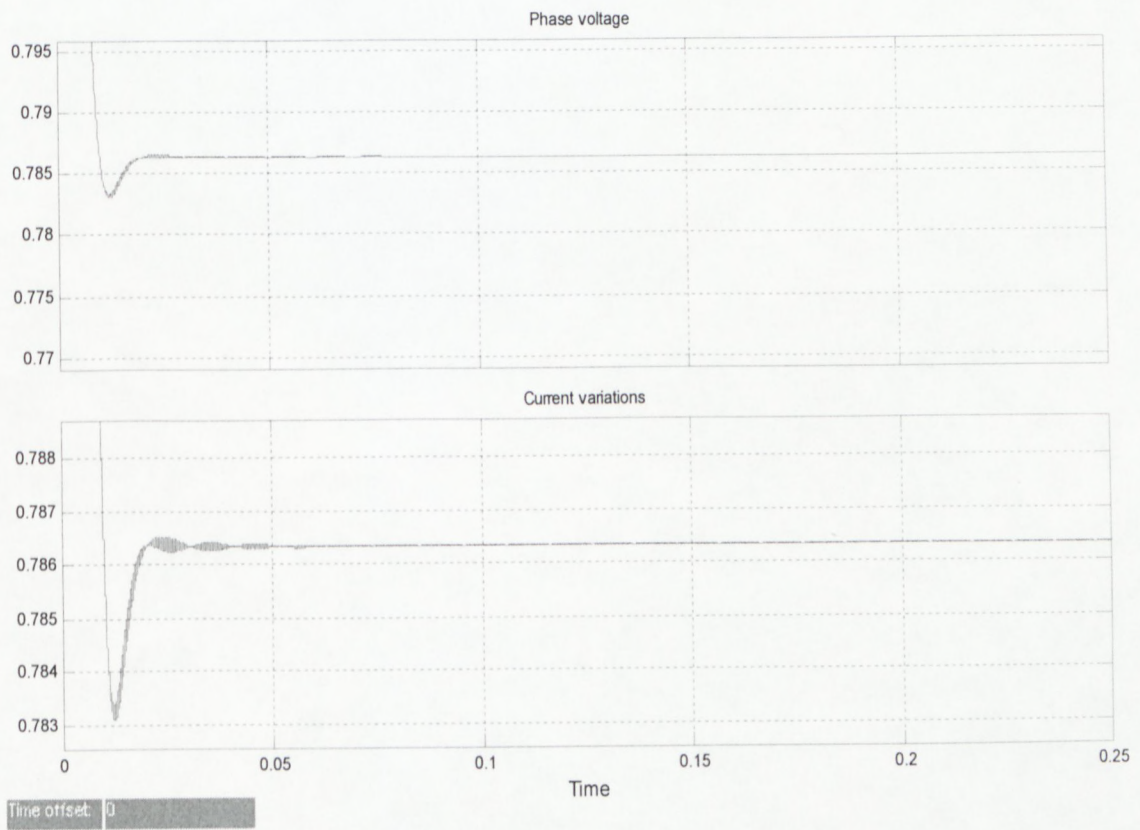


Figure 11.16: Phase Voltage and Current on the Same X-Y Plane

Figure 11.17 shows the active and reactive (P-Q) measurement taken from the supply and demand side (loads). The measurements of P-Q in either side of the plant exhibit the same results because the supply side feeds only one branch loads. It is also observed that, at the initial position the active and reactive power are 0; after initiation of switching, the P and Q have sharply increased due to the transients phenomenon caused by switching behaviour.



**Figure 11.17:** Active and Reactive Power



**Figure 11.18:** The Power Factor Measure in the Supply Side

Figure 11.18 shows the power factor measurement, whereby at 0-0.05s the system is shown to have some distortion due to switching, there after the transients settle down and operate at steady state.

#### 11.2.1.4 When All Loads Are Connected At the Same Time

Figures 11.19-11.21 show a 3-phase voltage and current, phase 'A' voltage and current and voltage and current in the same X-Y plane respectively. These simulations were carried when all plant loads were connected in the system at the same period, that is, at  $t=0$ s. In these figures, the increase of current and phase difference between voltage and current is noted whereas the voltage remain constant at any load condition.

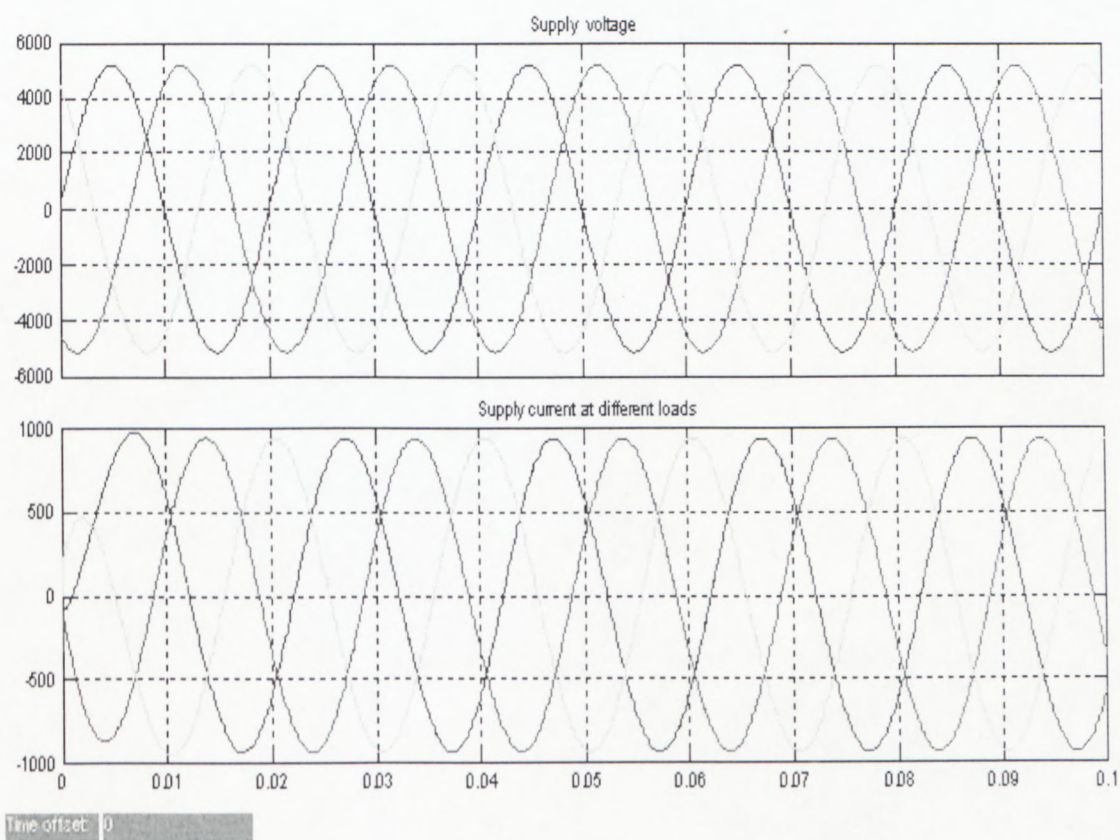
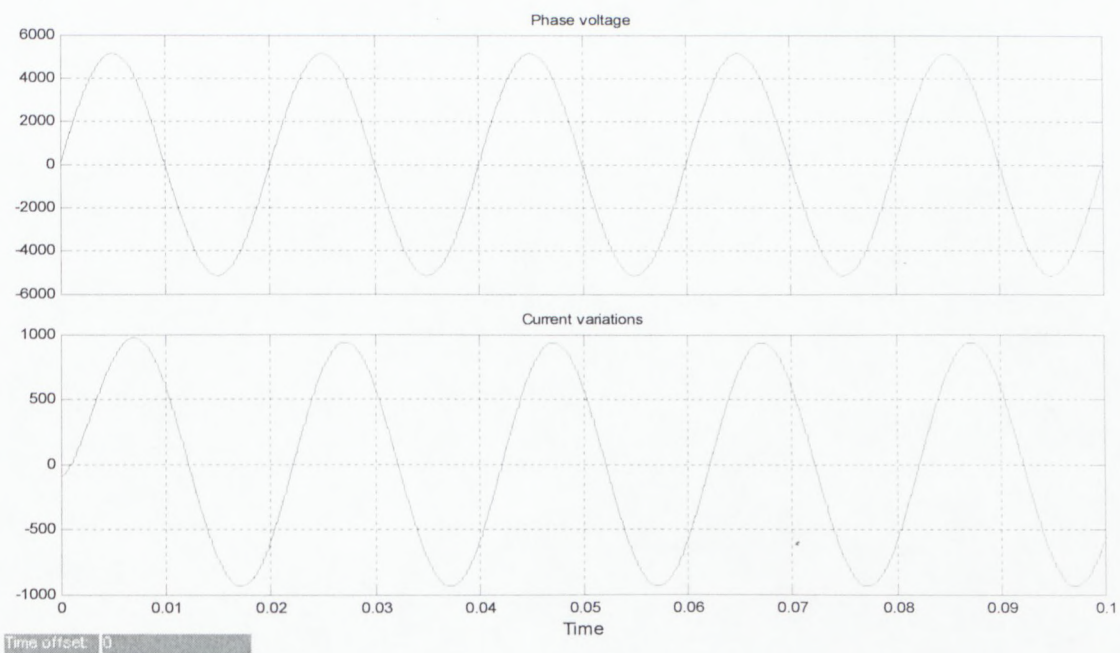
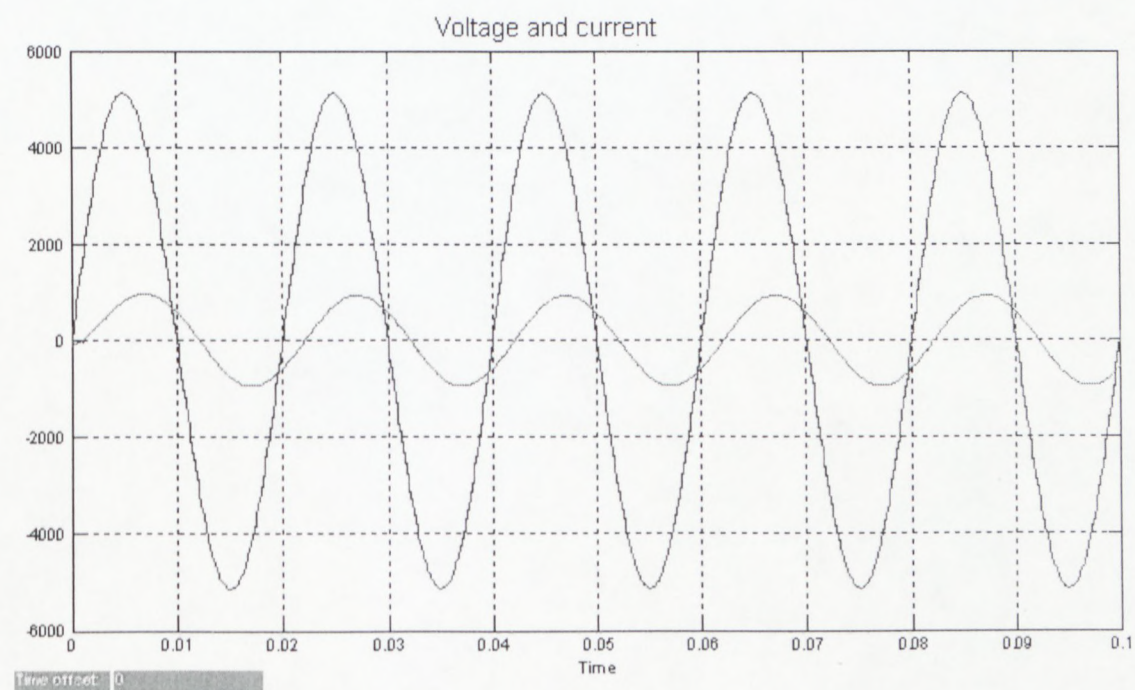


Figure 11.19: 3 Phase Voltage and Current

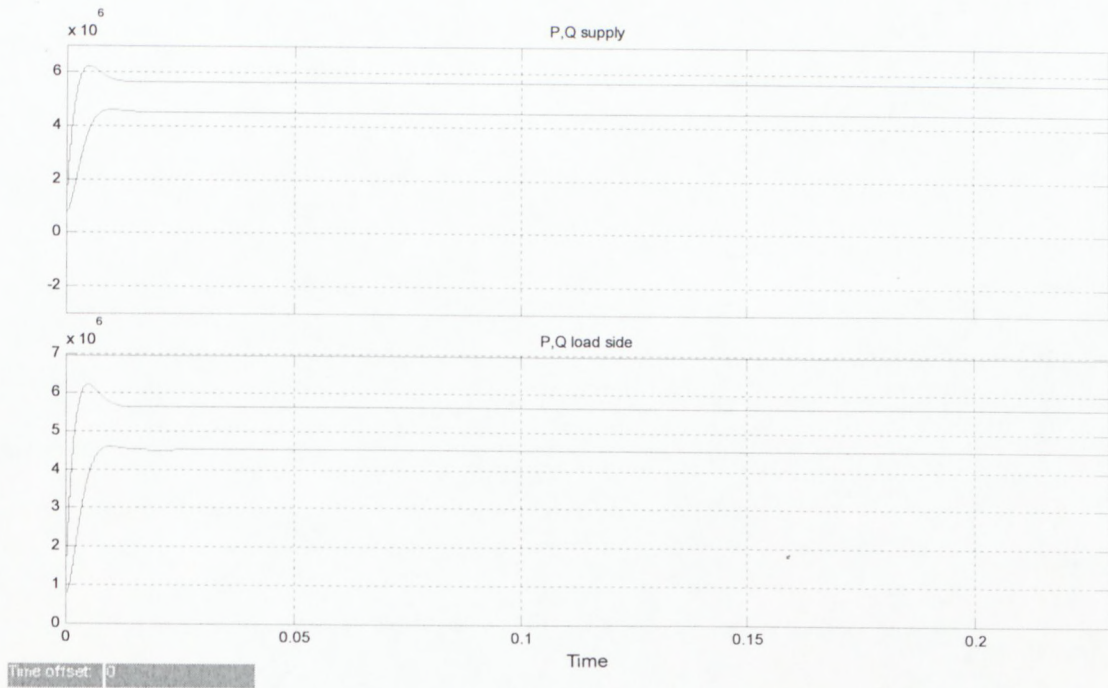


**Figure 11.20:** Phase 'A' Voltage and Current Measurement

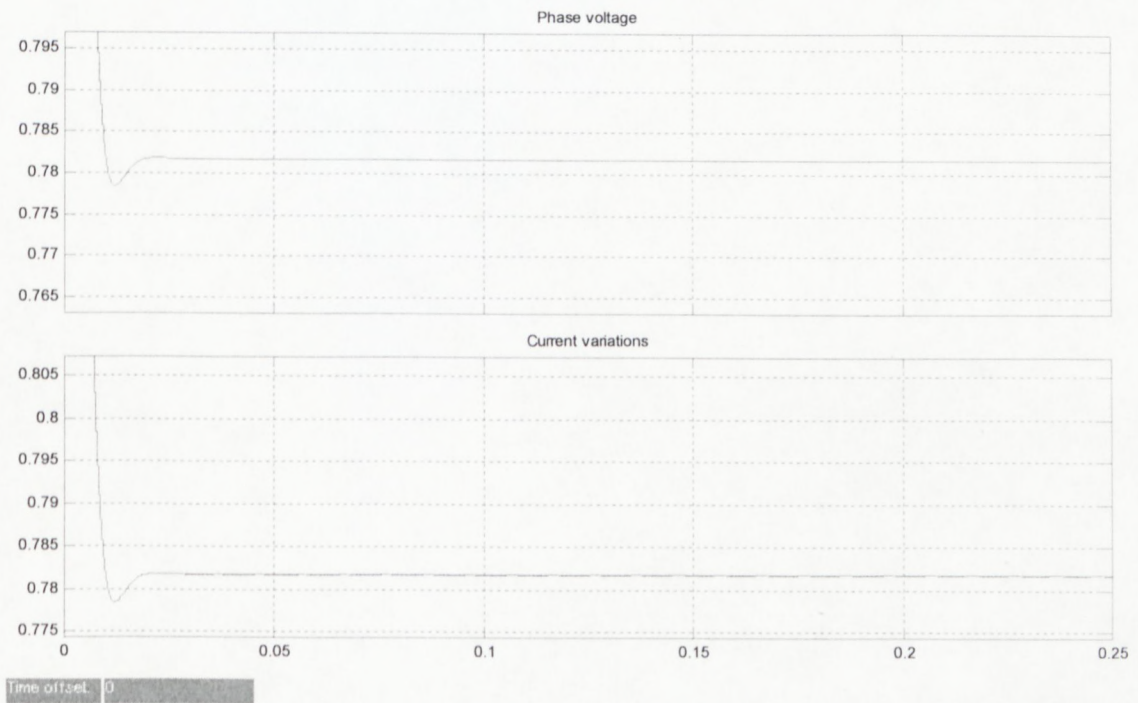


**Figure 11.21:** Single Phase Voltage and Current in the Same X-Y Plane

Figure 11.22 shows the measurement of active and reactive power. The power factor was measured and result displayed in Figure 11.23. At transient period, the PF was found to rise abruptly and oscillates for a short period before it settles down to a steady state period. So far active and reactive power and power factor measured in any power side are the same.



**Figure 11.22:** Active and Reactive Power Simulation



**Figure 11.23:** Power Factor Measurements

Figure 11.24 shows total harmonic distortion (THD). Figure 11.25 presents a THD at the increased time scale so as to analyse the transient period. Compared with above connection setup, in this scenario the harmonic distortion is high; this is due to the increase of total loads.

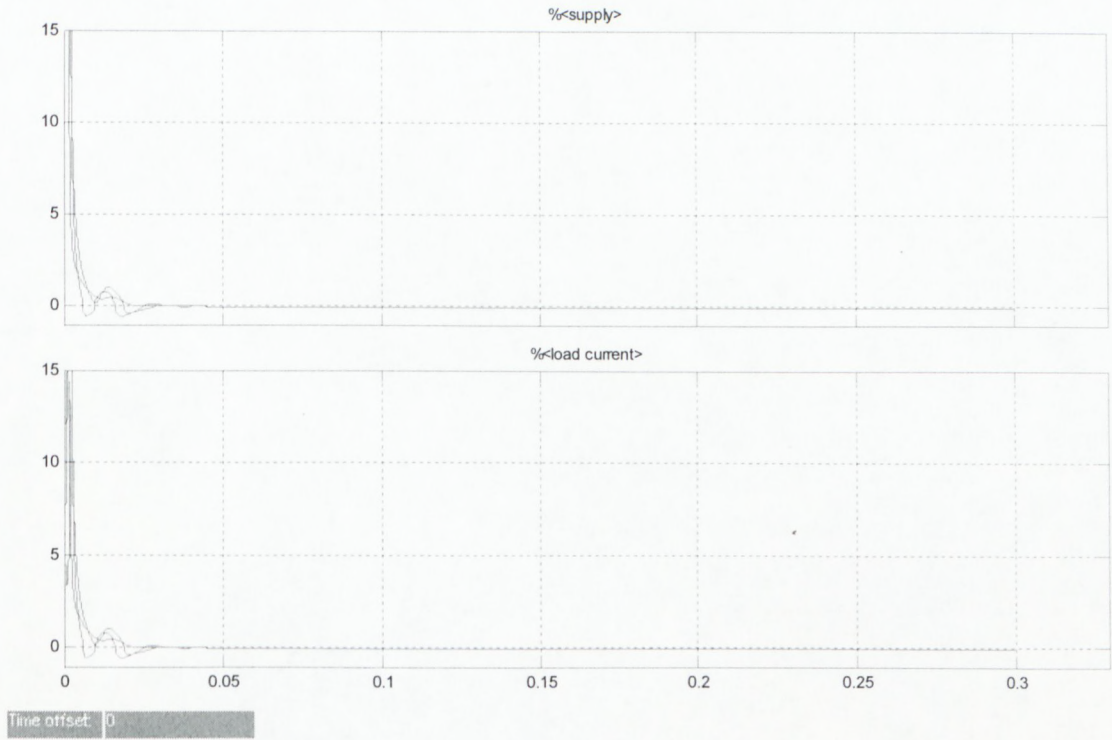


Figure 11.24: THD

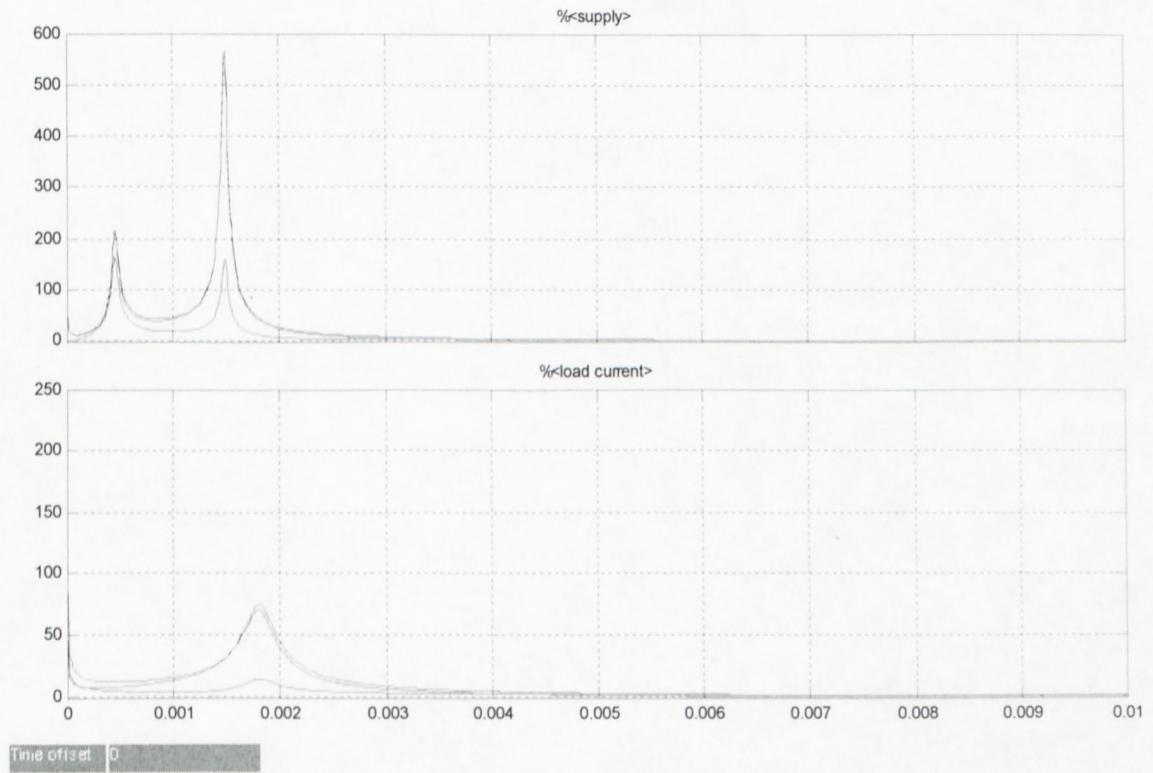


Figure 11.25: THD and Settling Down Period

### 11.2.1.5 When Plant Load Contain 10% of Nonlinear Load

In this simulation, the kiln and cement mill loads were considered as a main part of the plant loads and the 10 percent of nonlinear load was added to the system. The aim of this simulation was to analyse the influence of 10% of nonlinear load to the plant supply system.

Figure 11.26-28 show the V-I characteristics of the three phase supply, phase 'A' V-I measurements and phase 'A' measurements in the same X-Y plane. From these figures, it was observed that, nonlinear loads have big influence to the supply current. When only 10% of nonlinear loads were connected to the system, the voltage of the system seems to be constant irrespective of load type. The current of the system seems to distort. The power factor of the plant also has been affected by this distortion.

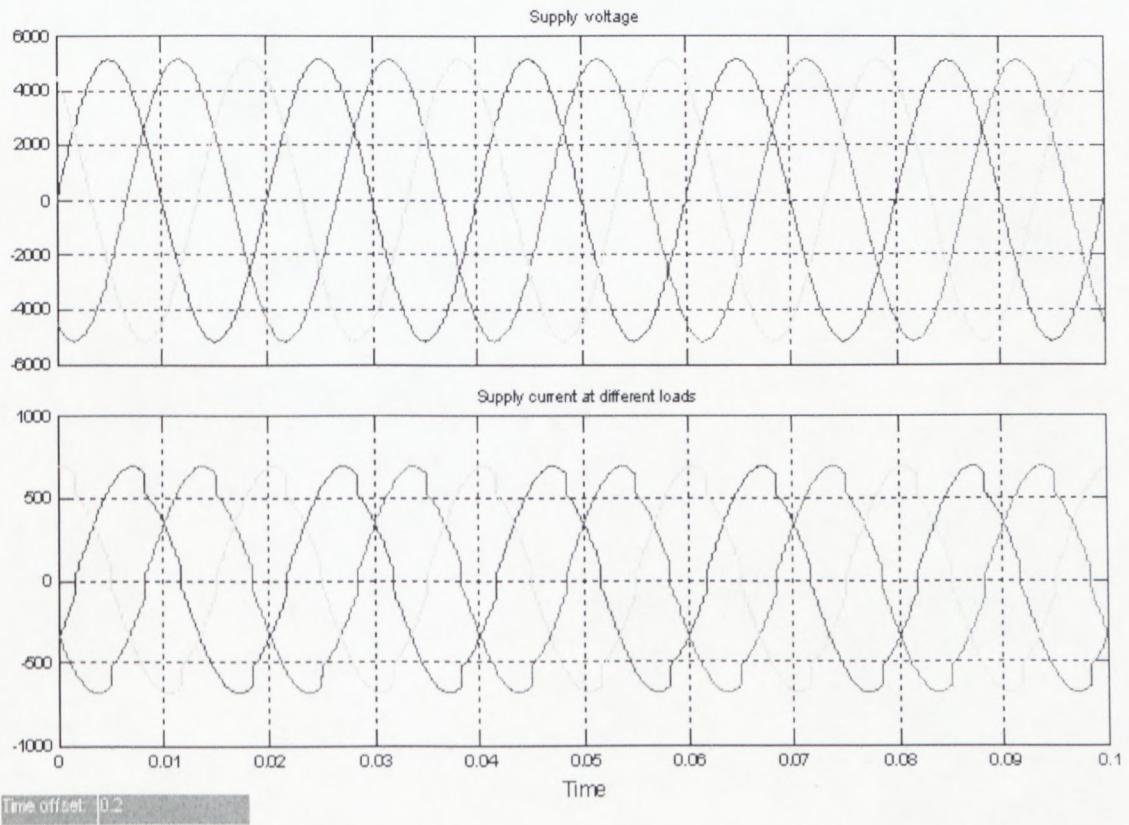
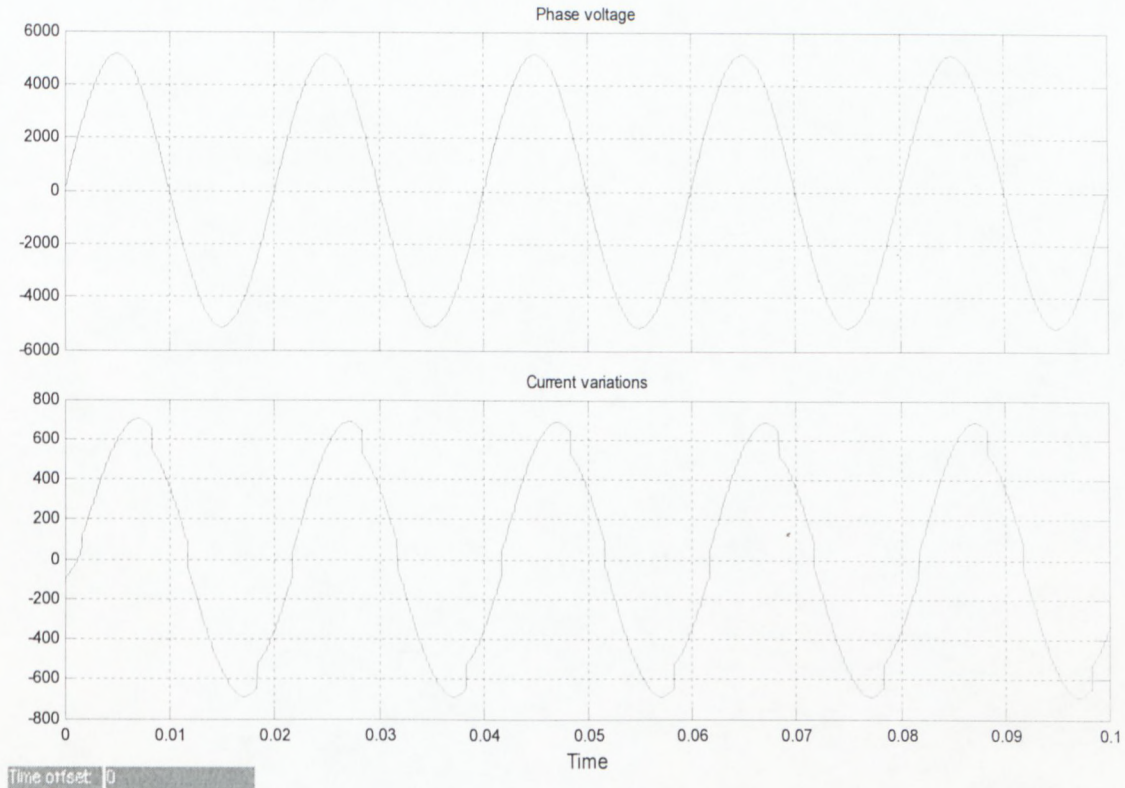
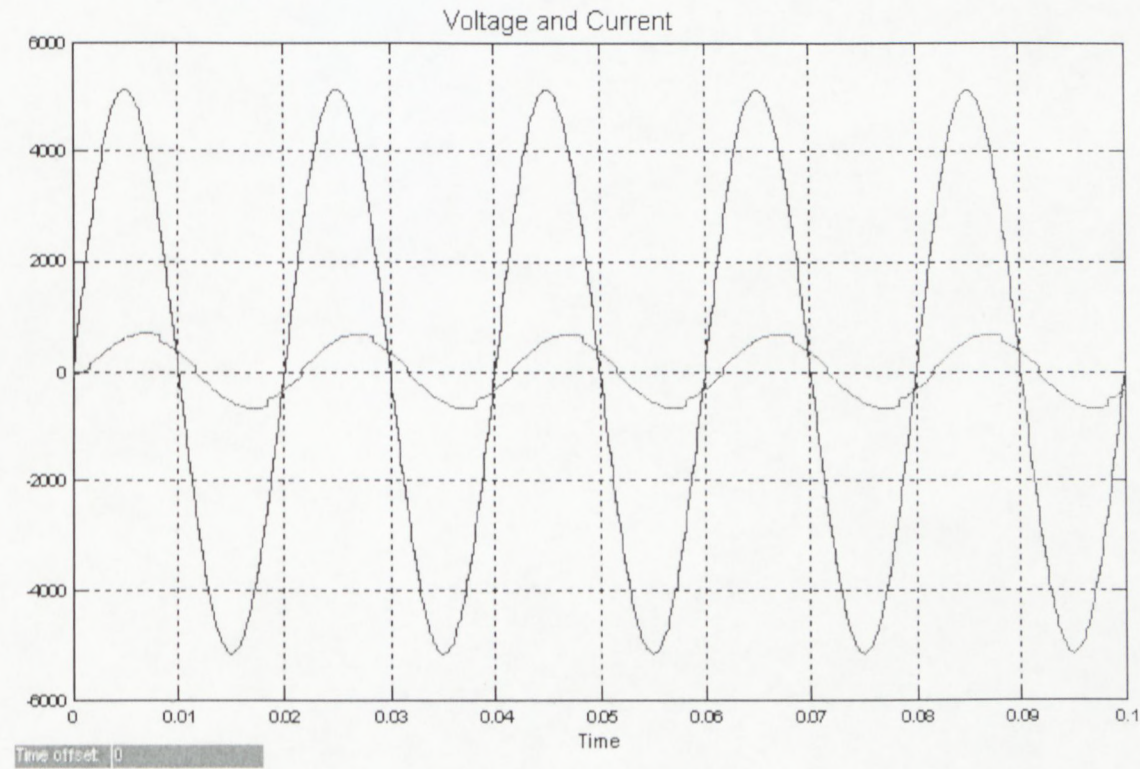


Figure 11.26: 3 Phase Voltage and Current



**Figure 11.27:** Phase 'A' Voltage and Current



**Figure 11.28:** Voltage and Current in the Same Plane

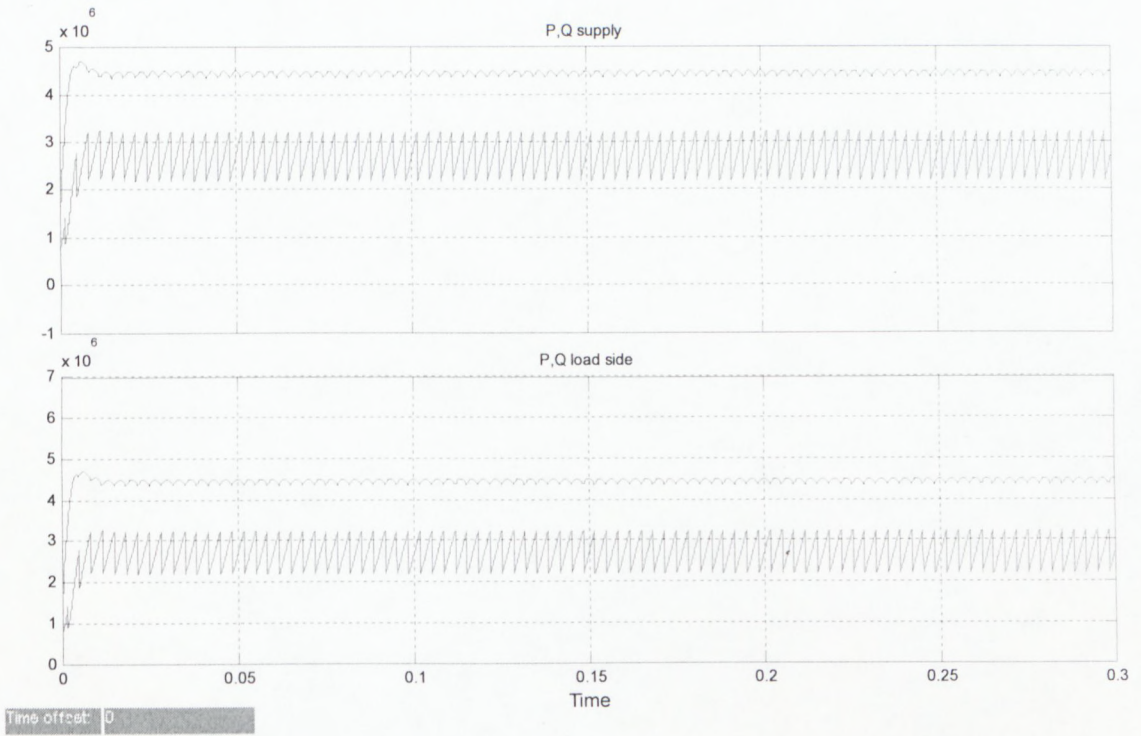


Figure 11.29: Active and Reactive Power in the Supply and Load Side

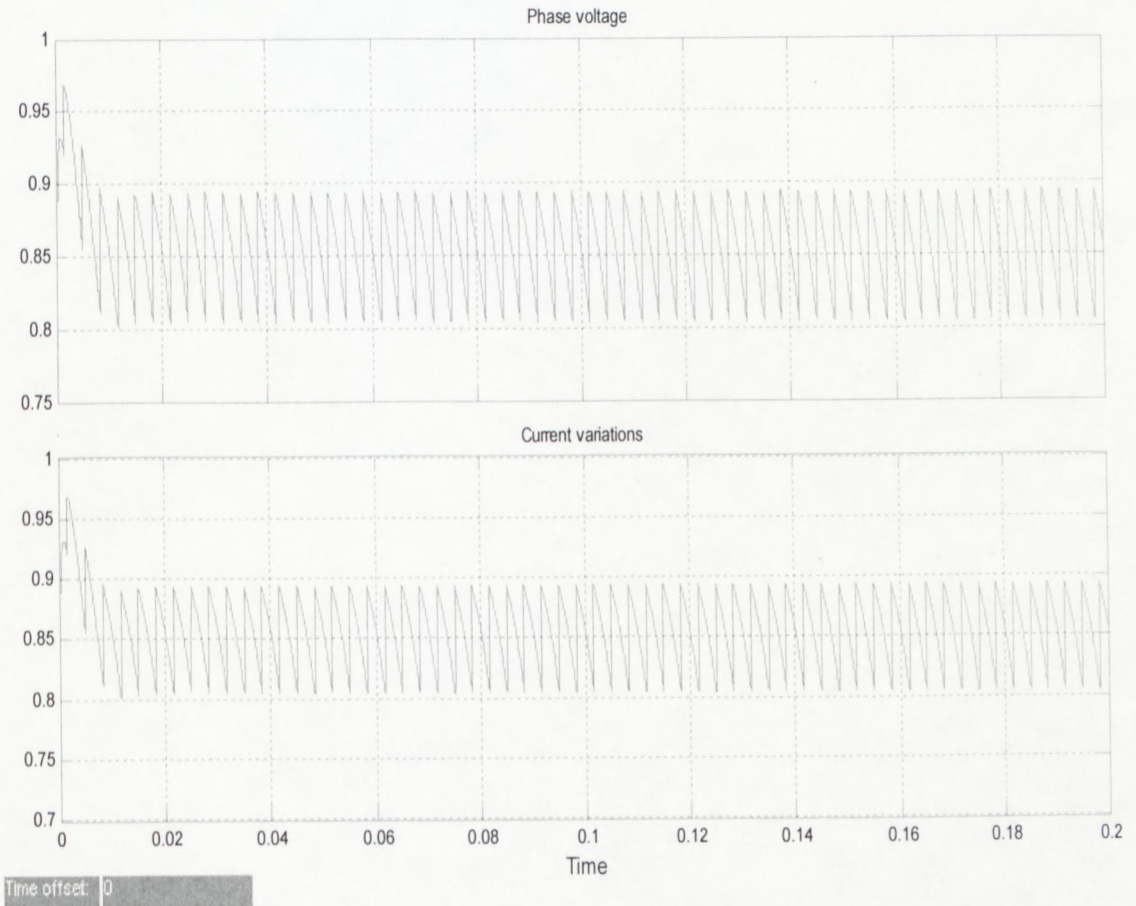


Figure 11.30: Power Factor

Figure 11.29 and Figure 11.30 present the P-Q and power factor measurements. Due to the influence of nonlinear loads, the curves have been affected by harmonic contents as it is seen in the figure.

**11.2.2 Compensator is Connected to the Plant System**

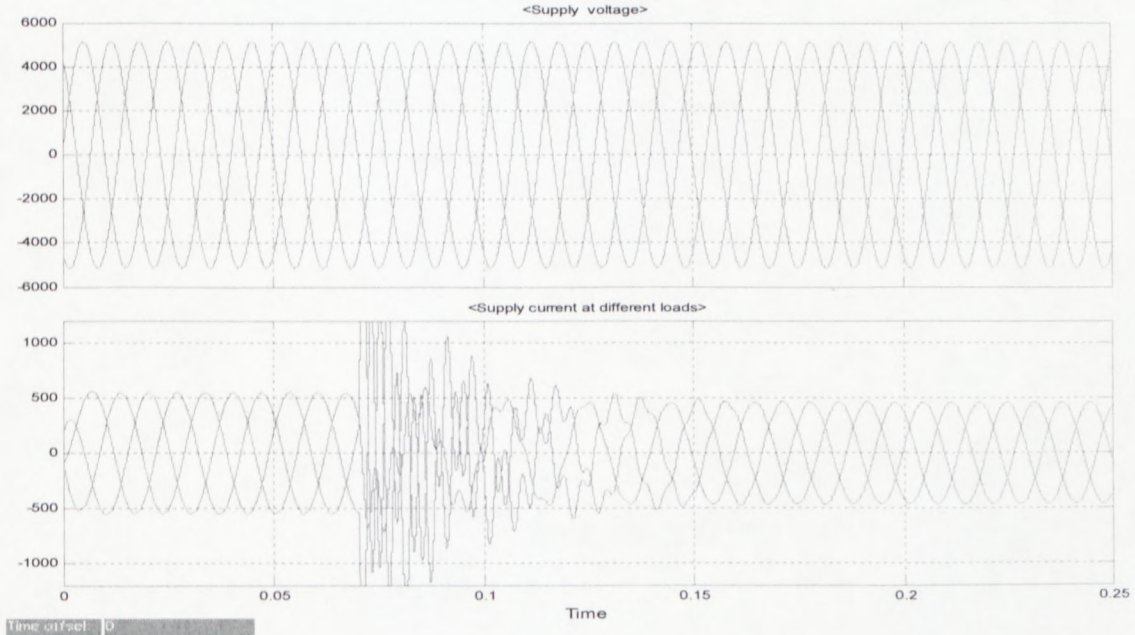
Theoretically, when a shunt compensator was connected to the industrial power input bus bar (power factor correction), the loads draw less power from the supply than the power drawn when the compensator is not connected to the circuit. Based on the connection diagram (refer Figure 8.4) and application of Kirchoff's Current Law, the current of the system can be calculated as:

$$i_s(t) = i_L(t) - i_c(t) \dots\dots\dots 11.1$$

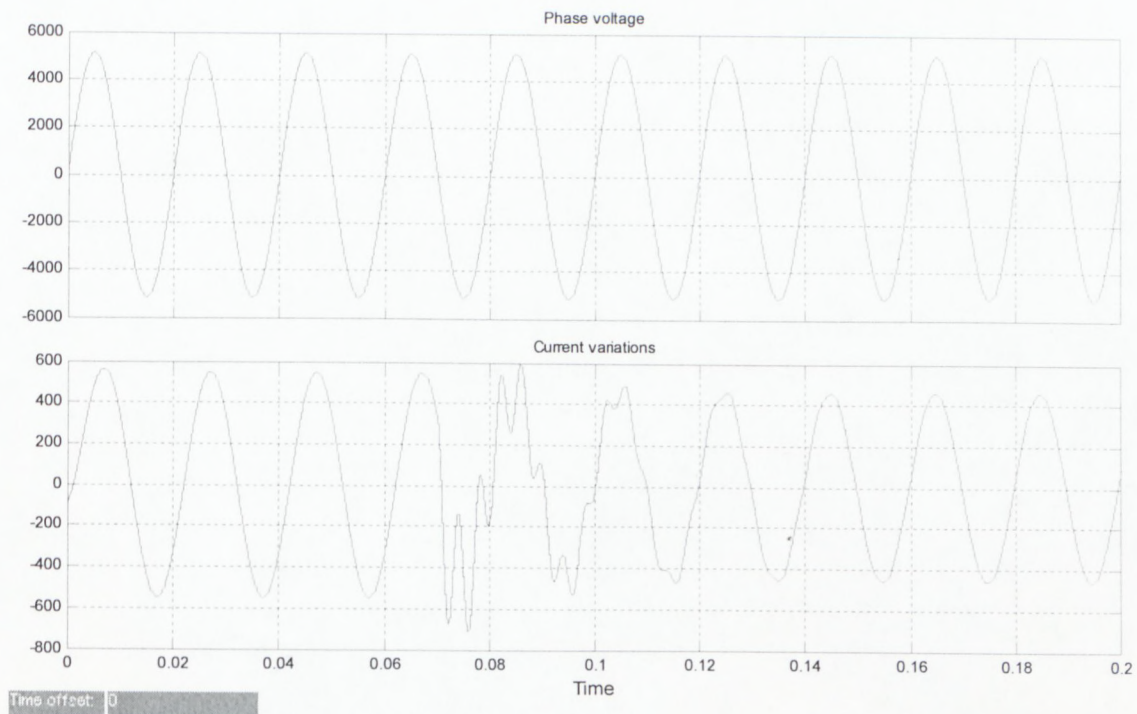
- Where  $i_s(t)$  current from the supply
- $i_L(t)$  Load current and
- $i_c(t)$  Compensator current

**11.2.2.1 Kiln and Raw Mill Section Loads**

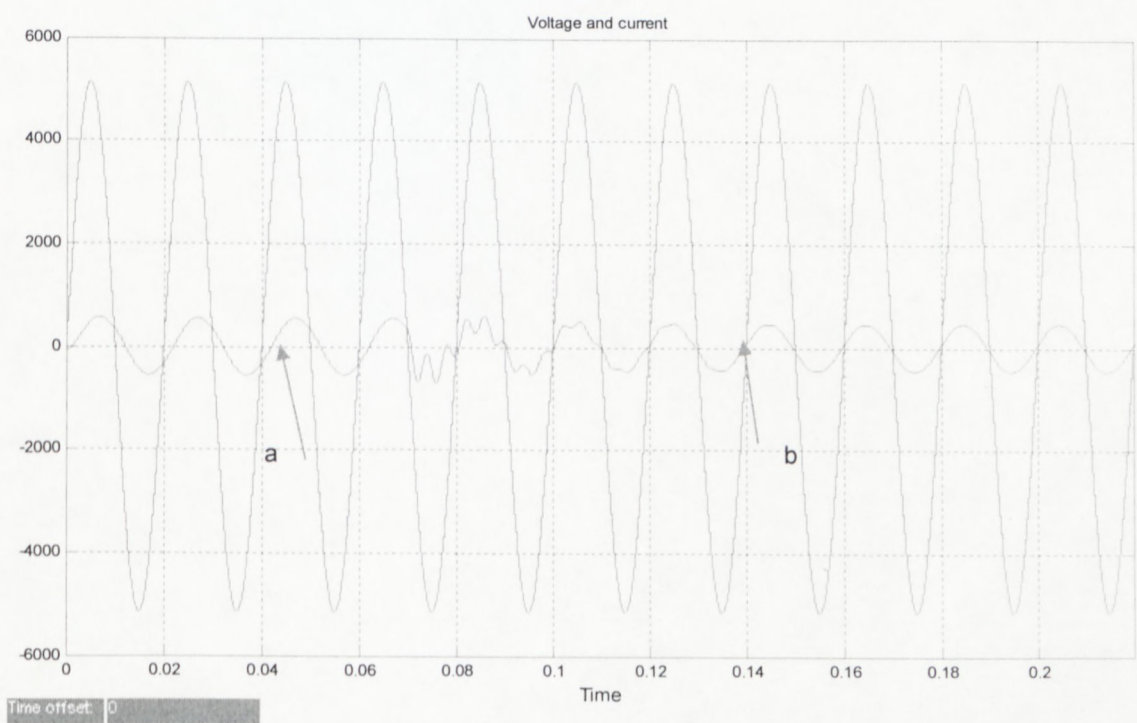
The following figures show the simulation results of industrial system behaviour, when the compensator was connected to the circuit. The analysed loads were the combination of kiln and raw mill section load. The shunt compensator is connected to these loads through a coupling transformer.



**Figure 11.31: 3 Phase Voltage and Current**



**Figure11. 32:** Phase 'A' Voltage and Current Measurement

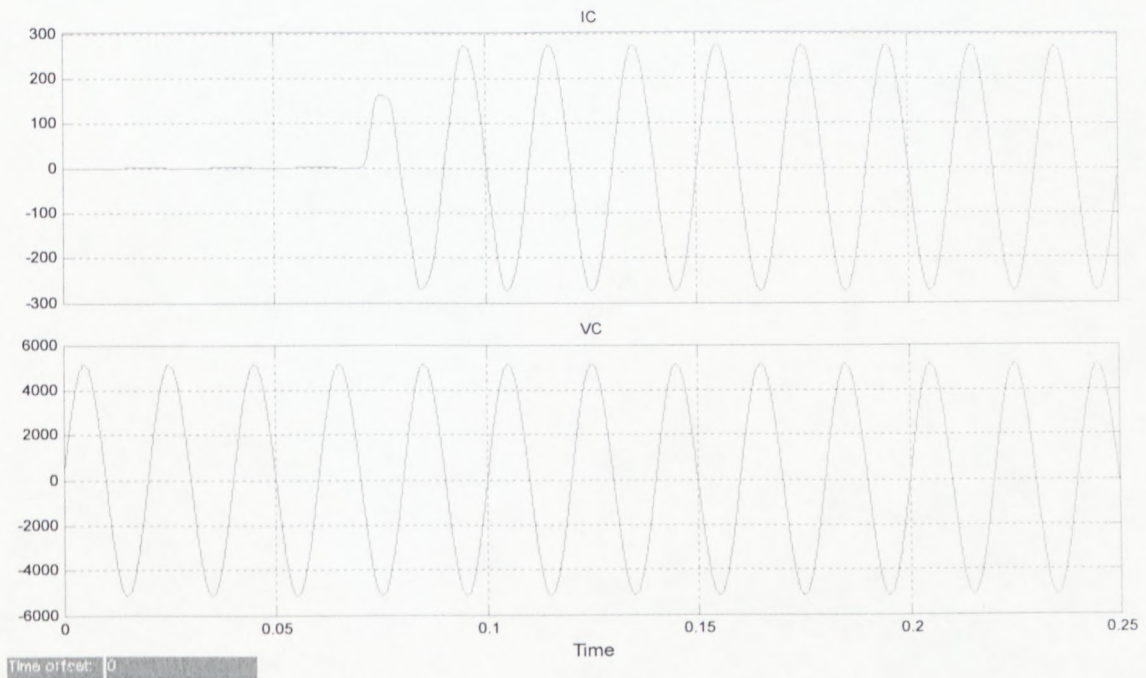


**Figure11. 33:** Relationship Between Voltage and Current (Increased Scale)

Figures11.31-33 show the measurement of 3phase voltage and current, voltage and current of phase 'A' and voltage and current at the same X-Y plane. In these simulations kiln and raw mill loads were connected to the supply at the initial plant

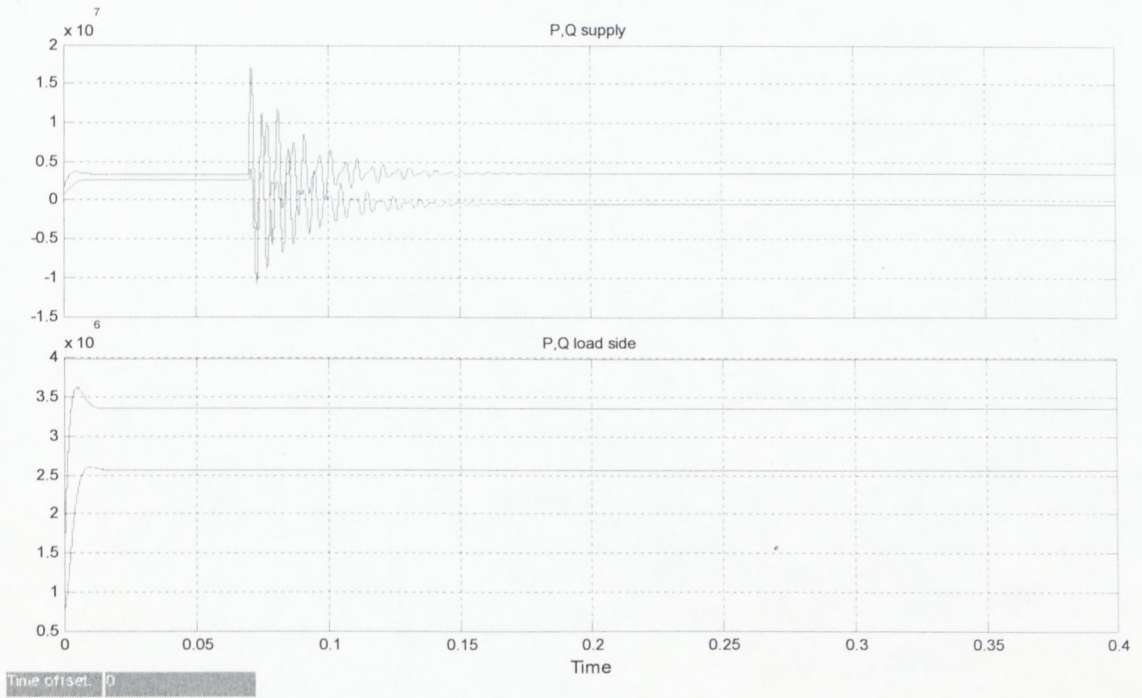
operating period, that is, at 0 second. Initially, the loads were connected to the system and operated without STATCOM, at 0.07s, STATCOM was connected to the circuit and the following was observed:

At the period 0-0.07s when loads operated without STATCOM, the phase difference between voltage and current was observed (refer arrow a) in Figure 11.33. This means that, the power factor without STATCOM is 0.79 lagging. The current was also higher compared with that obtained when STATCOM had switched on to the circuit. At 0.07s STATCOM was switched on, at the instant of switching, transients were noted, this occurs due to the influence of switching. These transients are lasting for short period, after 0.11s they settle down and the loads operate at steady state and the power factor has improved to 0.99 (refer arrow b Figure 11.33). The value of power factor can be also observed in Figure 11.36.

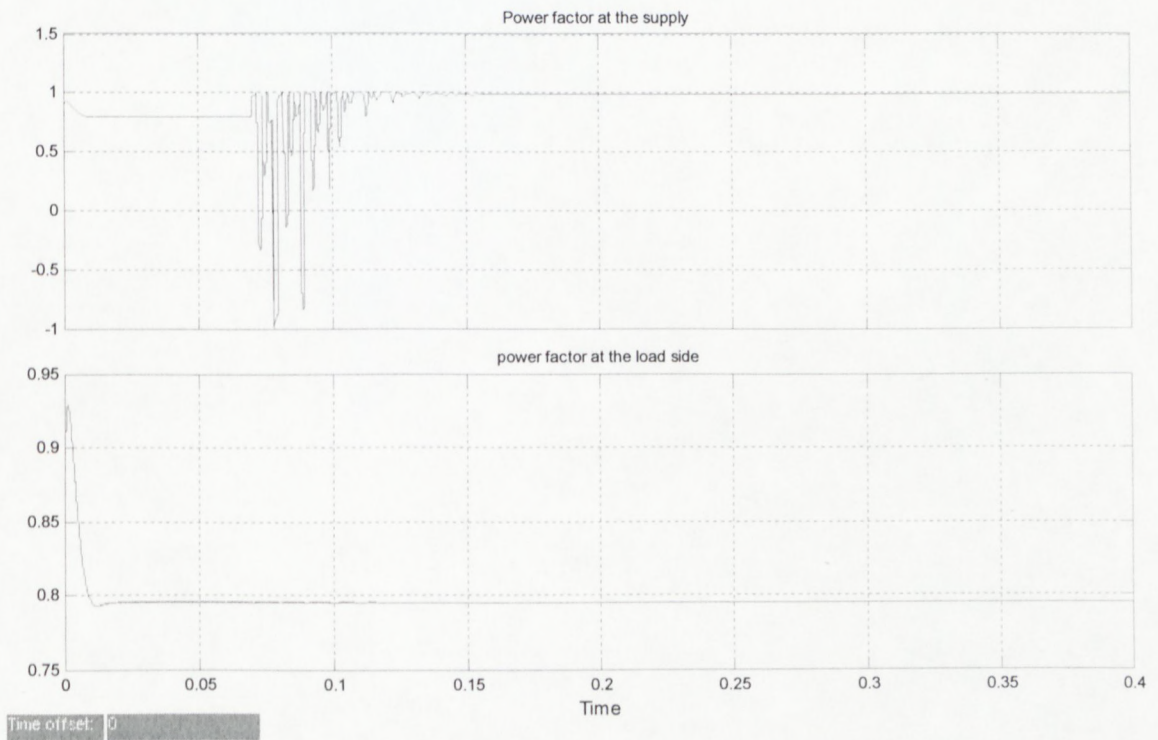


**Figure 11.34:** STATCOM Voltage and Current

Figure 11.34 shows the characteristics of STATCOM voltage and current before and after it is connected to the circuit. It was observed that, at the initial time, when  $t = 0$ , the STATCOM current is very small or negligible. The small value obtained is due to the leakage. Once it is connected to the system, the alternating current flows to the system.



**Figure 11.35:** Active and Reactive Power (P and Q) of the Loads When STATCOM Is In Operation



**Figure 11.36:** Power Factor Measured at the Supply and Load Side

Figure 11.35 and Figure 11.36 show the active and reactive power of the system when STATCOM was connected to the circuit. Again at the initial period when the STATCOM was connected, the active and reactive power oscillates for a short period. The transient period was slashed down and the system operated at steady state condition. From 0.15s steady state value of active and reactive power and power factor of the plant was observed. Figure 11.36 also shows the oscillating value of the power factor at the initial period, this is caused by the transients. At the initial period both active and reactive power is 0. After transients, reactive power in the supply side has reduced, thus leads the system to operate at the improved power factor.

### 11.2.2.2 Kiln and Cement Mill Loads

This section presents simulation results of the kiln and cement section loads with STATCOM. Figures 11.37-39 show the voltage and current measurements of the combined Kiln and cement mill loads, where the STATCOM was connected at 0.07s period. It was observed that, the performances are the same as the one explained for the Figure 11. 31-33, the only difference is, the current and phase difference is a bit bigger due to the high capacity of cement mill section loads.

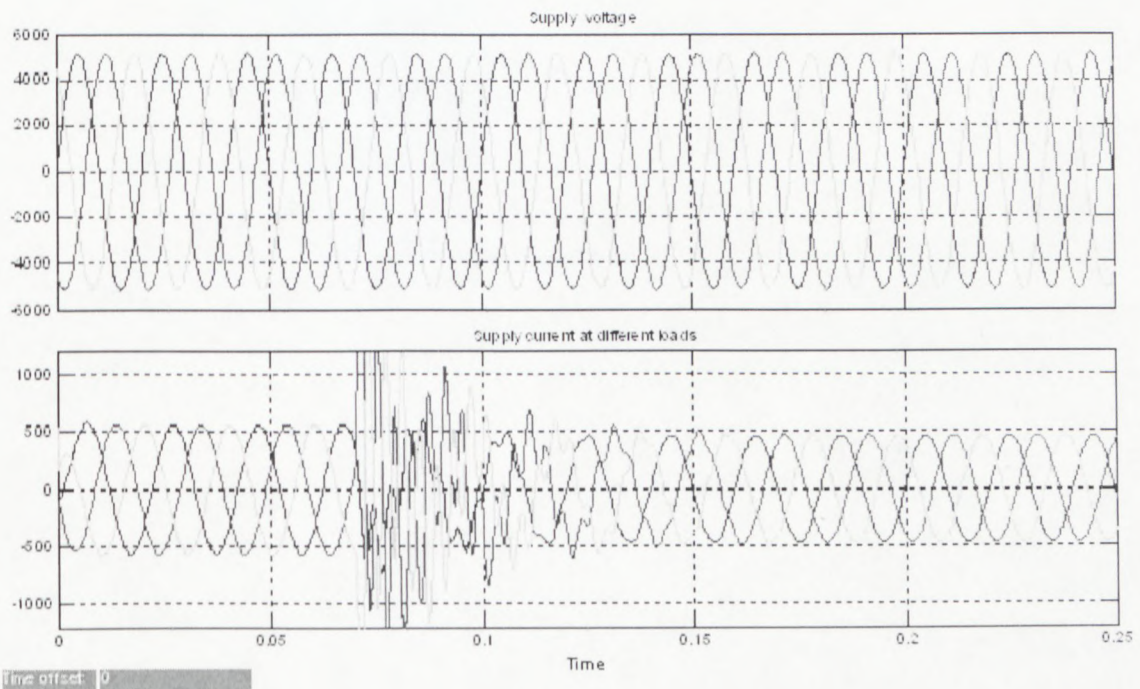
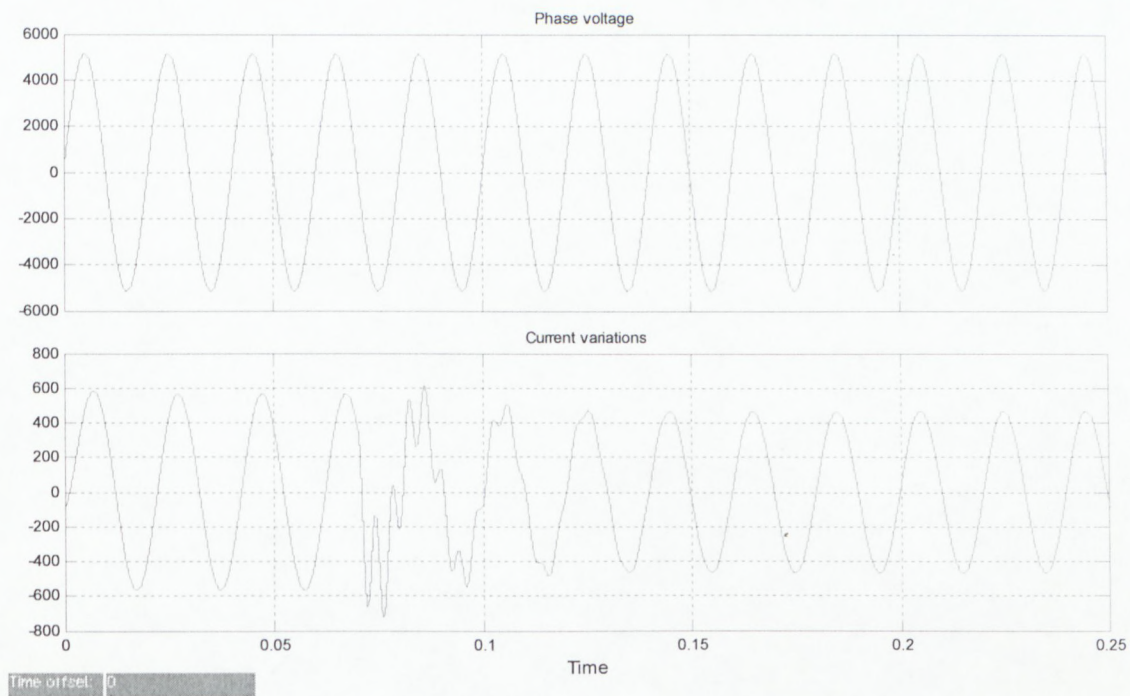
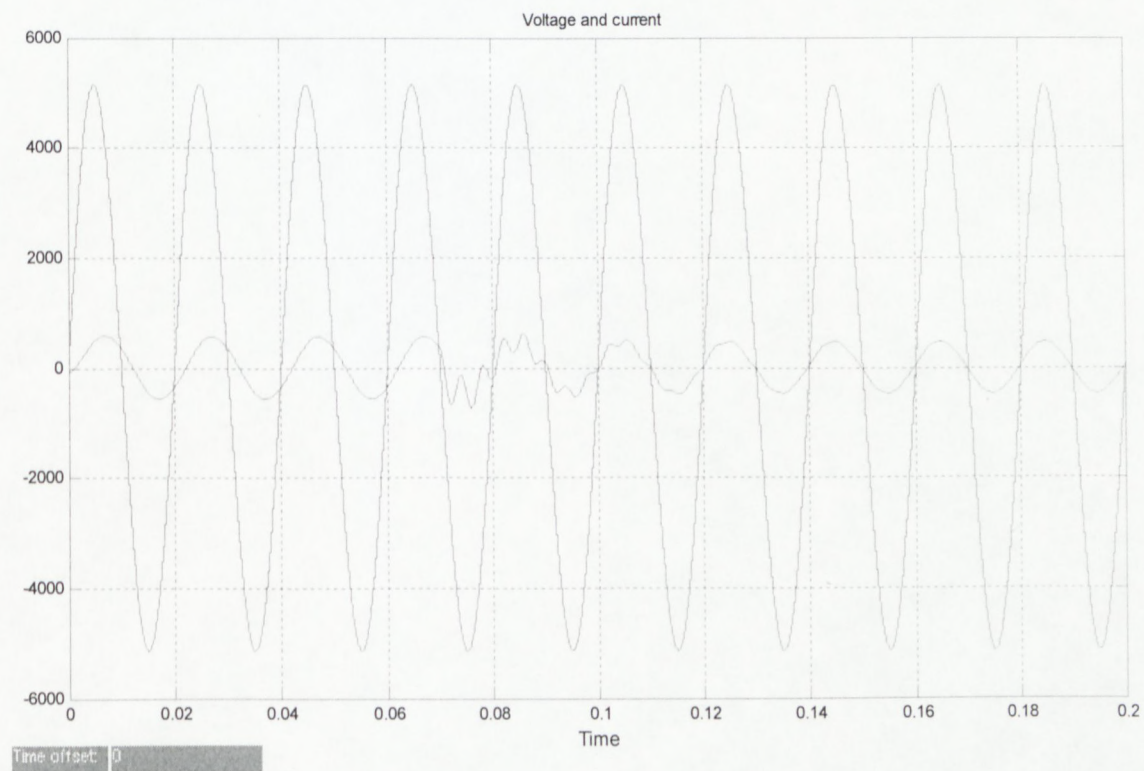


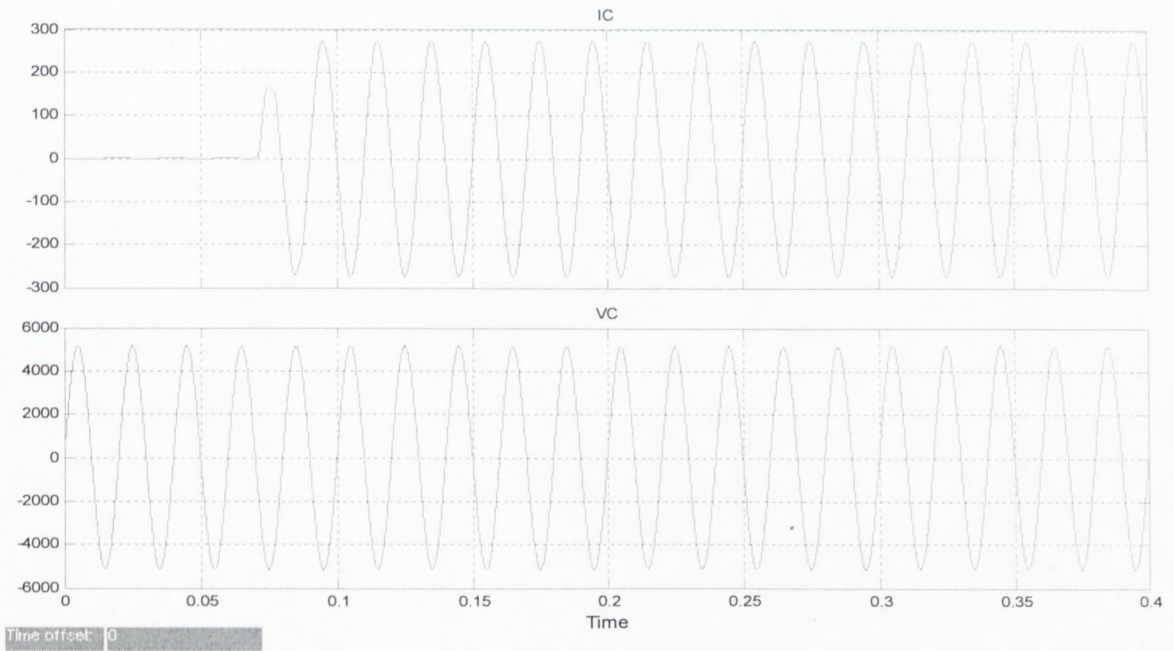
Figure 11.37: 3 Phase Voltage and Current



**Figure 11.38:** Phase 'A' Voltage and Current Measurement



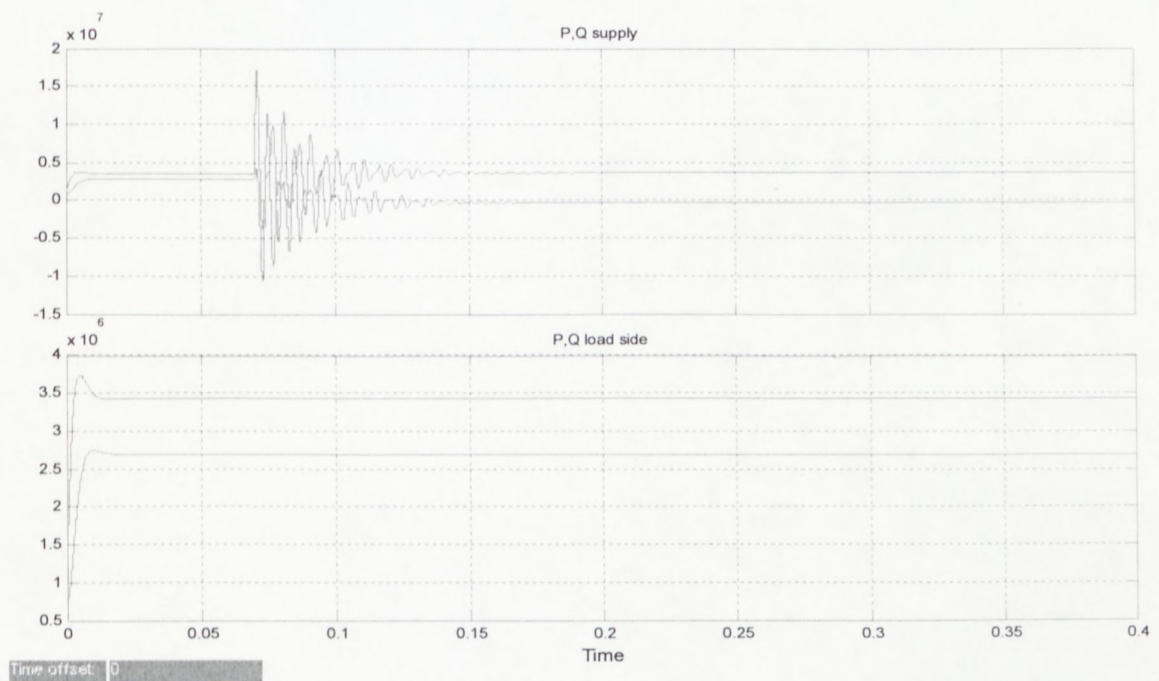
**Figure 11.39:** Relationship between Voltage and Current



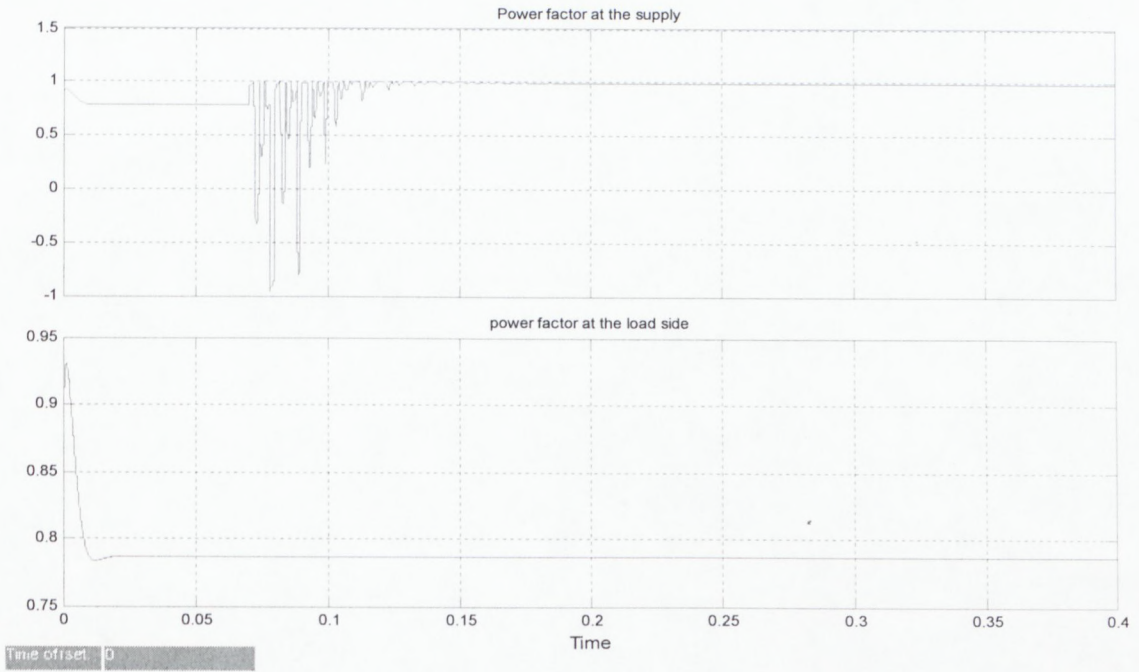
**Figure 11.40:** STATCOM Voltage and Current

Figure 11.40 is the STATCOM voltage and current characteristics. The behaviour and characteristics are the same as obtained in Figure 11.37.

Figures 11.41 and 11.42 are the measurement of active and reactive power and the power factor taken at the supply and load side respectively. Their characteristics again are similar to those explained in Figure 11.35 and 36.

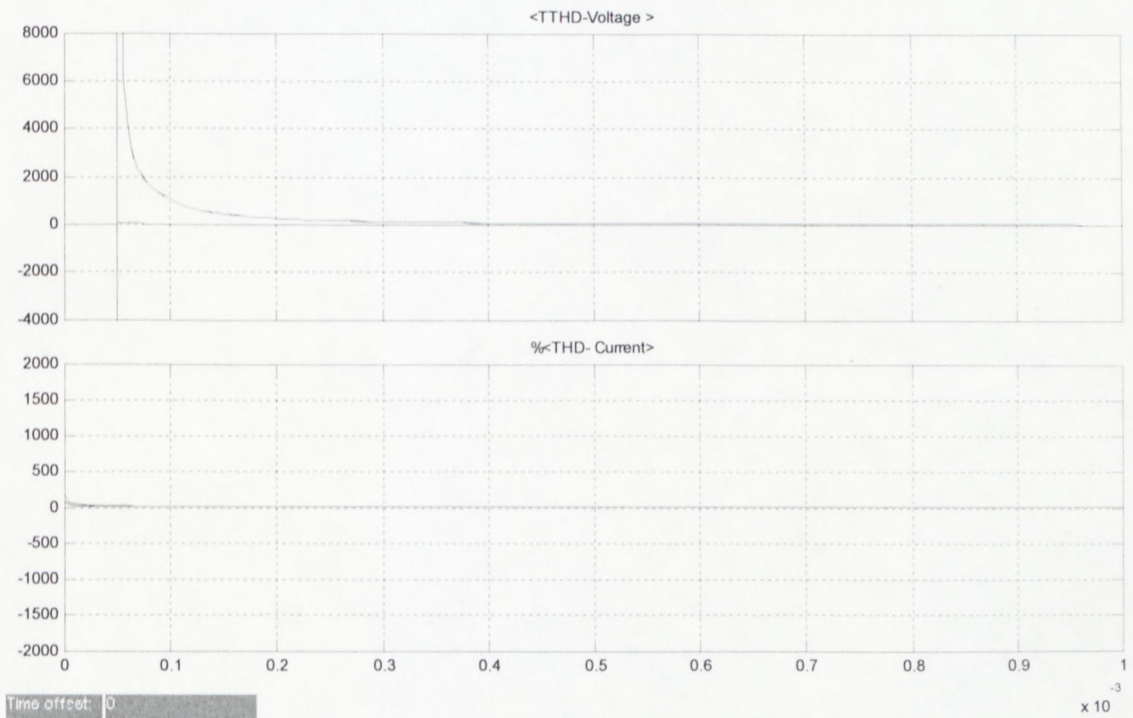


**Figure 11.41:** Measurement of Active and Reactive Power Measurement



**Figure 11.42:** Power Factor Measured at the Supply and Load Side

Figure 11.43 shows the total harmonic distortions, it was observed that, by connecting the STATCOM in the system the harmonic distortion was improved. The figure shows that, the harmonics presented in the system were almost negligible. The total transient period is 0.25ms.



**Figure 11.43:** THD of the System

### 11.2.2.3 STATCOM with Variable System Loads (All loads have been considered)

Figures 11.44 - 47 show the voltage and current measurements as presented in Figure 11.31-33. In these figures all loads were connected in the system but they are varied (switched on or off at the alternate time). At the initial period only kiln loads were connected to the system. After 0.05s the raw mill loads were also added to the system (kiln load). The time for the connection of raw mill loads was selected as [0.05—0.15, 0.25]. This means that, the raw mill section loads were on from 0.05-0.15s, whereas from 0.15-0.25 the raw mill loads were off and started again at 0.25s and remained until the end of the simulation period.

The STATCOM was switched at 0.08 and remain connected for the whole operating period. When the raw mill section loads were turned off at 0.15s, the cement mill loads were connected to the system for the remaining simulation period. From the figures it was observed that, at 0.25s all loads were connected to the system. This was the normal maximum load of which industry can operate. Before STATCOM [0-0.08s], there was a phase difference between the voltage and current, after the STATCOM was connected to the system, no matter the variation of loads the phase different is almost negligible that is the system power factor was approaching unity; thus the power factor has improved. For example at the period [0.25-0.4s] when all plants loads are connected the power factor is 0.978 lagging.

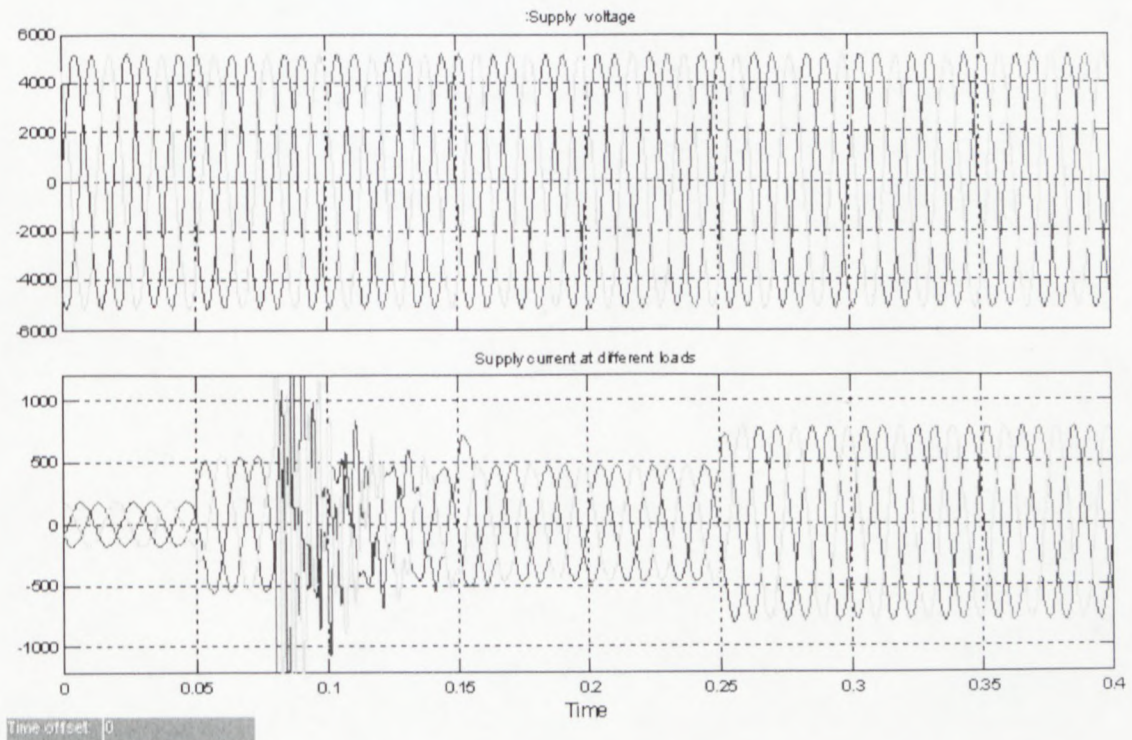
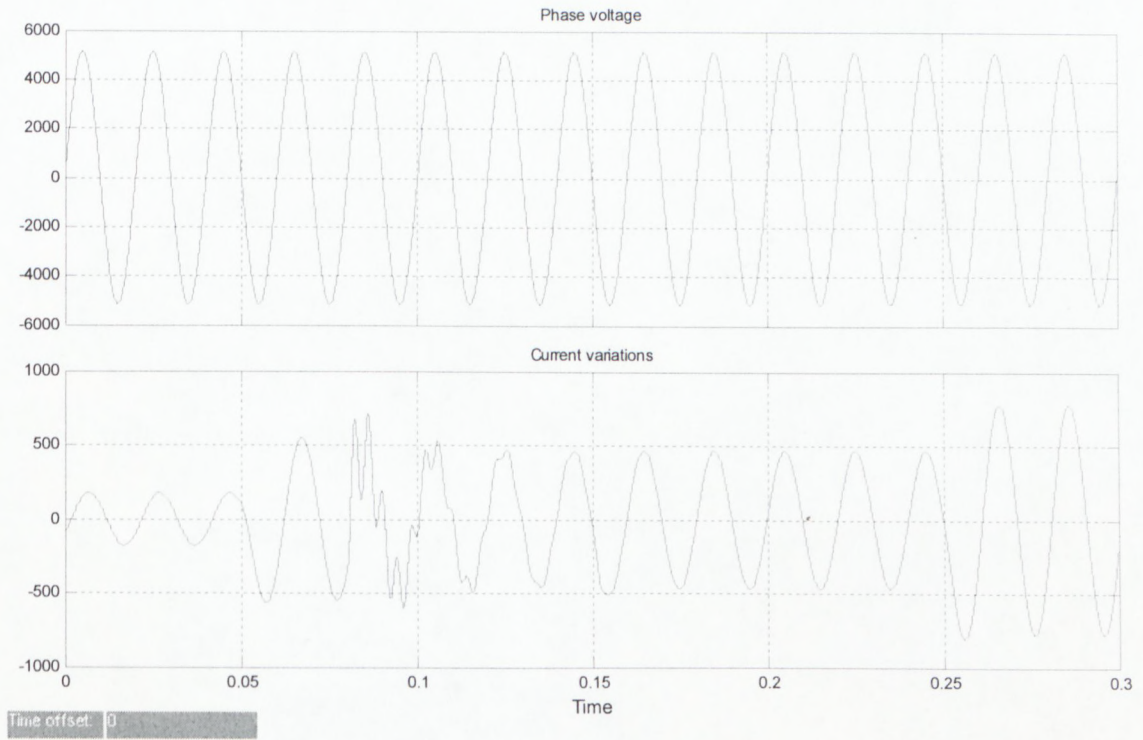
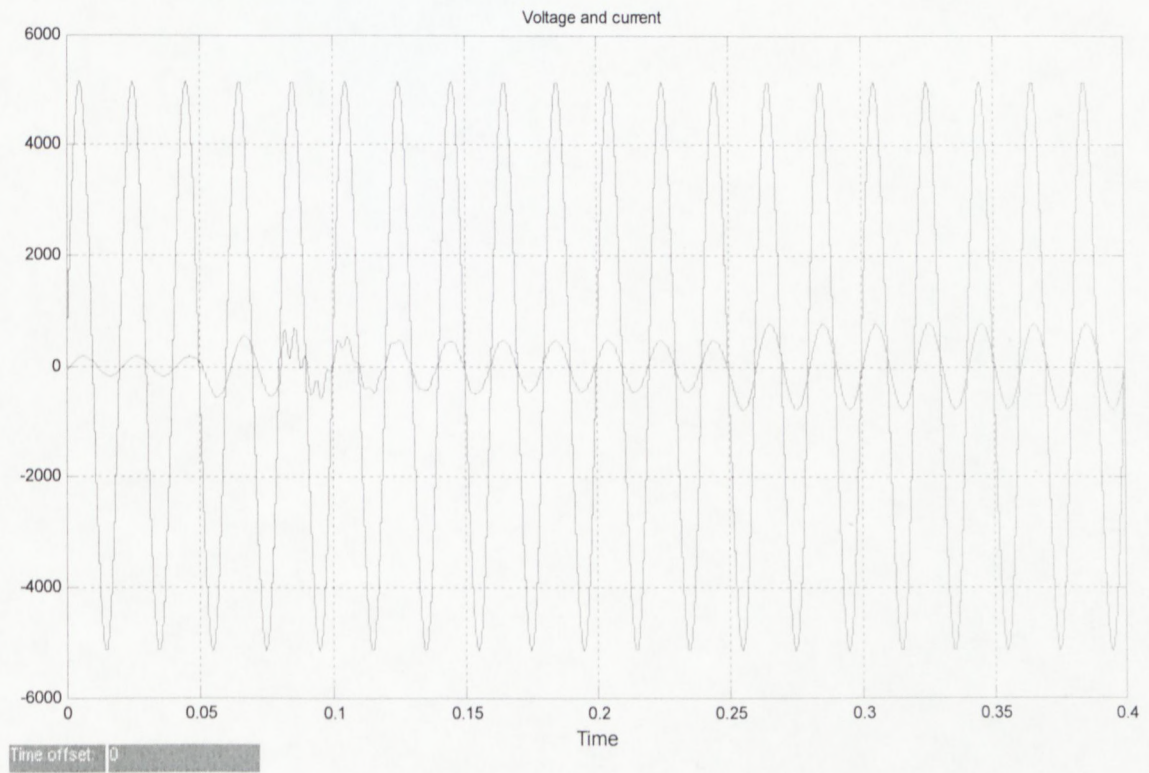


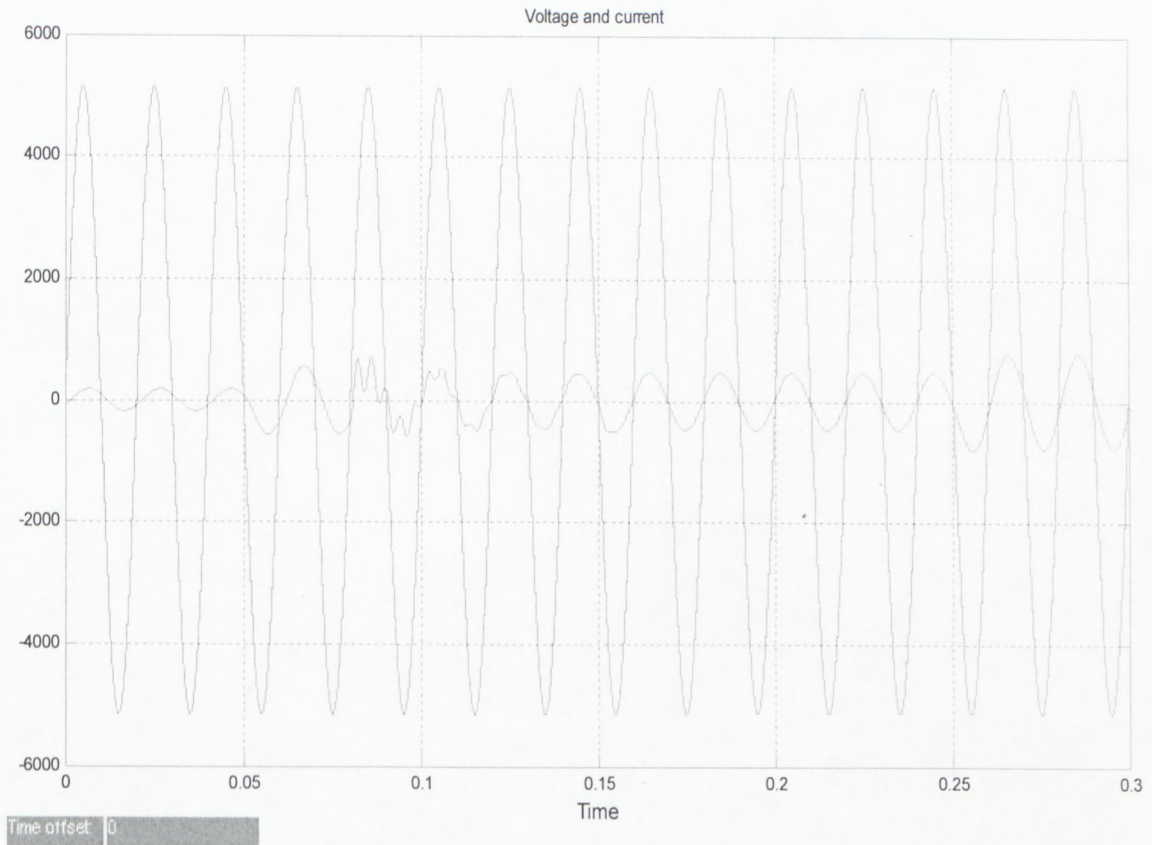
Figure 11.44: 3 Phase Voltage and Current



**Figure 11.45:** Phase 'A' Voltage and Current Measurement

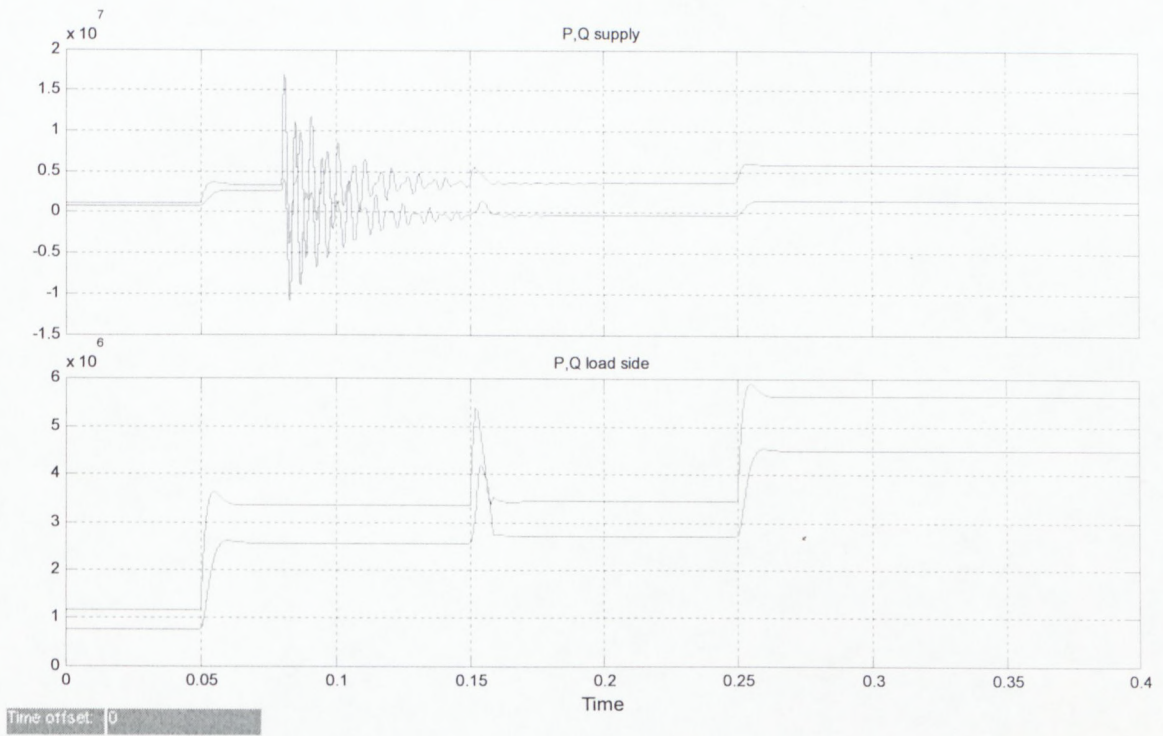


**Figure 11.46:** Relationship between Voltage and Current

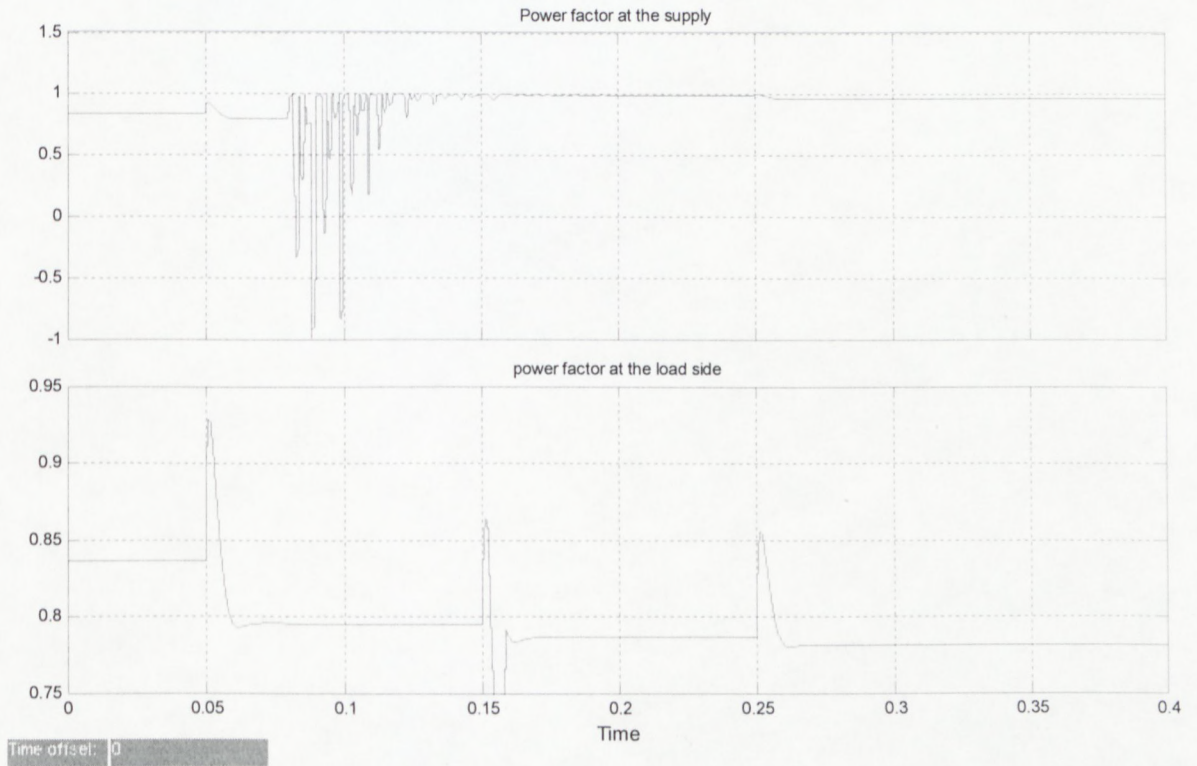


**Figure 11.47:** Relationship between Voltage and Current

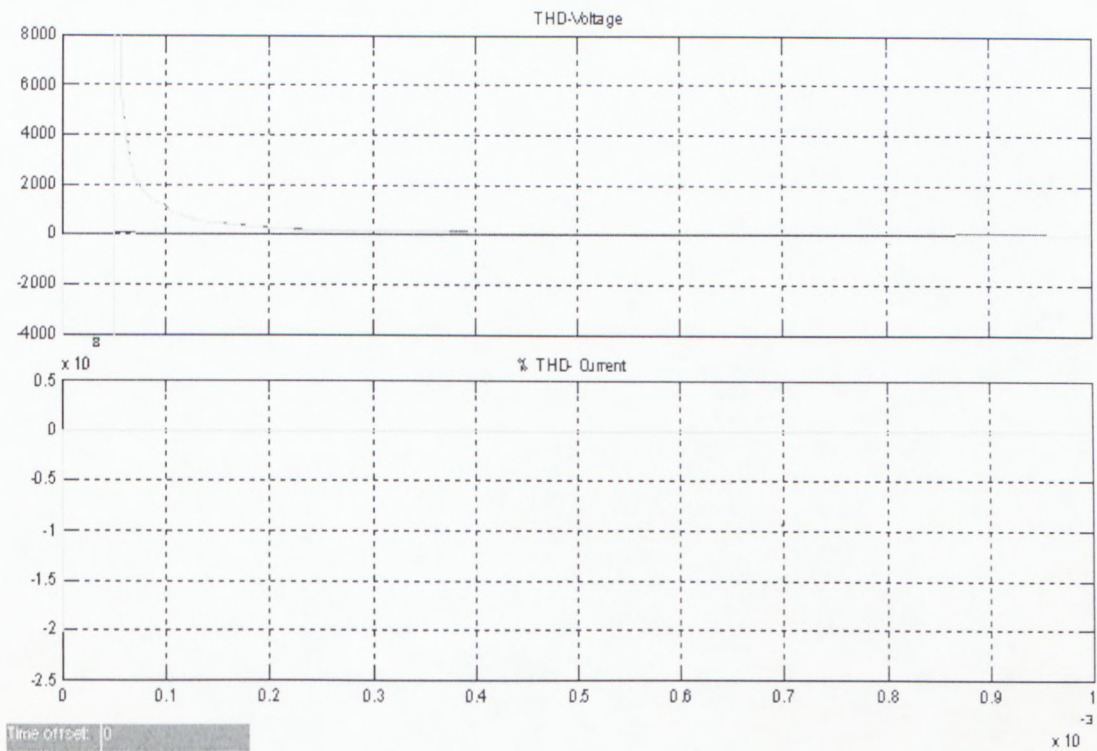
Figures 11.48 present the active and reactive power measurements and power factor measurements taken from the supply and the load side. The reactive power of the load was compensated by the use of STATCOM. In these figures it was observed that, without the compensator, the transient current is high at the instant of switching from one load to another. When STATCOM was connected, the load switching transient is reduced and this is observed in curves (load side measurement) of the Figures 11.49. Without STATCOM, the power factor is varying with variation of loads. With compensator, the power factor was improved to a near unity for any plant loads.



**Figure 11.48:** Active and Reactive Power (P and Q) at Variable Loads When STATCOM Is In Operation



**Figure 11.49:** Power Factor Measured At the Supply and Load Side



**Figure 11.50:** THD of the System

Figure 11.50 shows the total harmonic distortion of the system when plant operates at variable loads. It was observed that, the THD was negligible due to the influence of the compensator.

#### 11.2.2.4 STATCOM Connected at the Initial Time

The simulations intended to analyse the behaviour of STATCOM when it was switched on together with loads at the initial period [0s]. In this simulation, all loads were connected, but switched on or off in a variable manner.

Figure 11.51- 52 show voltage and current measurements of the industry under variable loads. In this simulation, the compensator was connected and switched together with loads at the initial period, 0s. The transient current occurs at the transient periods, when the compensator was connected to the system. The remaining period was the steady state period. At the steady state period, the power factor of the system improved.

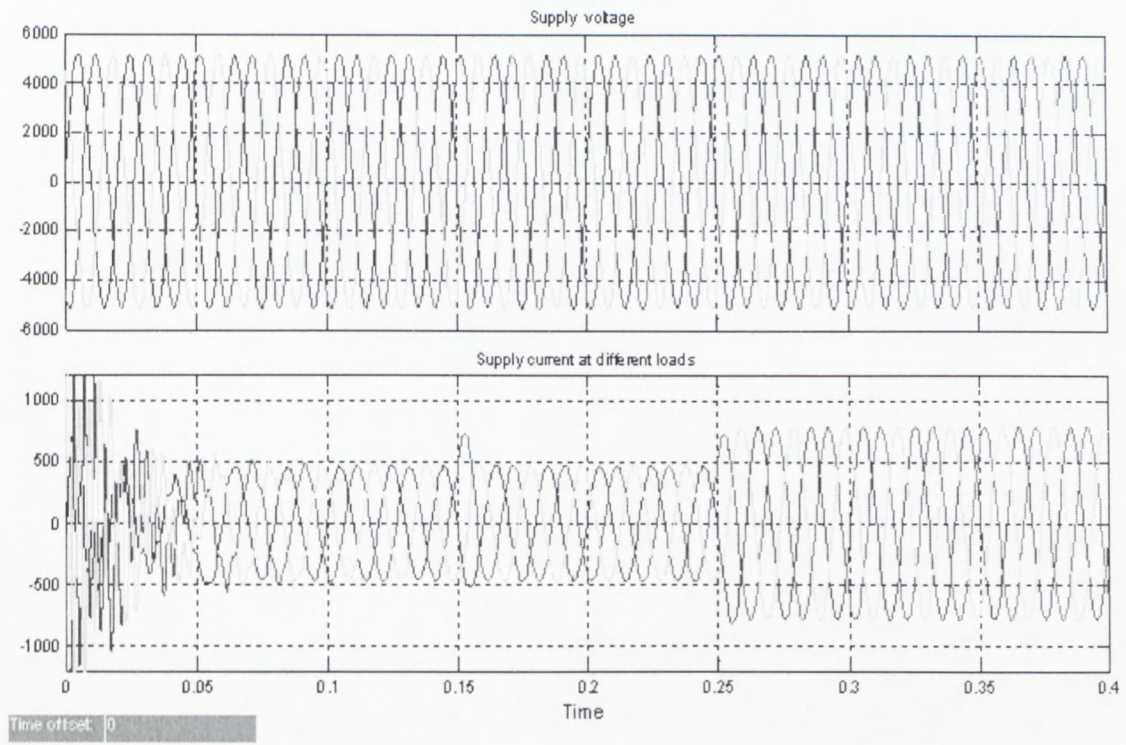


Figure 11.51: 3 Phase Voltage and Current

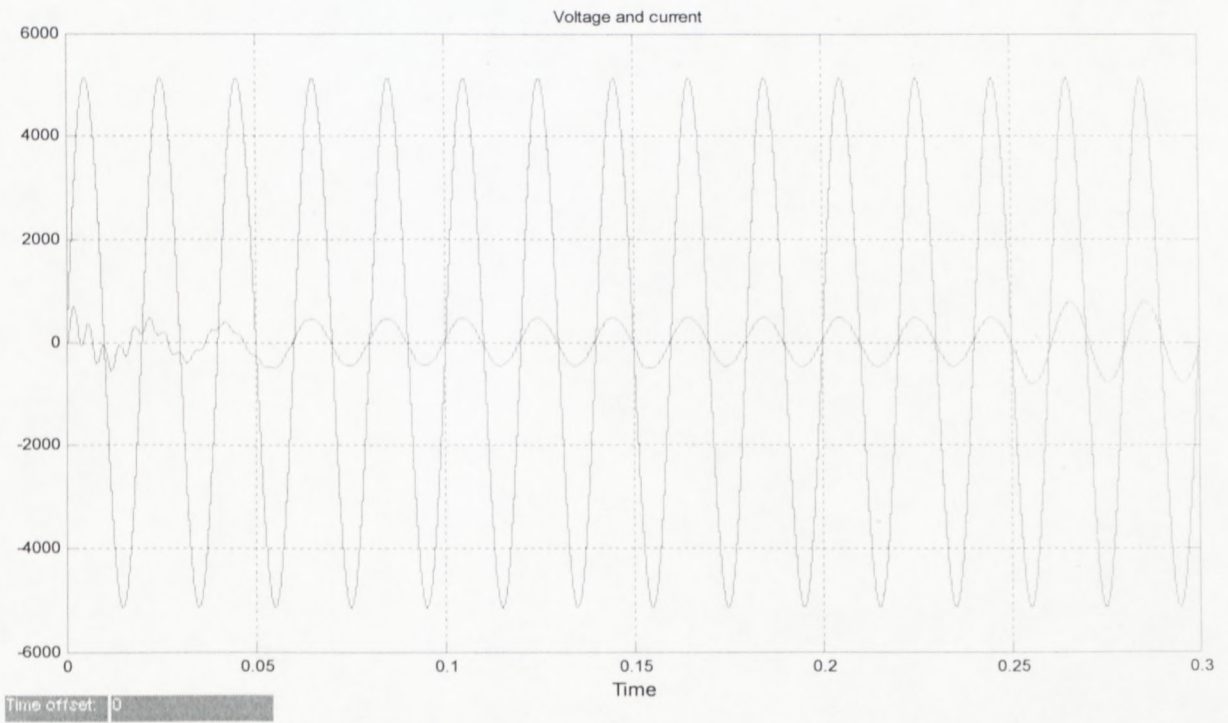
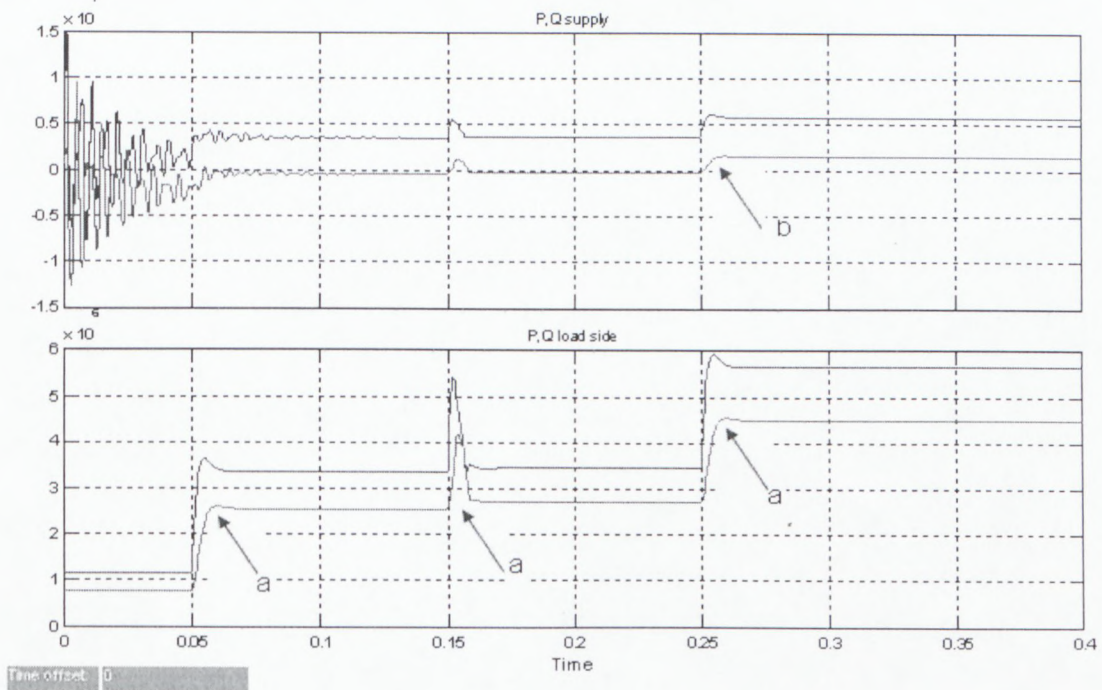


Figure 11.52: Relationship between Voltage and Current

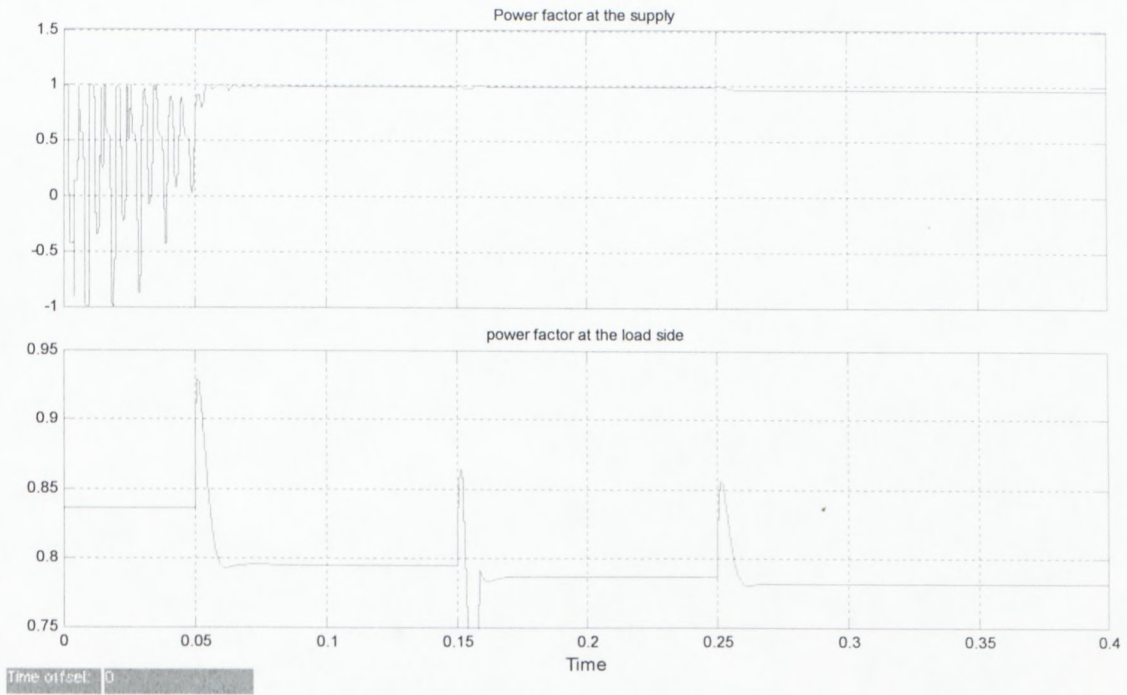


**Figure 11.53:** Active and Reactive Power (P and Q) Of the Loads When STATCOM Is In Operation

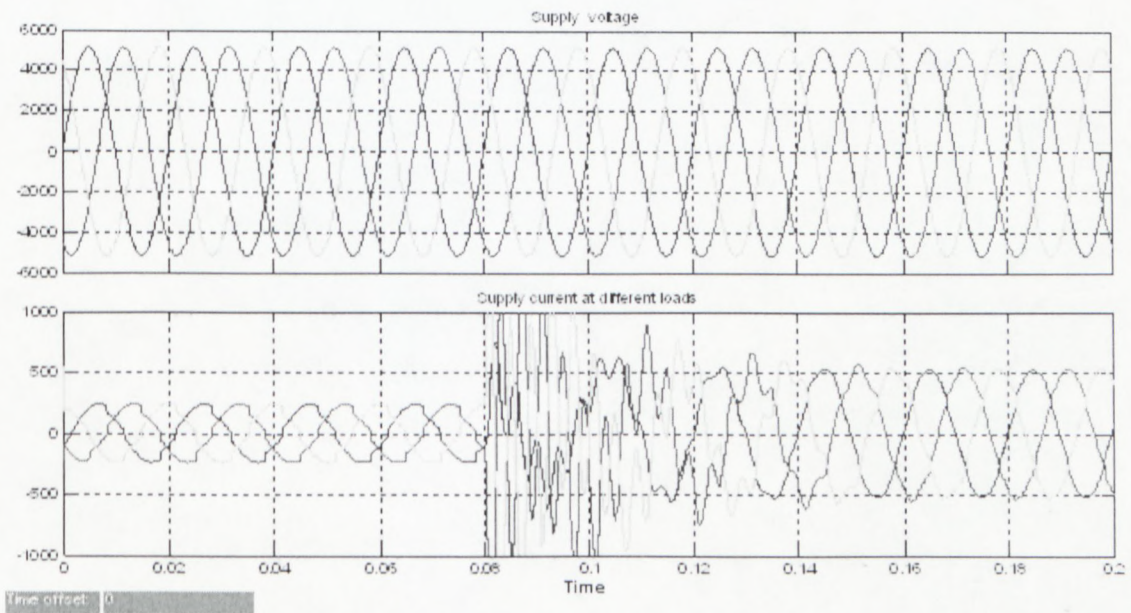
Figures 11.53 - 54 show active and reactive power and power factor of the plant. The Figure also shows the sudden raises of active and reactive power in the load side caused by switching of one load to another (point a). On the supply side this abrupt raise of active and reactive power has improved due to the influence of STATCOM (point b). For example at 0.15s when the raw mill is disconnected and the cement mills loads are switched on, at the load side measurement, the active and reactive power seems to be high, while the measurement at the supply side was improved below 5MW. The reactive power drawn from the supply also had decreased. The power factor of the whole system had immediately improved after transient period.

#### 11.2.2.5 Kiln Load, Cement Mill load + 5% Nonlinear Loads

The following simulations show the behaviour of plant load with STATCOM when 5% of total loads were nonlinear loads and were connected to the system at the initial period [0s]. The connected loads at the initial period were nonlinear load and kiln loads. STATCOM was switched on after 0.08s and cement mills loads were connected at 0.15s



**Figure 11.54:** Power Factor Measured At the Supply and Load Side



**Figure 11.55:** 3 Phase Voltage and Current

Figures 11.55-57 present the simulation results of voltage and current measurements of the industry obtained by considering variation of loads. Before the STATCOM was connected to the system the current distortion was observed. This distortion was caused by the presence of nonlinear loads. When the STATCOM was switched on to the system, the transient condition occurred for a period of transient, and there after

the distortion was compensated by the STATCOM current and steady state operating regime was reached.

The phase difference between voltage and current was also observed before the connection of the compensator. After the compensation, the voltage and current seem to be almost in phase.

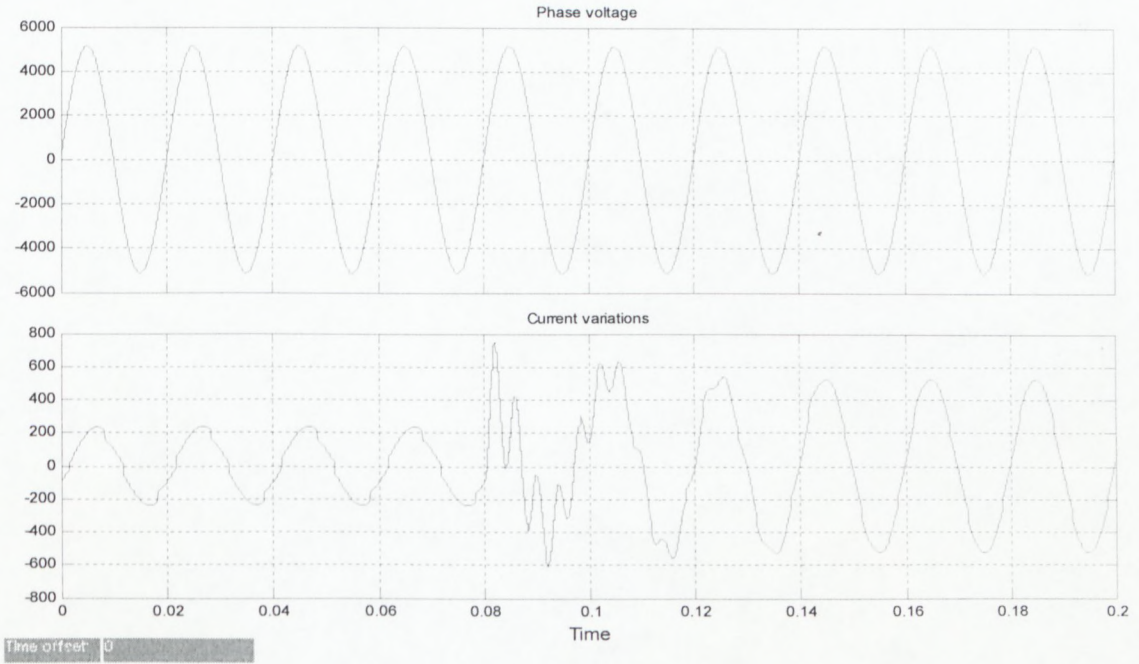


Figure 11.56: Phase 'A' Voltage and Current Measurement

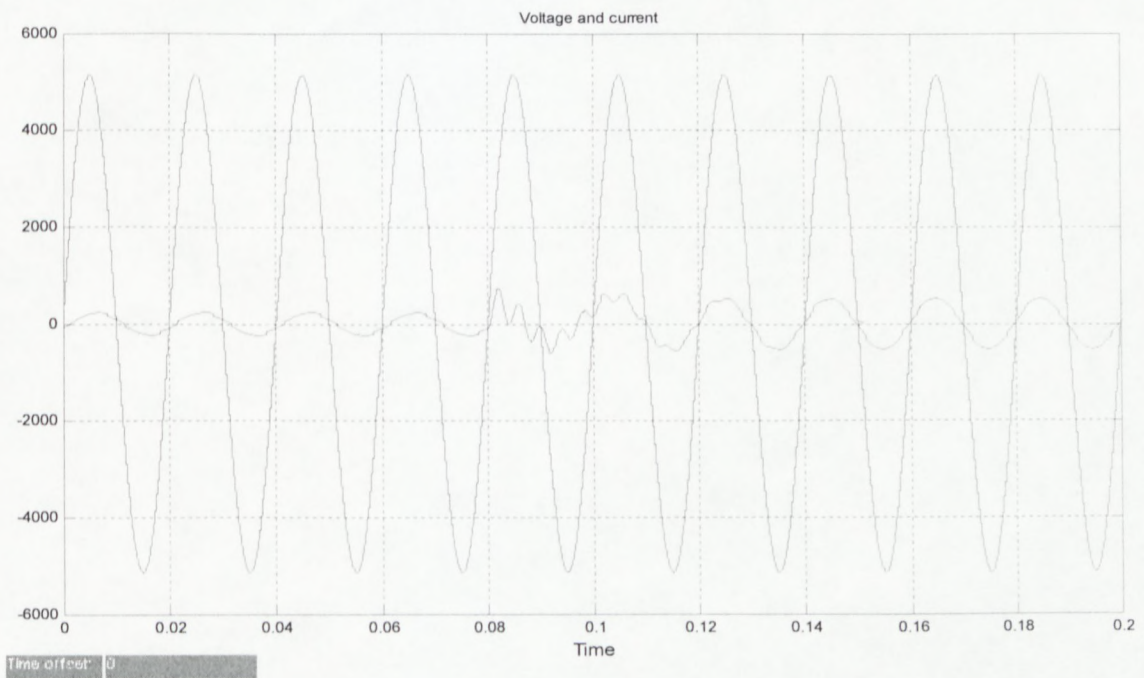
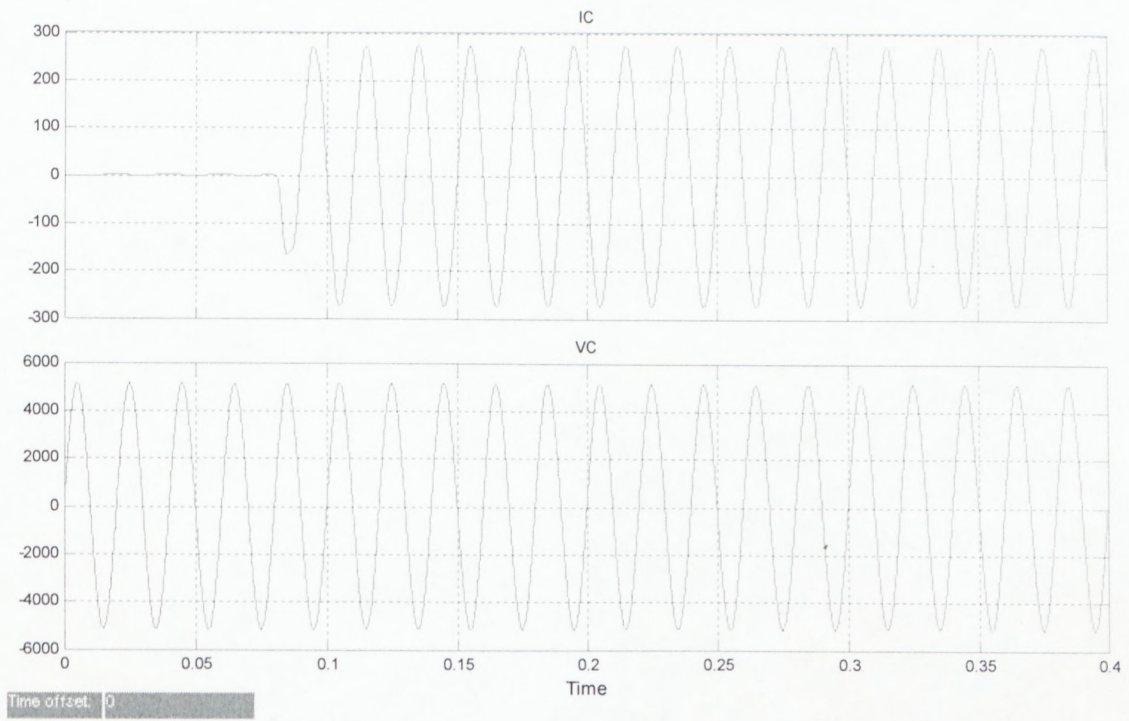
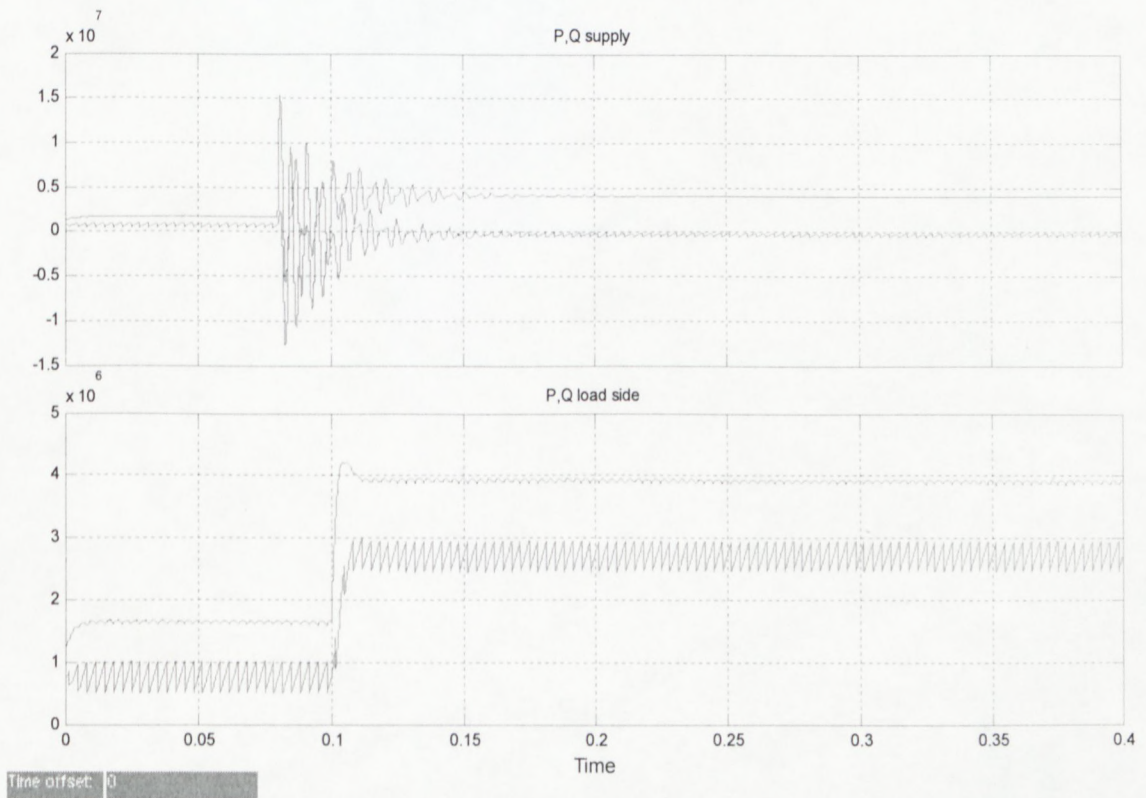


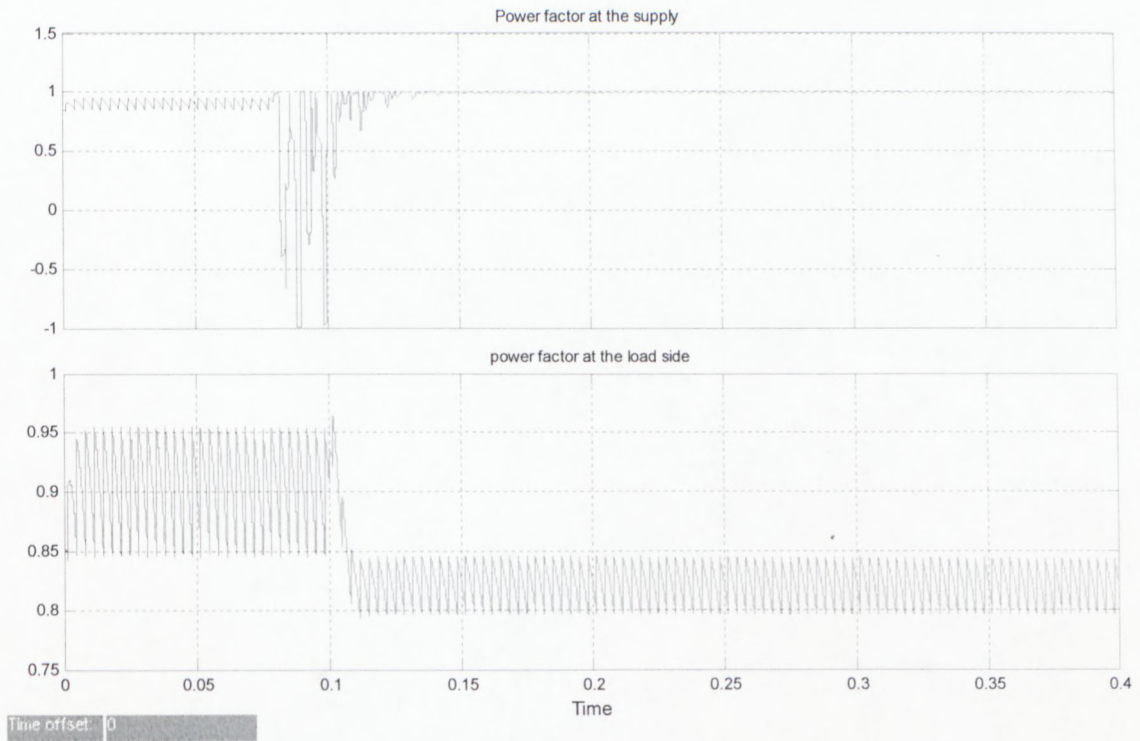
Figure 11.57: Relationship between Voltage and Current



**Figure 11. 58:** STATCOM Voltage and Current

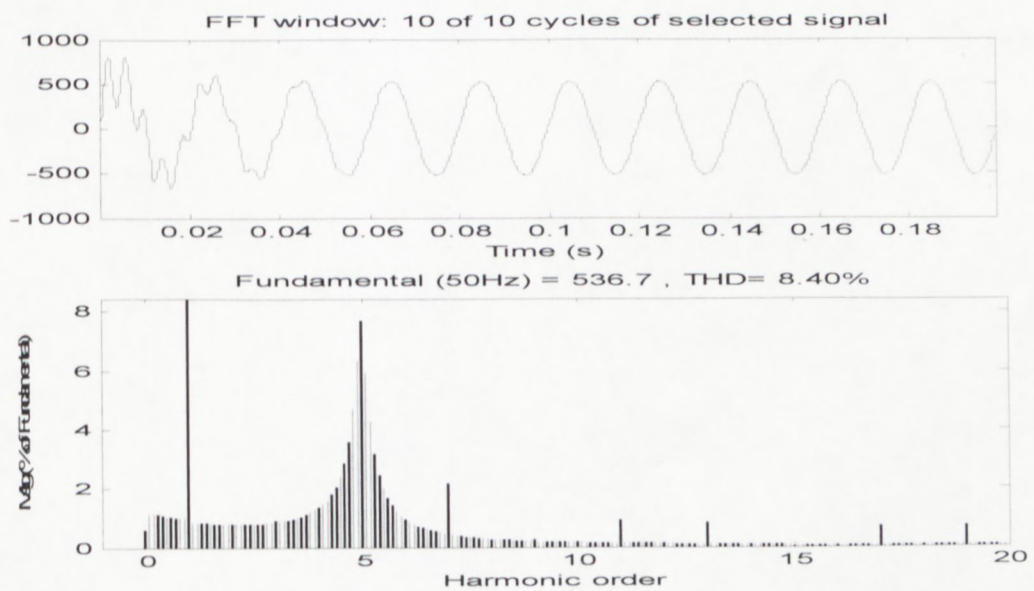


**Figure 11.59:** Active and Reactive Power (P and Q) of the Loads When STATCOM is in Operation



**Figure 11.60:** Power Factor Measured at the Supply and Load Side

Figures 11.59-60 present the active and reactive power measurements and power factor measured in the supply and load side respectively. The distortion of active and reactive power as well as power factor before compensation was higher compared to when the STATCOM was connected in the circuit at 0.08s. After the transient period, the power factor improved. Figure 11.61 shows the harmonic distortion of the system, again the distortion was of a small value, that is, equivalent to 8.4%



**Figure 11.61:** THD of the System

### 11.2.2.6 Simulation of Industrial Loads with 10% of Nonlinear Loads

This simulation analyse the capability of the developed compensator working with nonlinear load condition. Ten percentage of nonlinear loads were connected with the kiln and cement mill section load. The loading condition is the same as the one presented in sub- section 11.2.2.5. All loads were connected at the initial period. The load composition was the kiln and cement mills loads and 10% of the nonlinear loads. Figures11.62-64 show voltage and current measurement under variable load condition. The current distortion and phase difference is observed within the system, which was cleared by the STATCOM.

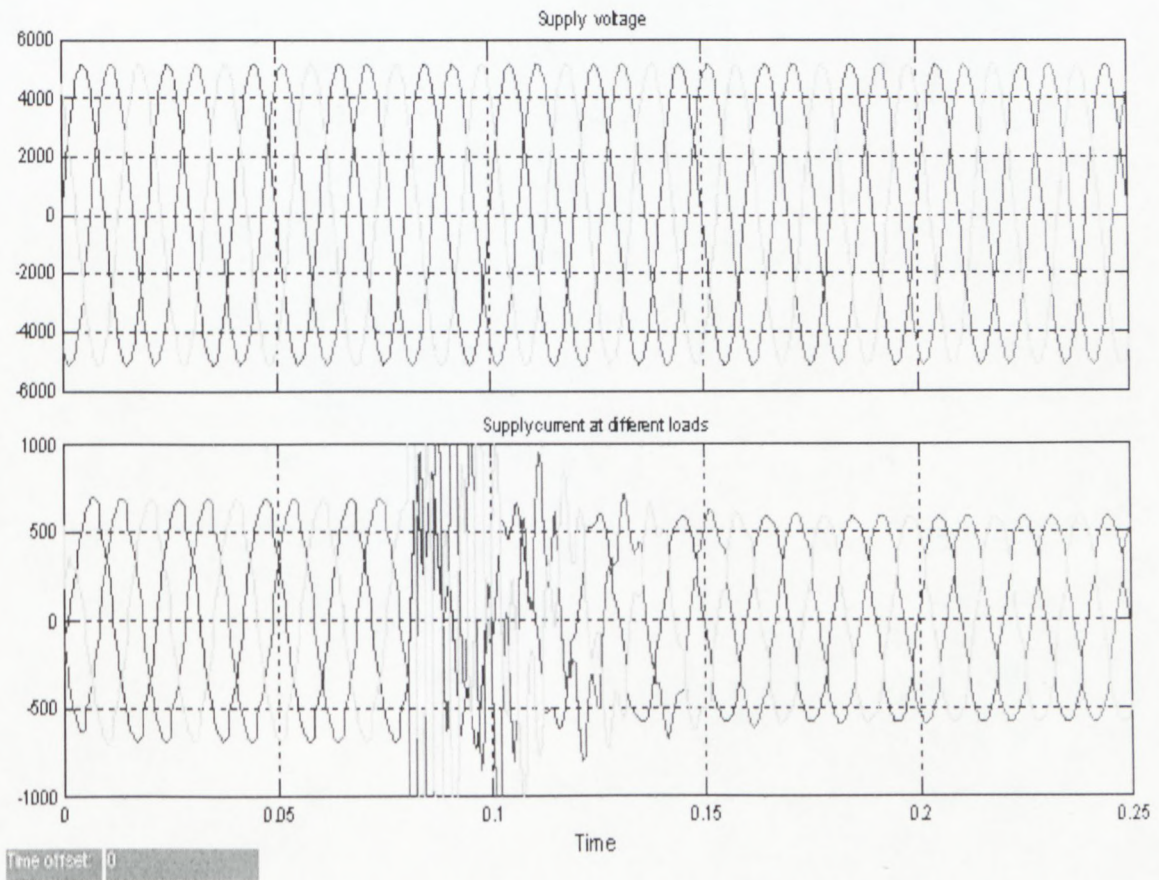
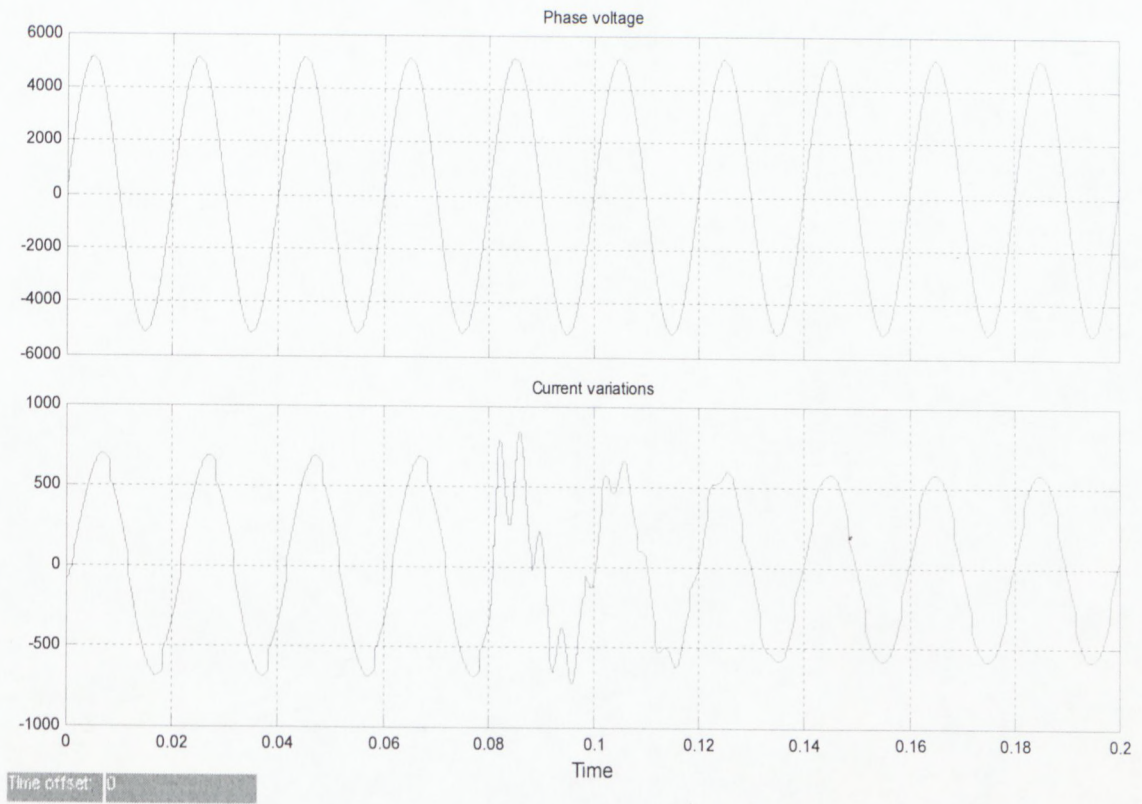
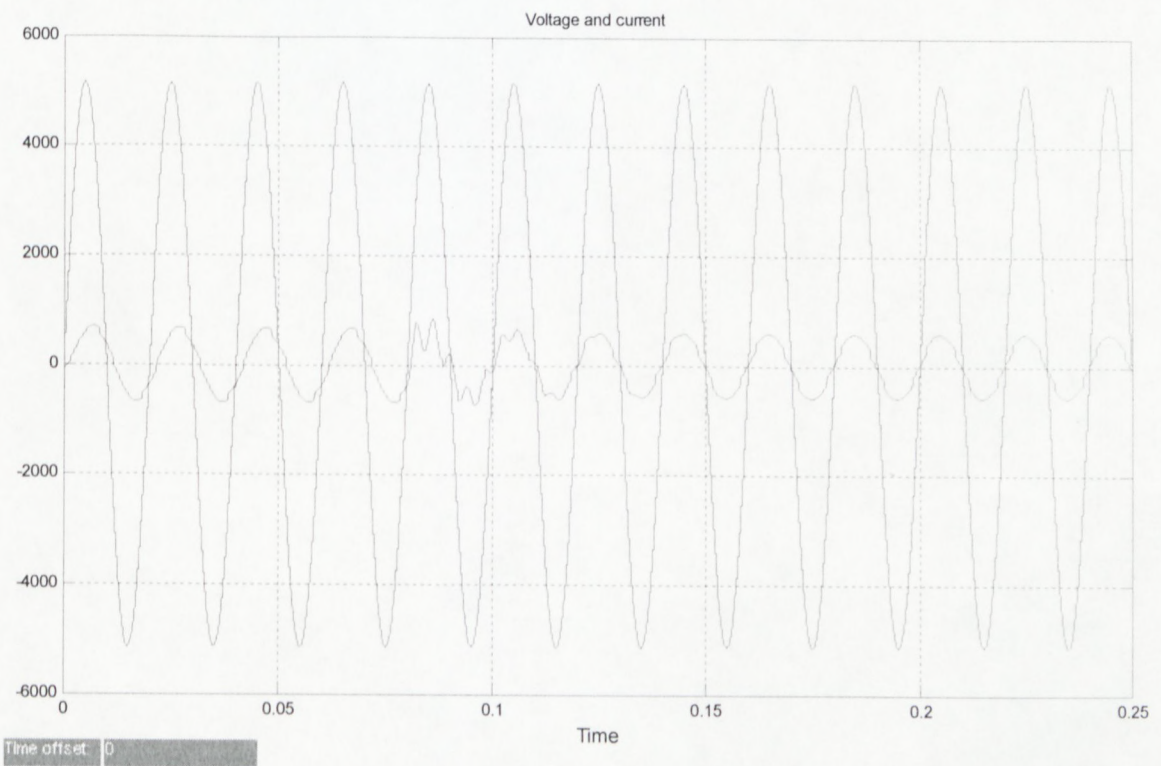


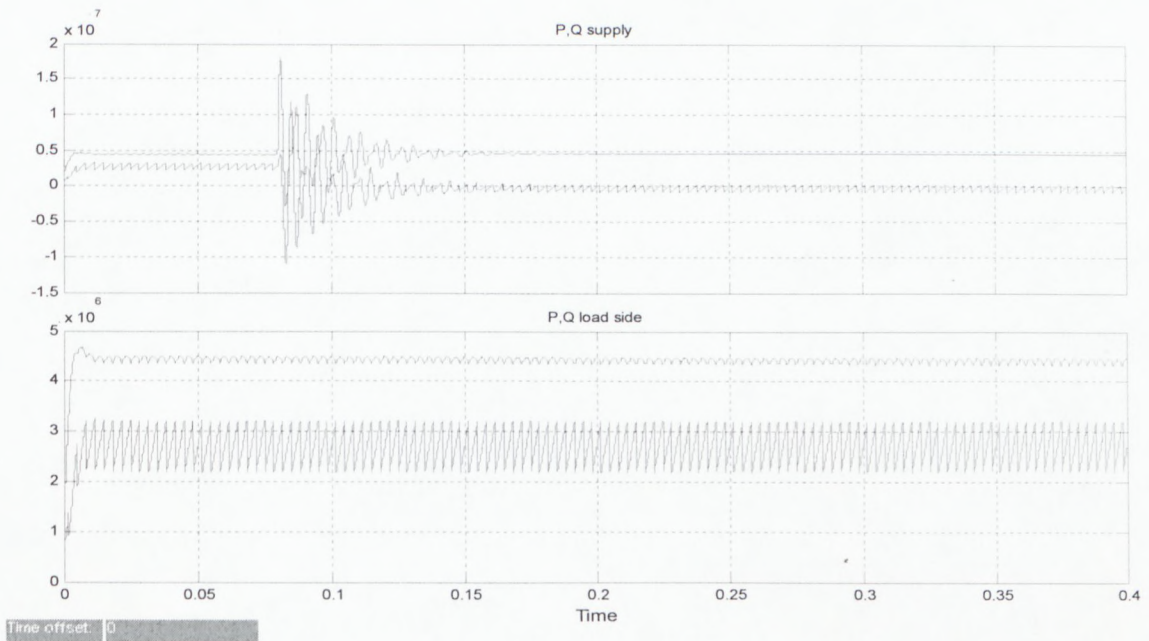
Figure11.62: 3 Phase Voltage and Current



**Figure 11.63:** Phase 'A' Voltage and Current Measurement

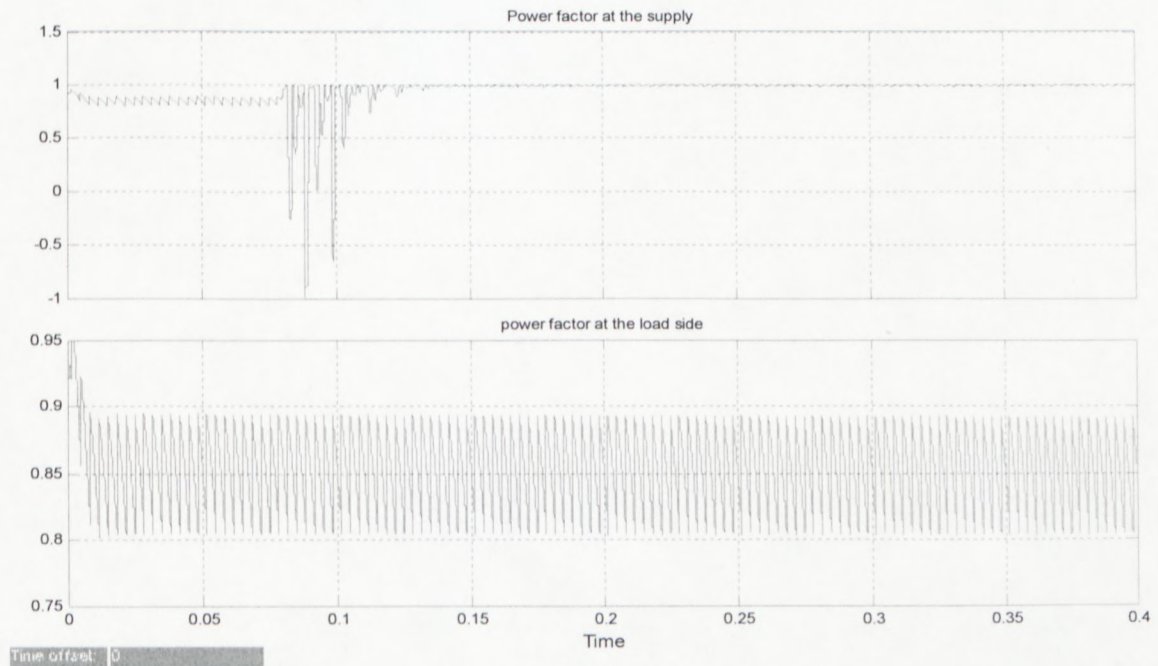


**Figure 11.64:** Relationship between Voltage and Current



**Figure 11.65:** Active and Reactive Power (P and Q) of the Loads When STATCOM is in Operation

Figure 11.65-66, present the active and reactive power and power factor measured before and after the compensation of loads under the mentioned loading condition. These measurements were taken in the load and supply side as well. Apart from the reduction of harmonics which was observed, the load side was not drawing reactive power from the supply as it draw from the STATCOM; hence the power factor of the supply system improved.



**Figure 11.66:** Power Factor Measured At the Supply and Load Side

### 11.3 Simulation Analysis with PSIM Software

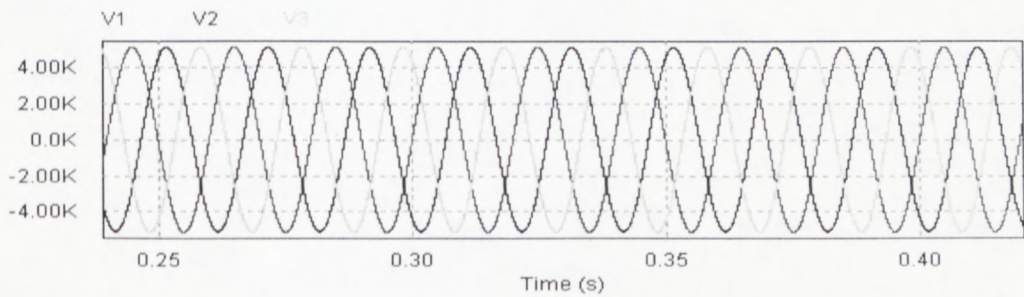
In these simulations, the following load connection scenarios were considered:

- Power factor value was analysed by considering industrial loads without the power factor improvement circuit (STATCOM).
- Power factor and other industrial parameters were analysed when the STATCOM was connected at 300ms.
- Power factor and other industrial parameters were analysed when STATCOM was connected in the system together with loads at the initial period of the plant operation. The plant setup was given as in Figure 8.17.

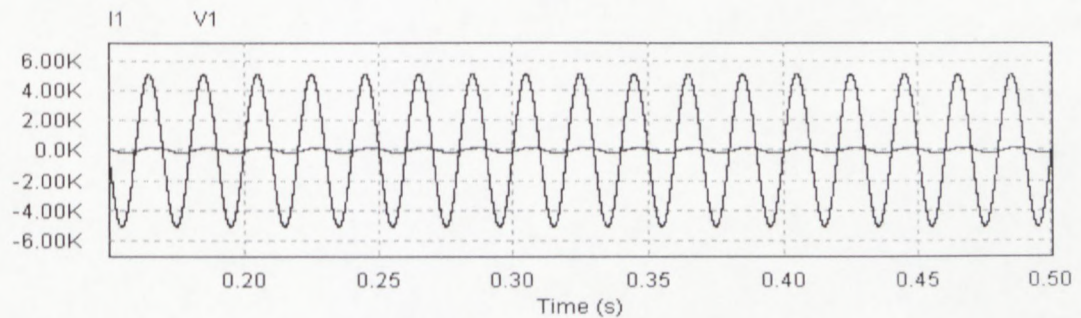
#### 11.3.1 Simulation without STATCOM

##### 11.3.1.1 Kiln Section Loads Only

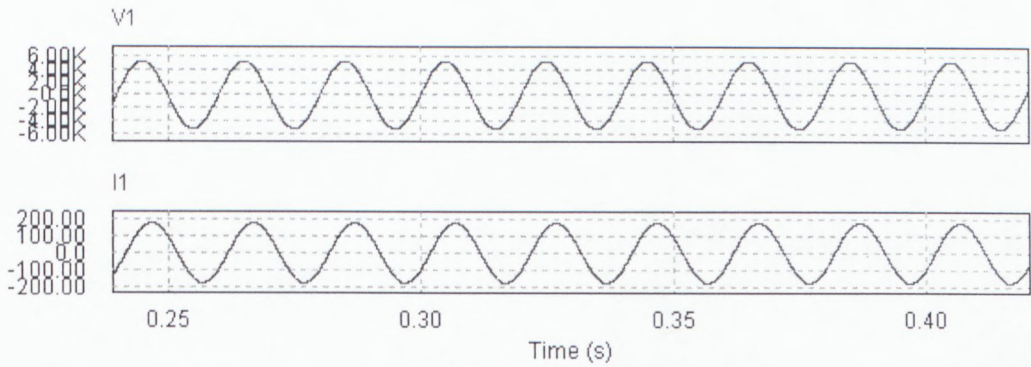
Figures 11.67- 71 show simulation results of the plant when load1 (Kiln) is connected to the power system. Figure 11.67 shows three phase voltage applied to the circuit and Figure 11. 68 and 69 shows the current and voltage in the same X-Y plane and in different Y axis. These results are presenting the real plant data without implementing any power factor correction.



**Figure 11.67:** The Three Phase Voltage Measurement

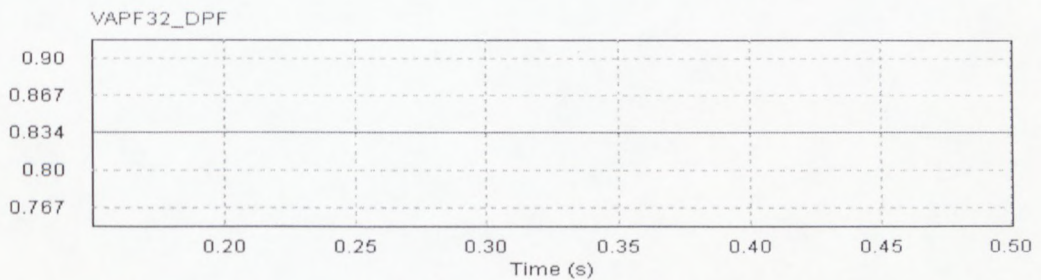


**Figure 11.68:** Voltage and Current Measurements

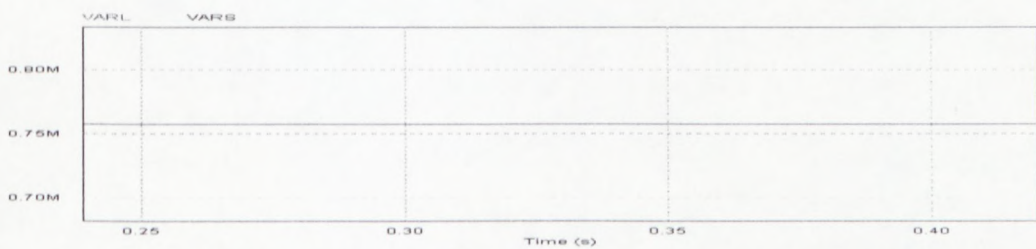


**Figure 11.69:** Phase 'A' Voltage and Current Measurement

Figure 11.70 shows the power factor measurement and Figure 11.71 shows the reactive power value. The reactive power was measured in the load and supply side by VARL and VARS meter respectively. The result showed that, the reactive power of both sides were the same because load and supply were connected to the same terminal. The result reflects the one obtained in MATLAB /SIMULINK analysis.



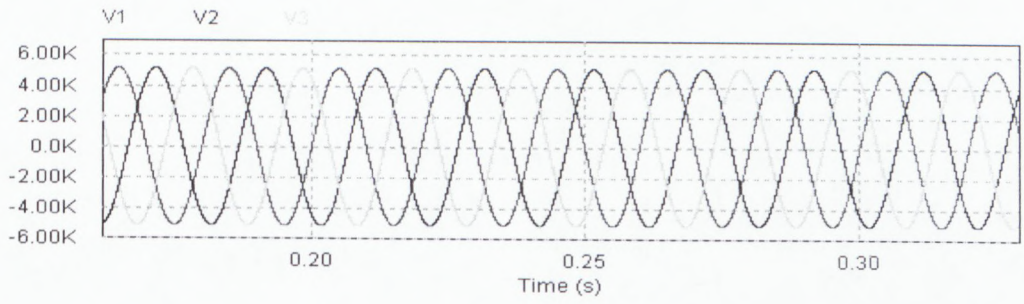
**Figure 11.70:** Power Factor Value



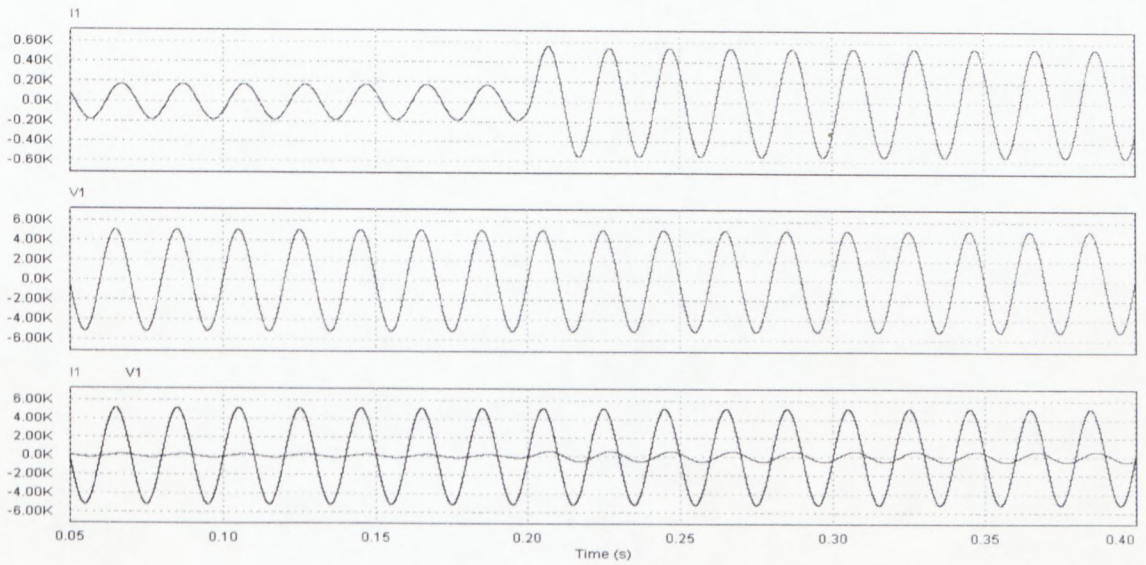
**Figure 11.71:** Reactive Power of the Plant when only Kiln Load is Connected

### 11.3.1.2 Raw Mill Connected With the Kiln Section Loads at a 200ms

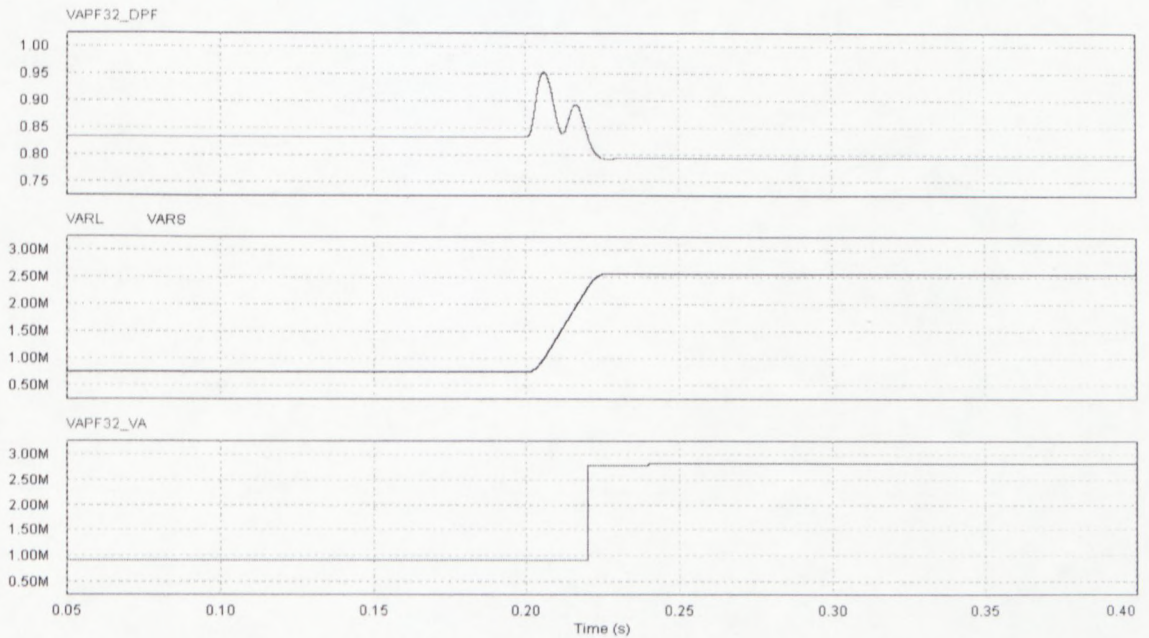
Figures 11.72-73 show the simulation results of the combination of two loads without STATCOM. The considered loads were kiln and raw mill section loads. Initially the only kiln loads were operated, at 200ms the raw mills loads were connected. It was observed that, when the plant operated with load1 the voltage and current were constant. When load 2 was connected to the circuit, the current increased while voltage remained unchanged.



**Figure 11.72: Three Phase Voltage**



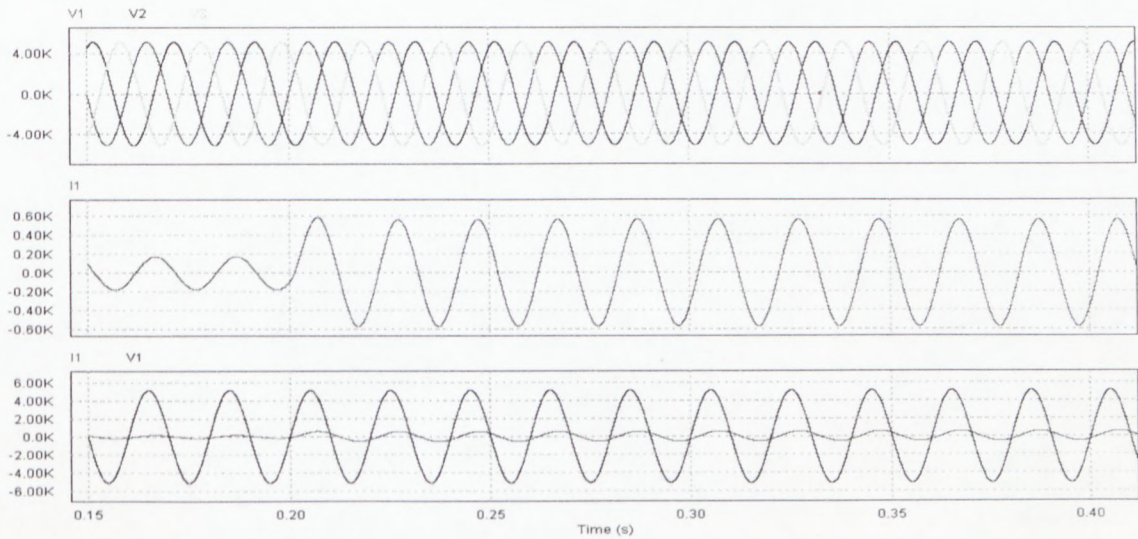
**Figure 11.73: Phase 'A' Current and Voltage Measurement**



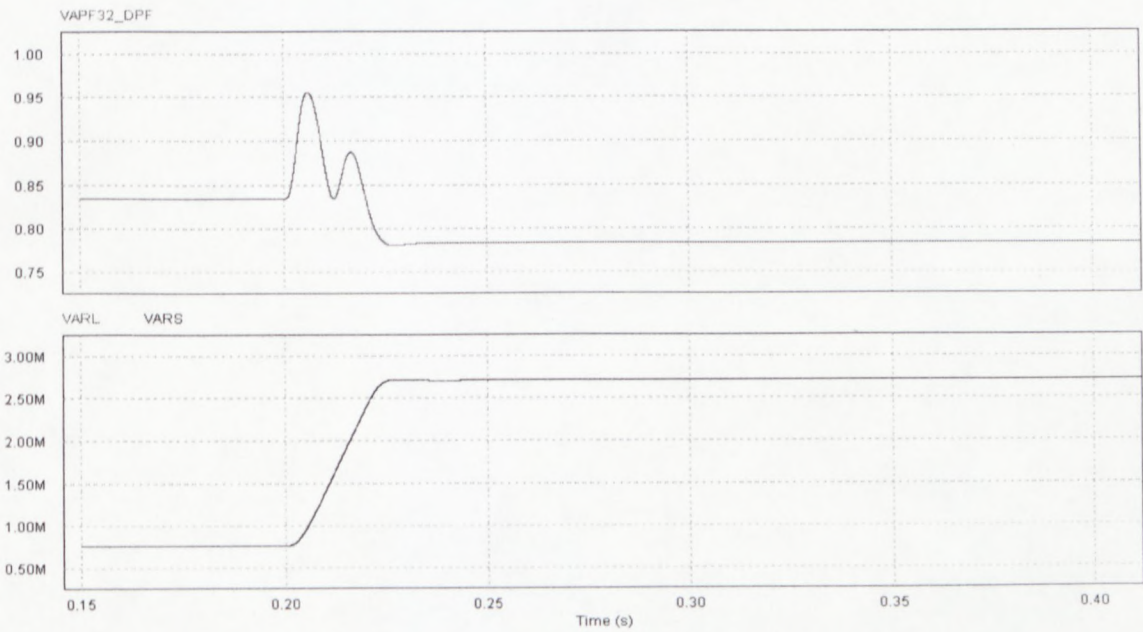
**Figure 11.74: Power Factor and Reactive Power Measurements**

### 11.3.1.3 Kiln and Cement Mill Load Connected at 200ms

Figure 11.75 shows the simulation results of the combination of the kiln and cement mill section loads. Initially the kiln operated alone, after, 200ms the cement mills loads were switched on to the circuit. When the cement mill loads were connected to the circuit, the current increased while the voltage remained constant. The measurement of power factor and reactive power is given in Figure 11.76, when cement mill loads were connected to the kiln loads, the total power factor dropped. This was due to the increase of reactive power shown in the same figure.



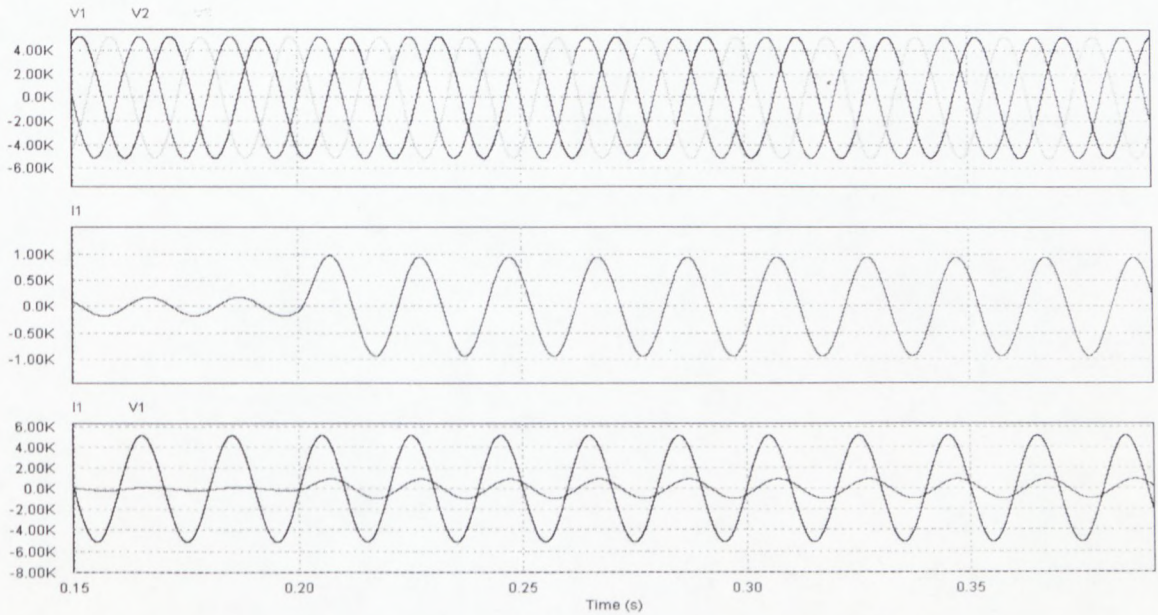
**Figure 11.75:** Three Phase Voltage, Phase 'A' Current and Voltage Measurement



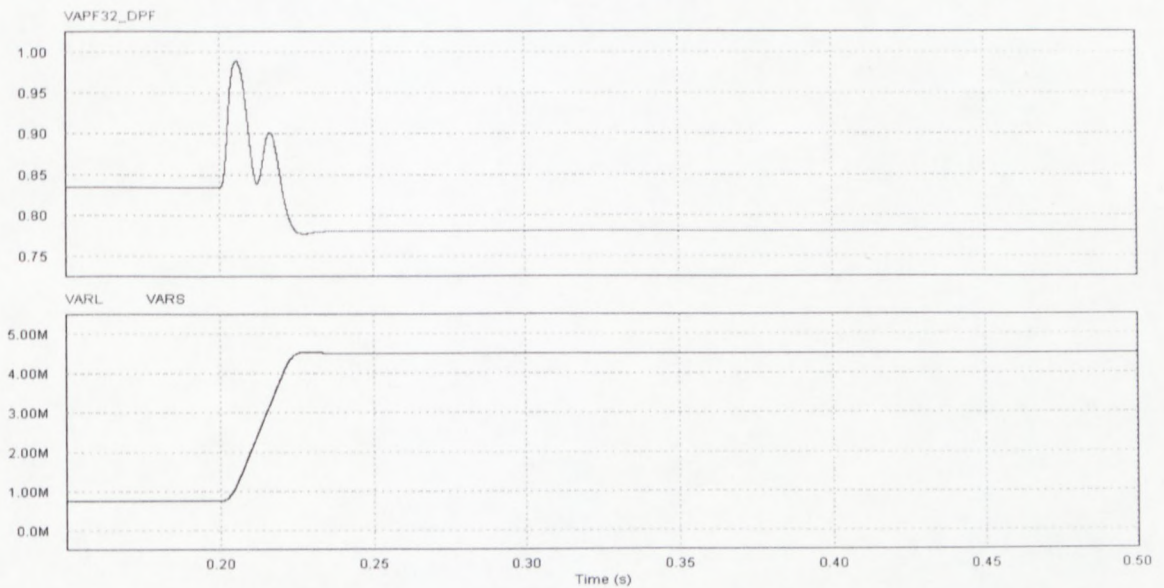
**Figure 11.76:** Power Factor and Reactive Power Measurement

### 11.3.1.4 All Loads Connected Without STATCOM

Figure 11.77-78, shows the simulation results of the plant when all loads were connected to the plant. Initially only kiln section loads were connected; at 200ms loads 1 and 2 were connected. The results in Figure 11.77 shows the measurement of the input voltage, and load current, and the current is seen to vary when loads were connected. Figure 11.78 shows the power factor and reactive power of the industry, thus the reactive power increased when load was connected, this led to the reduction of power factor.



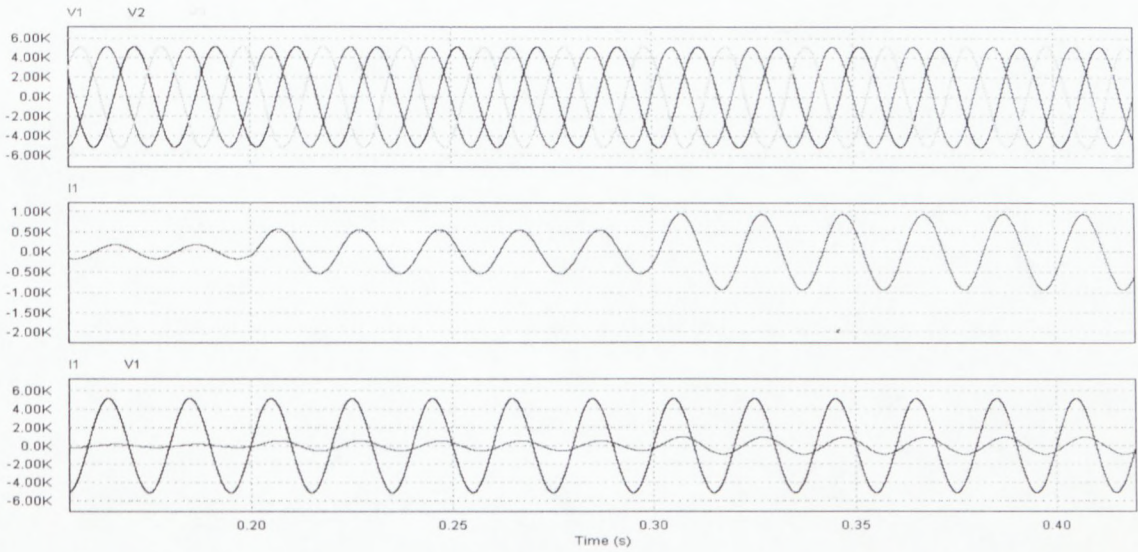
**Figure 11.77:** Three Phase Voltage and Phase 'A' Current and Voltage Measurement



**Figure 11.78:** Power Factor and Reactive Power Measurement

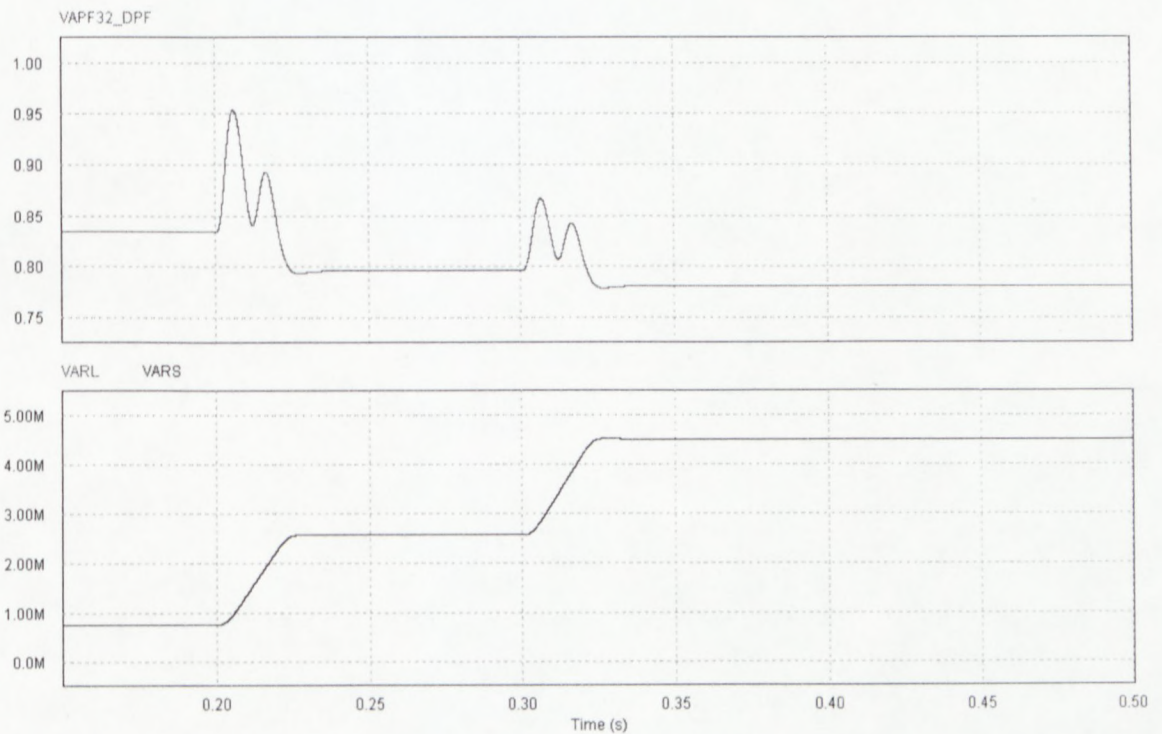
### 11.3.1.5 All Loads Connected at Different Period

Figure 11.79 -80 shows the simulation results of the plant loads when loads are connected in variable manners.



**Figure11.79:** Three Phase Voltage, Phase 'A' Voltage and Current Measurement

The voltage and current measurements are shown in Figure 11.79 and the power factor and reactive power measurement are in Figure 11.80. The current, power factor and reactive power are varying when loads are varying.



**Figure 11.80:** Power Factor and Reactive Power Measurement

### 11.3.2 Plant Loads With STATCOM Connected At 300ms

#### 11.3.2.1 Kiln Load Connected With STATCOM

Figure 11.81-83 shows the simulation results obtained when kiln load was connected to the STATCOM at 300ms, it was observed that, when STATCOM was connected to the supply bus at point of common coupling, the input voltage did not change, the reactive power drawn from the supply was reduced because, the load was carrying the reactive power from the compensator hence the power factor improved.

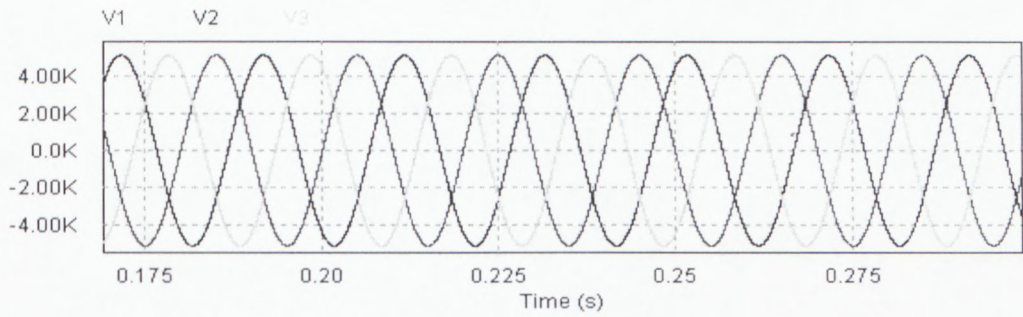


Figure 11.81: Three Phase Voltage Measurement

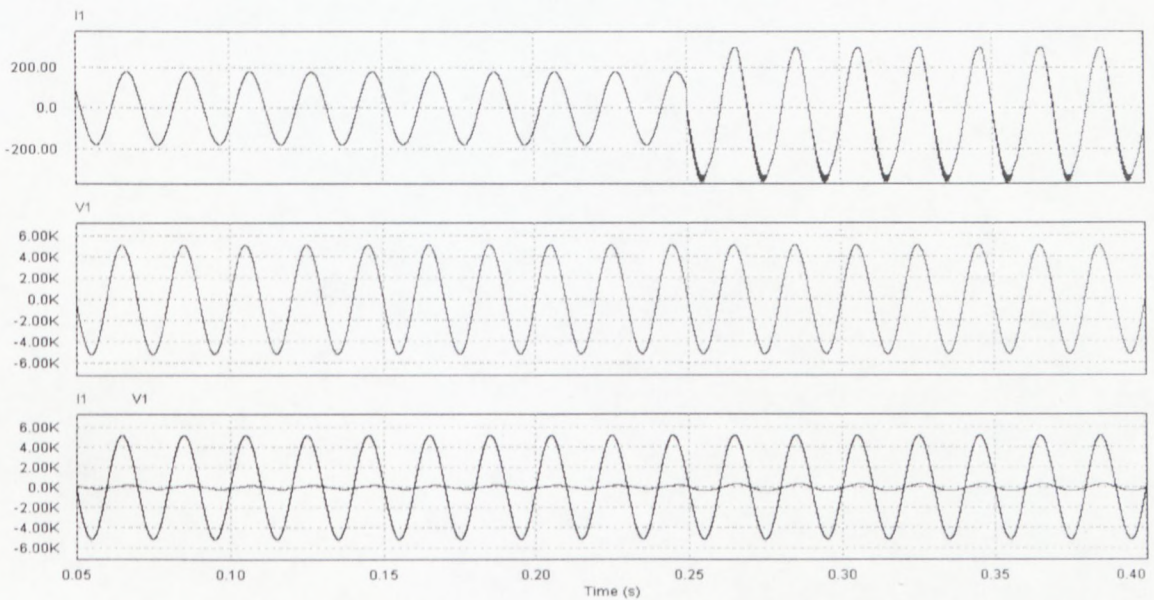
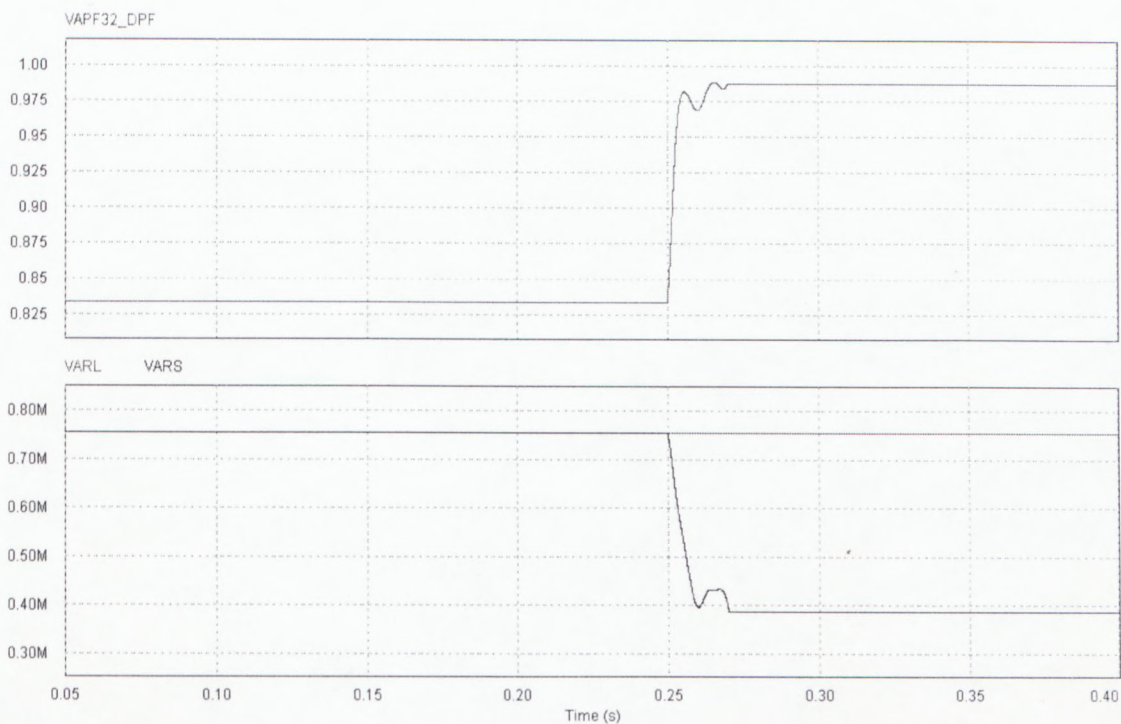


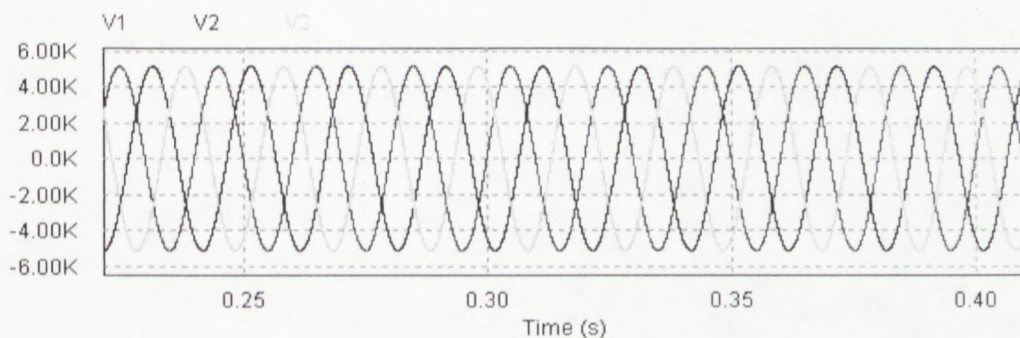
Figure 11.82: Phase 'A' Current and Voltage Measurement



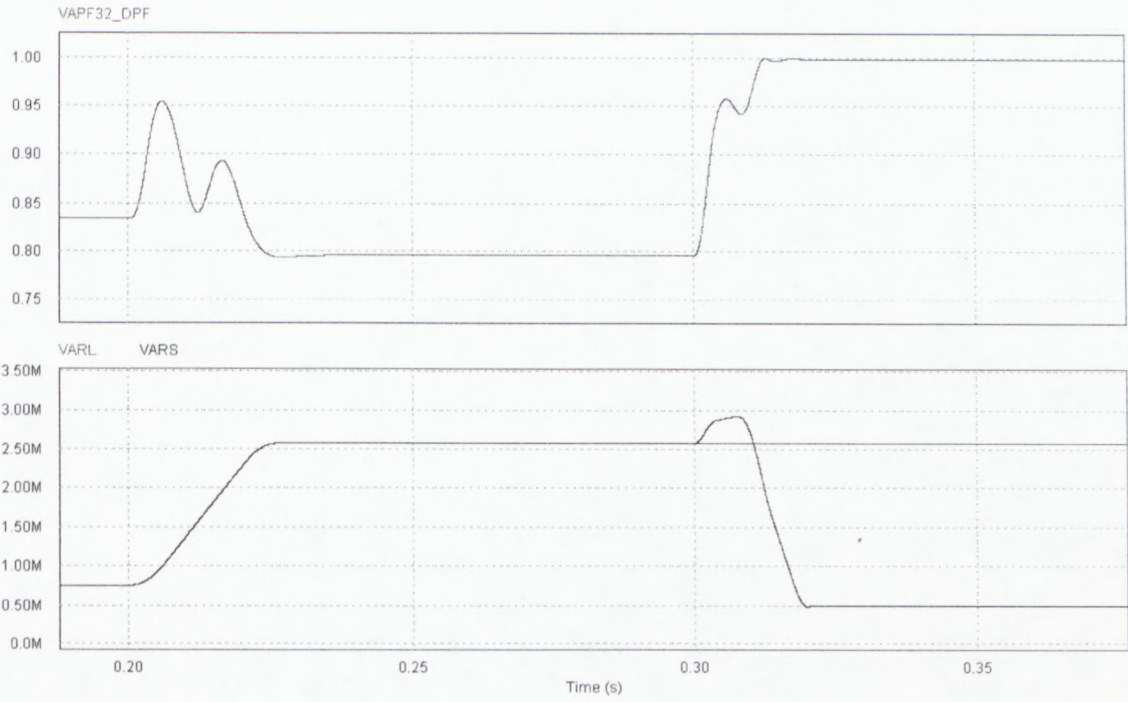
**Figure 11.83:** Power Factor and Reactive Power Value

### 11.3.2.2 Kiln and Raw Mill Section Loads (Load 1+ Load 2) with STATCOM at 300ms

Figures 11.84 -85 is the simulated results of the plant loads when STATCOM was connected to the circuit. At the initial period, the only kiln load was connected, after 200ms the raw mill loads was connected and STATCOM connected to the circuit after 300ms. Figure 11.84 shows a three phase voltage and it is fixed irrespective of load variation, whereby in Figure 11.85, shows that, the reactive power was high at the period of 200ms due to the increase of load and then decreased when the compensator was connected to the circuit after 300ms. The power factor increased to near unity.



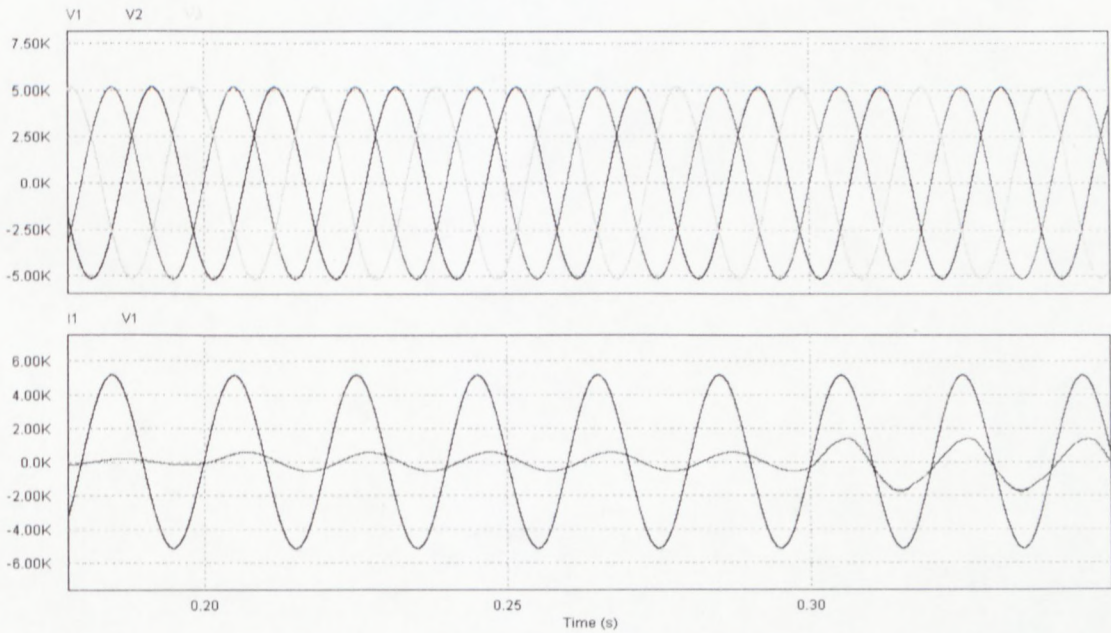
**Figure11.84:** Three Phase Voltage



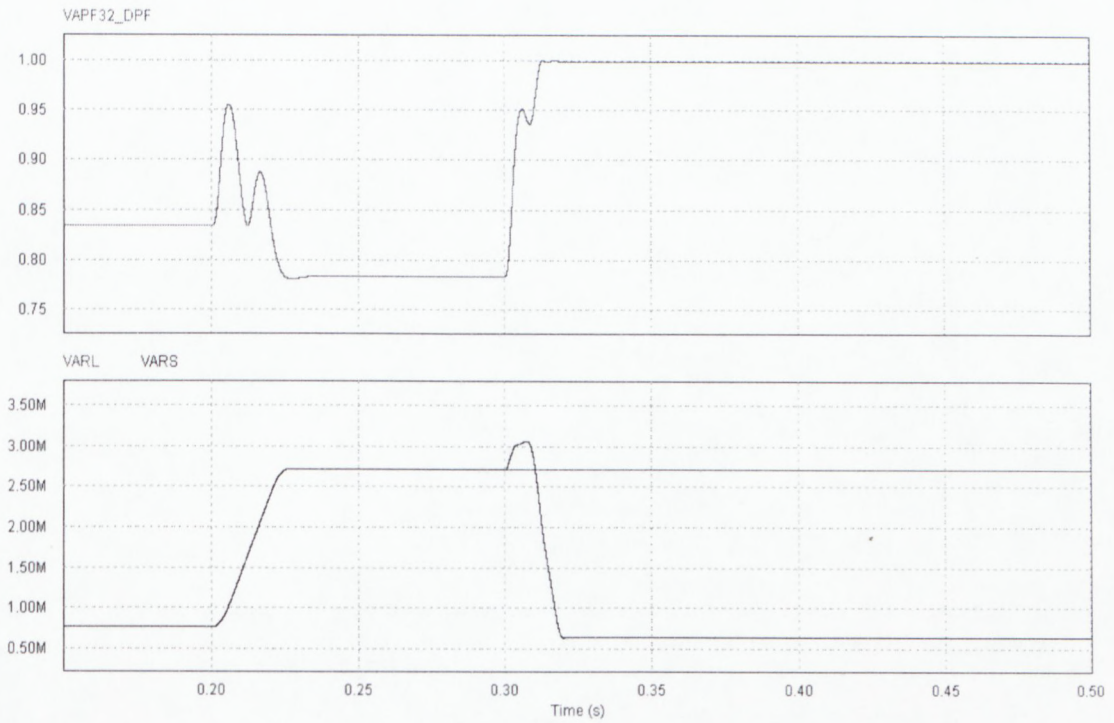
**Figure 11.85:** Power Factor and Reactive Power Measurement

### 11.3.2.3 Kiln and Cement Mill Section Loads with STATCOM at 300ms

Figures 11.86-87 show the simulated results of the kiln and cement mill loads and when connected with STATCOM at 300ms. The connection and performance are the same as indicated in Figure11.84-84



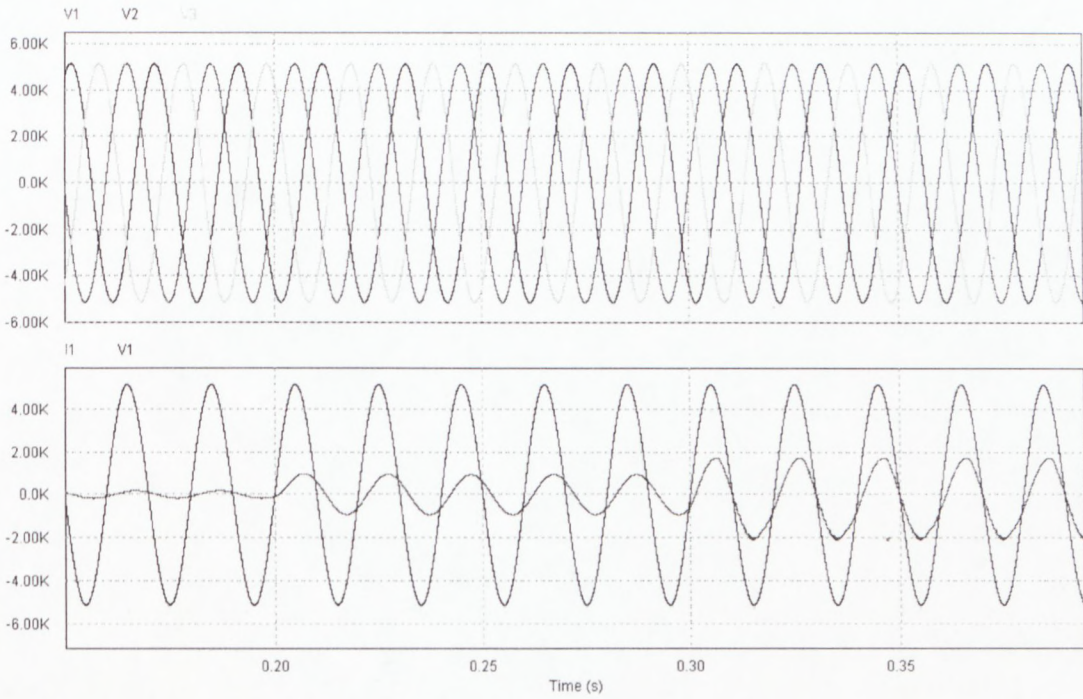
**Figure11.86:** Three Phase Voltage and Phase 'A' Voltage and Current Measurement



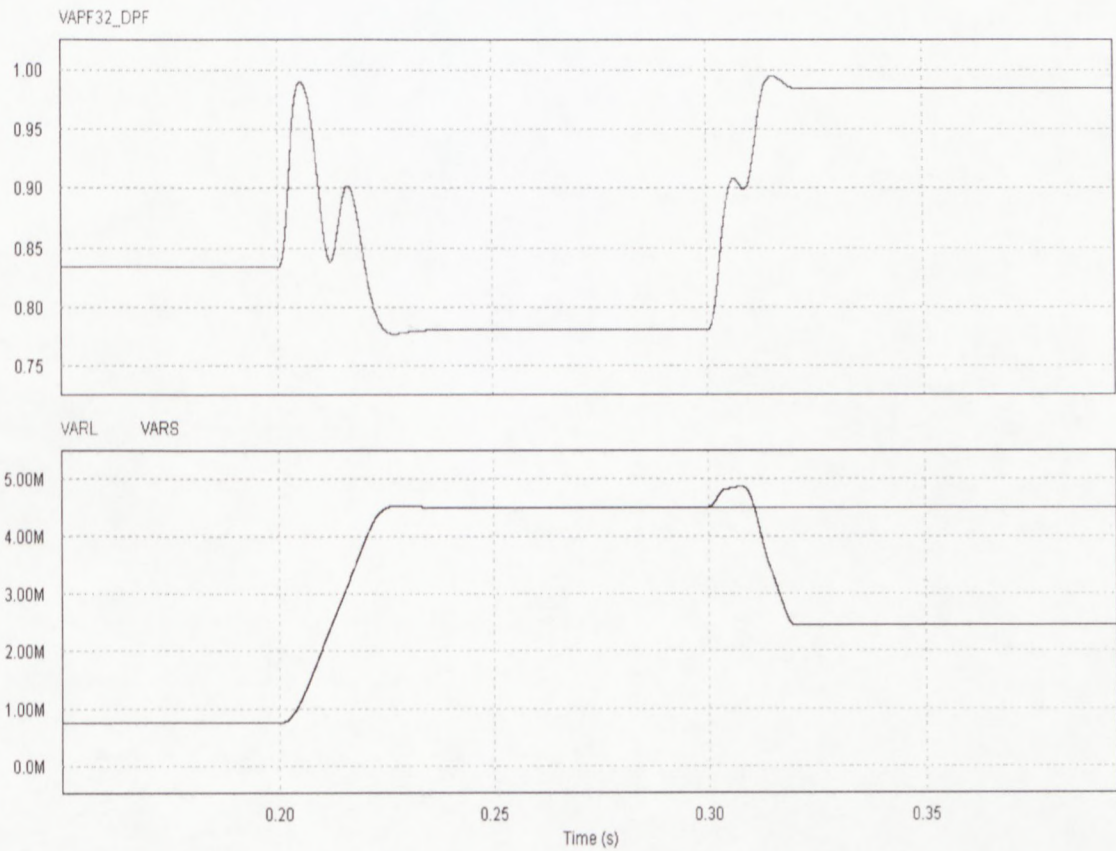
**Figure 11.87: Power Factor and Reactive Power Measurement**

#### 11.3.2.4 All Loads Connected with STATCOM at 300ms

Figure 11.88-89 show the simulation results of the plant when all three loads and STATCOM were connected to the circuit. At the initial period, only the kiln load was connected in the system, after 200ms the remaining loads were connected and at the 300ms the STATCOM was connected. The voltage, current, was analysed. It seems that, when the compensator was connected to the system the reactive power drawn from the supply decreased this led to the improvement of power factor (Figure 11.89).



**Figure11.88:** Three Phase Voltage and Current and Voltage of Phase 'A'



**Figure11.89:** Power Factor and Reactive Power Measurement

From the simulation results of the two softwares, it was observed that, the developed STATCOM was capable of operating at variable loads and improved the power factor to an acceptable level. The study has also showed that, at switching periods the simulation results using MATLAB/SIMULINK were subjected to more transient phenomenon and the transient period was higher than with PSIM refer figures. This may be caused by the switching mechanism used in these systems. PSIM used bidirectional switches, while MATLAB used breakers.

#### **11.4 Conclusion**

Power factor is one of the important parameter considered for demand management. The nature of cement industries loads is inductive; they draw large amounts of current or reactive power from the supply and thus lower the power factor. Currently, industrial power factor is mostly corrected by the use of fixed switch capacitor banks.

The proposed and developed STATCOM was capable to vary and correct the power factor at fixed and variable load situations. Hence, the industrial load scheduling can be easily instituted with the acceptable power factor value. This chapter showed the simulation results of the developed STATCOM. MATLAB/Simulink and PSIM software were used for the simulation. The intention was to analyse the performance of the developed STATCOM. The power factor and other plant parameters were measured and analysed before and after the compensation. The loads considered were fixed, variable and nonlinear loads.

Firstly, the simulation was carried by the use of MATLAB/Simulink software. Powersystem toolbox was used and the results compared with the real industrial data. Secondly, PSIM software was also used for verification. The results showed that, both simulation software portrayed similar results (refer to the simulation characteristics). Before compensation the power factor was low and after compensation, irrespective of the type and size of the load, the power factor was improved. This confirmed the capability of the developed STATCOM.

## CHAPTER 12: Conclusions and Recommendations

### 12.1 Conclusions

The power sector of many Sub-Saharan African (SSA) countries faces challenges of insufficient generating capacity, which have lead to unreliable supplies. The generated power is mainly used in the industrial, residential and commercial sectors. The common approaches used to deal with power shortage in SSA, is to run peak load power plant or to institute load scheduling at the period of power crises. To run peak load power plant has been proved to be very expensive and environmental threatening while implementation of customer loads scheduling is costly and uncomfortably to users. The key player in these approaches is supply side. In order to alleviate this problem, electrical energy management is proposed.

In this thesis electrical energy management is defined as a program employed by the demand side aimed at a reduction of energy consumption in industries through the use of various initiatives without causing disruption of the plant. The fundamental goal of any electrical energy management in industries is to minimize energy consumption in its production processes without affecting the quantity and quality of production as well as minimizing environmental effects.

It was observed that, there are similarities in approaches used to manage energy and demand on the utility or demand side; the only difference is the size and tactics. Energy management (EM) initiated by the supply side, aims to meet the demand growth, supply security and environmental constraints.

The aim of energy management is to reduce the amount of energy utilized by industrial consumers (cement). The purpose of the study was to develop alternative EM methods and strategies that can be used as a tool for electrical energy management in Sub- Saharan Africa manufacturing industries. This aims at reducing electrical energy consumed, hence limiting the power drawn from the supply.

The methods used to achieve the stated aim include; data collection, interview, review of historical energy consumption data, numerical analysis and computer simulation. In addition, the study has analyzed the load characteristics of the cement industries, examined the existing potential options and areas for Demand Side Management (DSM) in cement industries. The study has analyzed energy efficiency potentials and technologies used for energy saving and has studied the power factor correction methods used in the cement industries. It has also developed the static synchronous compensator (STATCOM) that can be used for provision of variable power factor

correction and developed strategies for electrical energy management to ensure the sustainable EM in industry.

Through industrial survey it was observed that:

- Most of SSA countries do not have any legal energy efficiency standards; hence many appliances and equipment are not bound to energy efficiency standards. Energy labelling is also not applicable, therefore in most cases; energy is inefficiently utilized in equipment or systems.
- Some manufacturing industries consider maintenance of their systems and equipment as a strategy for continuous production and energy management.
- Poor housekeeping leads to inefficient energy consumption. This is caused by inadequate skills which result in major loss of electrical energy in cement industries. Inadequate strategies for monitoring and managing energy consumption and demand cause the industry to pay more money on penalties charged by exceeding the contracted maximum demand consumption, low power factor and for the high energy consumption.
- Many cement industries in SSA use energy management methods such as capacitor bank for reduction of energy demand drawn from the supply.
- Lack of energy management strategies in cement industries; result in variable energy performance indicator (higher than best practice) because there is no energy consumption benchmark.

In order to make the energy management program useful, it should be strategic, continuous and considered as a part of industrial day to day activities. Strategic EM can be enhanced by the use of the following steps:

- Assessment of load characteristics; where energy auditing and monitoring are performed
- Assessment of load control impact; where different techniques for energy management is considered
- Load control implementation; and
- Measurement and verification.

The literature review for electrical energy management (EEM) in supply and demand side was done and came out with several EM techniques of which some have been adopted in this thesis. It has been observed that, many methods of load management developed on the utility industries world wide are less or not applicable in many SSA countries, for example, DSM has been developed in few countries.

The energy management principle can be started by the appointment of energy managers followed by energy accounting and auditing in order to get a clear picture on how electricity is consumed in different sections and identify potential areas for

energy conservation. It has been observed that, energy conservation is mainly influenced by target setting, operational control and improvement and process optimization.

Finally by using the data collected in the industrial survey, the load profile of the case study industry was developed, tested and the energy consumption characteristics was analysed. It was observed that, there is a big deviation on energy consumption in some months, that is, a large amount of energy was used in some months while in other months electrical energy consumption was moderate for about the same quantities of production. This reinforced the need for implementing EM in that industry. The techniques considered for energy saving include energy efficient equipment, reactive energy control and peak load reduction. From the plant data it was shown that, there was a possibility of scheduling of sections or influenced machines, this can influence demand management that can lead to monetary saving.

The important steps for DSM programs were identified, and energy use profile was studied and explained as important action to this process as it gives an understanding of end-uses electricity consumption and helps identify options that can offer maximum DSM potentials. The method for screening DSM options was developed and used to analyse the potential options for DSM program in SSA countries cement industries. This analysis was done by using tools that had been developed for DSM options screening.

However some barriers for development of DSM in the region include; market which are associated with lack of awareness and information about the benefits of DSM programs and technologies, lack of technical information, lack of capital or access to financing whereby the institutional barriers involves lack of efforts at national level to coordinate energy efficiency actions initiated by different players.

The potentials of energy efficient technologies in cement industries in an SSA country (the case study was in Tanzania) were identified and analysed in order to get a viable energy efficient method for energy consumption reduction. The results revealed that there is a big potential for using energy efficiency techniques such as motors and lighting but none of them was implemented. In this study, an energy consumption model has been developed and used to identify energy consumption benchmarking. The energy consumption benchmarking can be used in the development of an energy policy strategy and to identify the best value of consumption that is suitable for the production levels. In addition the use of high-efficiency motors in place of standard-efficiency ones was analysed. It was observed that, most high efficiency motors have

high power factor compared to standard motors, thus they can be used as an alternative to power factor correction. This result is valid for only smaller-sized motors.

There are many mechanisms that can be used for energy management in the industrial sector. The study concentrated on a few of them but other methods and techniques depending on the area and situation of utilization can be analysed in depth in future researches. The summary of the techniques presented used brushless synchronous motors (SM) especially big size machines instead of slip ring induction motors. Through the study it was found that, synchronous motors can operate at variable power factor, whereby the power factor of the plant can be varied to suite the requirement of the supply authority at a particular time depending on the load connected to the system. The analyses compared the efficiency of SM motors and the payback period for replacing induction motors with SM. In this study, the result revealed that if induction motors are replaced with SM and its control system, the payback period is about 5 years. Hence the saving of the remaining operating period (more than 10 years) will be the profit.

Energy management by differential tariff structure has also been discussed, where TOU and real time pricing was found to be commonly used for energy management in many countries. However, these tariff structures are not used in many SSA countries though the few countries which use these tariffs, especially in the industrial sector, realize energy and money savings.

The use of energy storage system is another alternative energy management technique which has been discussed. The energy storage methods which have been presented include ultracapacitors, batteries and superconducting magnetic storage. These devices can store energy during off peak and to be used at the peak period. In a situation where tariff structure is not time dependant, the energy storage is found to be useful because energy can be stored during off peak consumption and used in peak time to minimise maximum demand consumption.

For a long time, power factor correction has been used as a tool for energy conservation because of its ability to increase system capacity and reduce electricity costs to the end user. This is for cases where the power utility is offering a tariff where reactive power demand charges are part of the monthly electricity bills.

Flexible power factor correction using STATCOM was developed in this thesis. This technique provides flexible variation of industrial loads and maintains the acceptable level of power factor. It is also capable of smoothing the harmonics when nonlinear

loads are parts of the plant load. In this case STATCOM was used to maintain the power factor level irrespective of the type and characteristics of the load. The technique has the ability of varying power factor of the industry from lagging to leading and vice versa.

The importance of institutionalization of strategic demand and energy management program in industries is the guarantee that ensures sustainable monitoring and control of electric demand and energy by undertaking a set of activities including limiting the use of energy at peak hours while at the same time keep the production at the accepted level and standards. This leads to money saving on the demand side and reliability of the power supply utility on the supply side.

The algorithm for demand /energy control (load scheduling and power factor) was developed. This research proved that, using materials stored during off peak period, it is possible to switch off the plant section or part of the load for a predetermined period (peak period); without affecting the production output of the plant. The maintenance schedule also can be undertaken during the period of plant/ section schedule. The algorithm for overall load management has been developed. Energy auditing and accounting were found to be the preliminary steps in EM and lastly monitoring and evaluation have been shown to have a special and important role as shown in CUSUM analysis in this thesis.

It was observed that, the amount of electrical energy consumed percentage wise has close relationship to the economic level which is measured in terms of lifestyle, income level of the population and the overall economic status of the country. Human Development Index (HDI) is another indicator which relates longevity, knowledge and standard of living to the use of energy. As observed, the HDI of most countries in SSA is less than 0.6 units. For this to improve, overall energy consumption of the respective country must be improved by the generation of more electricity. This results in undesired environmental, social, and economic conditions. The role of deregulation and energy trading based impact was studied and showed the possibility of increasing GHG. In this situation electrical energy management in the industrial sector plays an important role on mitigating negative energy related impacts.

Finally, energy management techniques presented in this thesis were analyzed against energy related impact and it was concluded that, although the use of electrical energy management techniques lead to the optimum use of electrical energy in the industries, some techniques have been noted to have inherent undesired effects. These effects include power quality problems arising from the

connection of many energy efficient lighting in the system, and special disposal care for the mercury content existing in the energy saving lamps. However, in comparison with the impacts caused by electricity generation, these effects are found to have less hazardous.

It has been observed that, there are few initiatives on energy management in industries. On the demand side there are relatively extensive studies on energy management in the residential sector, specifying the management of hot water by geysers. Hence this research contributes to energy management study in the industrial sector.

To answer the question “does the use of electrical energy management techniques, tools and strategies in industries are capable of minimizing electrical energy consumption and reduce the level of electricity demand in the industry?” The research used several energy management methods mentioned above and considered the existing situation found during the industrial survey aimed at meeting the stated objective. By using DSM concepts, algorithm for assessing DSM programs options in industries was developed. The developed algorithm was used in the case study industry as screening techniques to identify energy management gaps and opportunities. It was also used in the surveyed industries to analyse the application of energy management techniques in the cement industry, which revealed that only 25% of the energy saving techniques are currently applicable in the cement industries.

In addition, this research also has contributed to the development of energy consumption model, regression statistical method and industrial historical data was used, the model parameter was computed by using Excel and MATLAB software. This model may be used in the development of energy use benchmarking. This model can also help industries to set an energy efficient target that can be used for planning purposes and development of policy. Based on best practice indicators, this model was used to identify and set the energy performance indicator. Hence energy benchmarking is a key indicator for energy management opportunities.

Most of the load scheduling algorithm developed so far based on time dependant tariff (TOU). This thesis contributed to the development of an algorithm to provide steps to be followed when load scheduling is used as LM method. It incorporated the production and storage limitation and could work in both two part tariff and time dependant tariff.

Capacitor bank power factor correction is predominate power factor correction (PFC) technique. Due to the drawback of the control system, wave of change of load characteristics and the low performance of the capacitor compensator, this study used the Flexible AC Transmission system (FACTS) concepts, and p-q instantaneous reactive power theory to develop an alternative fast PFC based on static var generator STATCOM to be used in the industrial environment. It corrects the power factor and mitigates the harmonics. The development of STATCOM answered the question; "can the flexible power factor correction (STATCOM), play a role in managing reactive power under variable plant load?" The research also analysed the influence of unbalanced load, under and over load condition in energy losses. This analysis aimed at finding the relationship between energy losses. Hence it was considered in the developed energy management strategies.

The question; "can the implementation of electrical energy management in the industrial sector improve reliability of the electrical power utility industry?" This scenario has been created aimed at looking the possibility of improving energy system in the supply side by improving energy management on the demand side. This has been analysed through DSM study. Due to the link existing between supply and demand, for example the implementation of the DSM objectives during peak period; such as load scheduling, strategic conservation and peak clipping on the demand side leads to the reduction of power drawn from the supply hence relief and improve system reliability.

To answer the question on: "how inefficient consumption of electrical energy plays a role in environmental degradation?" It has been observed that, 66.6% of the energy generated in SSA is from thermal power plants. The level of greenhouse emission caused by electricity production and industrial operations is about 60%. The predominant load of industries is a standard motor which consumes 70% of the electrical energy consumed in industry. The motors used are standard type. Through the analysis it has been proved that, the use of energy efficient motors reduces energy consumption; this leads to reduction of power demand requirement from the supply and it defers the construction of new power plant and mitigates the negative environmental impact caused by power plant electricity production.

The developed energy consumption model used the data collected from the plant and was validated by using ANOVA with Excel software. The developed STATCOM, used the data from the cement industry (the case study) of which the circuit operation was confirmed by the simulation results that was performed in MATLAB/Simulink Simpower system toolbox environment. The model was also tested in PSIM

software. The simulation results presented is divided into two cases; the first was to test the model without the compensation. In this way the power factor, reactive power, current and voltage level were determined. Secondly, the simulations were carried out when STATCOM was connected on the industrial bus bar and allowed variation of loads, so as to test the behaviour of the STATCOM under load scheduling condition.

Again the power factor, reactive power, voltage and the current behaviour were observed and they have been improved its profile. Thus when the plant loads were assumed to vary, the power factor also varied as presented in the simulation results and the results show the similarities.

The study used the responses obtained in the surveyed results to identify the gaps and developed a final energy management strategy for the cement industry. In order to enhance the sustainable energy management practice proposed in this work, energy management gaps and appropriate energy management opportunities should be monitored and continuously improved.

## **12.2 Recommendations and Future Research Work**

- The case study of this work was cement industries, but the concept of energy management can be extended to suite other manufacturing industries.
- An energy management awareness program should be included in the development of energy management strategies because it was noted that, many none technical personnel are not aware or participated in energy management program.
- An industrial energy policy should be developed.
- The utility customer's behaviour in SSA countries should be continuously studied so as to identify the appropriate LM method.
- Legal energy efficiency standards and label should be instituted in SSA countries.
- The predominant motors used in cement mills are three phase slip ring induction motors. This research recommends more torque capability analysis on the use of alternative technology such as brushless synchronous motors so as to benefit from these motors.
- The developed energy consumption model of industries has to be improved, to involve other economic parameters so as to research economic and social indicator of energy management.

### 12.3 Publications

The study has contributed to the following publications:

- Afua Mohamed and Mohamed Tariq Kahn, 2009, "A review of electrical energy management technique: supply and consumer side (industries), *Journal of energy South Africa*, vol.20, no. 3 pp14-21
- A. K. Mohamed and M T E Kahn, 2008, "Contribution analysis of electrical energy management in the industrial and commercial sector: a challenge to the Tanzania utility industry" *Journal of energy South Africa*, vol.19, no.1, pp.55-61
- A.K. Mohamed and M. T. E. Kahn, 2009, "Electrical energy management techniques: Supply and manufacturing industries" Conference proceeding of the Institute of Engineers Tanzania, 7-8 December, 2009 , Arusha, pp152-159
- Afua K. Mohamed and M.T.E. Kahn, 2007, " Evaluation of energy efficiency potential in commercial and house hold sector: Challenge to Tanzania energy prospective", Conference proceeding of the Institute of Engineers Tanzania, 6-7 December , 2007, Dar es Salaam, pp.6-14
- A. K. Mohamed and M.T.E Kahn, 2009, "Analysis of Electricity Demand Management Potentials in Tanzania Residential Sector" 11<sup>th</sup> Conference proceeding (CD)of Botswana Institute of Engineers, October 7-9, 2009, Gaborone
- A.K. Mohamed and M.T.E. Kahn, 2007, "Assessment of energy efficiency technology Potentials for energy management in Sub-Saharan Africa" 10<sup>th</sup> Conference proceeding (CD)of Botswana Institute of Engineers, October 8-10 Gaborone , 2007
- S.T.Wara, A abayomi, Afua Mohamed and M.T.E. Kahn , 2008, " Investigation of electricity cost savings in Igibinedion University Campuses" Conference proceeding of Industrial and commercial use of Energy, 28-30 May 2008, Cap Town, pp.105-112
- A. K. Mohamed and M.T.E. Kahn, "Energy efficiency potentials for DSM opportunity: Study of SSA manufacturing industries". On review for journal of New sciences Generation (JNGS)

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## APPENDICES

**APPENDIX 1.1: Electricity Generation by Country in Sub-Saharan Africa –Billion kWh (1992-2004)**

Region/Country	Abbr	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
Angola	AO	1.28	1.33	1.34	1.35	1.38	1.33	1.52	1.30	1.40	1.59	1.72	1.94	2.19
Benin	BN	0.02	0.02	0.05	0.03	0.05	0.05	0.06	0.07	0.08	0.06	0.06	0.07	0.08
Botswana	BC	1.09	1.03	1.04	1.05	0.76	0.87	1.03	1.04	1.05	1.08	0.99	0.87	0.82
Burkina Faso	UV	0.19	0.21	0.21	0.23	0.26	0.28	0.31	0.37	0.32	0.33	0.34	0.36	0.40
Burundi	BY	0.11	0.11	0.12	0.12	0.12	0.12	0.11	0.10	0.10	0.12	0.13	0.13	0.14
Cameroon	CM	2.70	2.70	2.74	2.81	2.93	3.10	3.13	3.34	3.44	3.50	3.26	3.64	3.92
Cape Verde	CV	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Central African Republic	CT	0.09	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.11	0.11	0.11	0.11	0.11
Chad	CD	0.08	0.08	0.08	0.08	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Comoros	CN	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Congo (Brazzaville)	CF	0.42	0.36	0.32	0.35	0.45	0.45	0.34	0.25	0.30	0.34	0.39	0.34	0.35
Congo (Kinshasa)	CG	6.01	5.49	5.26	6.11	6.05	4.99	4.68	5.27	5.96	5.84	6.01	6.20	6.85
Cote d'Ivoire (IvoryCoast)	IV	1.67	2.12	2.40	2.96	3.13	3.85	3.83	4.63	4.60	4.68	5.06	4.87	4.63
Djibouti	DJ	0.17	0.17	0.17	0.17	0.17	0.18	0.18	0.18	0.18	0.18	0.19	0.20	0.20
Equatorial Guinea	EK	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.03
Eritrea	ER	NA	NA	0.15	0.16	0.18	0.18	0.18	0.20	0.20	0.22	0.24	0.26	0.28
Ethiopia	ET	1.28	1.51	1.49	1.51	1.58	1.60	1.61	1.63	1.67	1.79	1.99	2.04	2.29
Gabon	GB	1.03	1.07	1.07	1.18	1.19	1.24	1.28	1.29	1.28	1.34	1.42	1.46	1.54
Gambia, The	GA	0.07	0.07	0.07	0.07	0.07	0.08	0.08	0.09	0.12	0.13	0.14	0.14	0.15
Ghana	GH	6.58	6.25	6.06	6.05	6.59	6.82	4.53	5.83	7.12	7.72	7.11	5.74	6.49
Guinea	GV	0.50	0.51	0.51	0.52	0.53	0.62	0.64	0.73	0.74	0.77	0.77	0.78	0.79
Guinea-Bissau	PU	0.04	0.04	0.05	0.05	0.05	0.05	0.05	0.05	0.06	0.06	0.06	0.06	0.06
Kenya	KE	3.16	3.34	3.48	3.89	4.08	4.27	4.39	4.17	3.72	4.25	4.42	4.74	5.71
Lesotho	LT	0	0	0	0	0	0	0	0.20	0.29	0.29	0.31	0.35	0.25
Liberia	LI	0.28	0.29	0.29	0.29	0.29	0.29	0.30	0.31	0.31	0.32	0.32	0.32	0.33
Madagascar	MA	0.58	0.58	0.58	0.61	0.66	0.70	0.75	0.78	0.78	0.79	0.78	0.90	0.98
Malawi	MI	0.78	0.79	0.83	0.85	0.86	0.89	1.02	0.98	1.02	1.04	1.16	1.18	1.29
Mali	ML	0.27	0.29	0.28	0.31	0.33	0.38	0.39	0.39	0.40	0.40	0.40	0.40	0.41
Mauritius	MP	0.88	0.93	0.97	1.06	1.20	1.32	1.45	1.49	1.68	1.80	1.84	1.96	2.11
Mozambique	MZ	0.41	0.39	0.39	0.40	0.47	0.99	1.51	7.63	8.76	8.76	12.58	10.49	11.58

Namibia	WA	0	0	0	1.16	0.88	0.63	1.01	1.20	1.40	1.40	1.43	1.48	1.40
Niger	NG	0.16	0.16	0.17	0.17	0.17	0.22	0.22	0.22	0.22	0.22	0.23	0.23	0.23
Nigeria	NI	14.25	13.91	14.88	13.89	14.37	14.70	14.73	15.43	14.13	14.84	20.67	19.36	19.06
Reunion	RE	1.05	1.06	1.07	1.15	1.22	1.41	1.50	1.50	1.51	1.51	1.55	1.55	1.58
Rwanda	RW	0.17	0.16	0.16	0.16	0.14	0.16	0.16	0.13	0.11	0.09	0.10	0.10	0.09
Saint Helena	SH	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Sao Tome and Principe	TP	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.02	0.02	0.02	0.02	0.02	0.02
Senegal	SG	0.96	0.95	0.98	1.02	1.09	1.17	1.23	1.27	1.39	1.55	1.62	1.54	1.45
Seychelles	SE	0.10	0.11	0.12	0.12	0.13	0.14	0.15	0.16	0.18	0.20	0.21	0.21	0.21
Sierra Leone	SL	0.22	0.22	0.22	0.23	0.23	0.23	0.24	0.23	0.23	0.24	0.24	0.24	0.24
Somalia	SO	0.25	0.25	0.26	0.26	0.26	0.26	0.26	0.26	0.27	0.27	0.27	0.27	0.27
South Africa	SF	157.10	163.29	170.73	176.07	187.01	196.02	191.91	189.40	196.46	197.82	205.67	215.93	227.24
Sudan	SU	1.59	1.64	1.80	1.80	1.99	2.07	1.90	2.34	2.36	2.47	2.79	3.21	3.84
Swaziland	WZ	0.40	0.40	0.40	0.41	0.41	0.41	0.41	0.41	0.45	0.45	0.46	0.46	0.46
Tanzania	TZ	1.79	1.85	1.68	1.81	1.96	1.66	2.41	2.35	2.44	2.77	2.86	2.70	2.56
Togo	TO	0.21	0.32	0.24	0.34	0.28	0.19	0.28	0.28	0.27	0.16	0.23	0.29	0.29
Uganda	UG	0.98	0.97	1.01	1.04	1.12	1.25	1.27	1.26	1.56	1.55	1.68	1.76	1.89
Western Sahara	WI	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.09	0.09	0.09
Zambia	ZA	7.72	7.72	7.71	7.84	7.09	7.86	7.52	7.68	7.72	9.03	9.02	9.48	9.96
Zimbabwe	ZI	7.65	7.36	6.29	7.43	6.99	6.97	6.30	6.81	6.74	7.58	8.26	8.54	9.41
<b>Africa</b>	<b>AF</b>	<b>316.22</b>	<b>327.71</b>	<b>340.22</b>	<b>354.16</b>	<b>367.10</b>	<b>384.76</b>	<b>386.91</b>	<b>403.55</b>	<b>416.96</b>	<b>432.29</b>	<b>460.35</b>	<b>478.81</b>	<b>505.44</b>

**APPENDIX 1.2: Electricity Access and Electrification Rate in Sub-Saharan Africa**

**ELECTRICITY ACCESS IN SUB-SAHARAN AFRICA, 2002**

Region/Country	Electrification rate %	Populatiopn without electricity, million	Population with electricity, million
Angola	5	12.5	0.7
Benin	24.8	4.9	1.6
Botswana	26.4	1.3	0.5
Burkina Faso	10	11.4	1.3
Cameroon	40.7	9.3	6.4
Congo (Brazzaville)	19.6	2.9	0.7
Congo (Kinshasa)	8.3	46.9	4.3
Cote d'Ivoire (Ivory Coast)	50.7	8.1	8.3
Eritrea	18.4	3.3	0.7
Ethiopia	2.6	67.2	1.8
Gabon	47.9	0.7	0.6
Ghana	48.5	10.5	9.9
Kenya	9.1	28.7	2.9
Madagascar	8.3	15.5	1.4
Malawi	5.8	11.2	0.7
Mauritius	100	0	1.2
Mozambique	8.7	16.9	1.6
Namibia	34.7	1.8	0.7
Nigeria	44.9	66.6	54.3
Senegal	31.4	6.8	3.1
South Africa	67.1	14.7	30
Sudan	31	22.7	10.2
Tanzania	9.2	33	3.3
Togo	17	4	0.8
Uganda	4	24	1
Zambia	18.4	8.7	2
Zimbabwe	40.9	7.6	5.3
Other SSA countries	7	83.9	6.3
Sub-Saharan Africa	23.5	526.3	161.6

Source: [www.worldenergyoutlook.org](http://www.worldenergyoutlook.org)

**APPENDIX 1.3: Per Capita Electricity Consumption in Sub- Saharan Africa (2006)**

<b>COUNTRY</b>	<b>Electricity consumption per capita (kilowatt-hours)</b>
South Africa	4595.6
Seychelles	2716.5
Mauritius	1683
Gabon	1229
Zimbabwe	998
Morocco	649
Zambia	631
Djibouti	455.5
Mozambique	399
Ghana	285
Papua New Guinea	251.5
Cameroon	226
Congo	206
Côte d'Ivoire	209
Senegal	192.5
Angola	178
Nigeria	162
Kenya	154
São Tomé and Príncipe	102.5
Gambia	101.5
Sudan	101
Cape Verde	100.5
Togo	91
Guinea	89.5
Congo DRC	86
Benin	82
Tanzania	78
Malawi	77.5
Eritrea	62
Uganda	59.5
Equatorial Guinea	51.5
Madagascar	50.5
Sierra Leone	49.5
Guinea-Bissau	45.5
Niger	40.5
Rwanda	39.5
Mali	38.5
Central African Republic	35.5
Ethiopia	33
Comoros	32.5
Burkina Faso	32.5
Burundi	23.5
Chad	11.5

Namibia, Botswana, Swaziland and Lesotho data are included in data for South Africa.

**SOURCE:** United Nations, Correspondence on energy consumption. Department of Economic and Social Affairs, Statistics Division 2004

**APPENDIX 1.4: Common Manufacturing (Energy intensive) Industries Existing in Sub Saharan Africa, (2001/2002)**

Country	Industrial products	Industrial % GDP	Electricity generation Billion kWh
Angola	Petroleum, Iron ore, Basic metal product Textile and small scales industries, cement	7	1.475
Benin	Textile, Petroleum	13.5	0.51
Botswana	Mining, Food	46	0.61
Burkina Faso	Textile, Mining	27	0.285
Burundi	-		
Cameroon	Petroleum production and refining, Textile, Lumber, cement	20.1	3.47
Central African Republic	Mining, sawmills, textiles, footwear, Assembly of bicycles and motorcycles	20	0.102
Chad	Cotton textile	14	0.09
Comoro	Textile	4	0.017
Congo	Petroleum extraction, cement kilning, lumbering	48	0.302
Cote d'Ivoire	Wood product, oil refining, truck and buss assembly, textiles, fertilizer	18	4.06
Democratic republic of Congo	Mining, mineral processing, textiles, cement	17	5.268
Djibouti	Brick clay firing, cement	22	0.18
Equatorial guinea	Petroleum , sawmilling	60	0.021
Eritrea	Textile	27	0.165
Ethiopia	Textiles, chemicals, processing metals, cement, pharmaceuticals	12	1.625
Gabon	Textiles, lumbering and plywood, cement, petroleum extraction and refining chemicals , ship repair	60	1.02
Ghana	Mining, lumbering, light , cement manufacturing, aluminium smelting	25	5.46
Guinea Bissau	Textile, cement	15	0.055
Guinea	Mining, light manufacturing	35.3	0.75
Kenya	Plastic, batteries, textiles, oil refining, cement, paper, chemicals	13	4.225
Lesotho	Textiles	38	From RSA
Liberia	Rubber processing , mining	10	0.43
Madagascar	Tanneries, textiles, cement, automobile assembly, paper, petroleum, mining	14	0.81
Malawi	Sawmills product, cement	29	1.025
Mali	Mining	21	0.445
Mauritania	Mining, cement	31	0.151
Mauritius	Textiles, Chemicals, metal product, transport equipment	29	1.26
Mozambique	Chemicals, Petroleum products, textiles, cement	19	2.3
Namibia	Mining, cement	25	1.198
Niger	Mining, cement, brick, textiles, chemicals	18	0.2
Nigeria	Crude oil, mining, rubber, wood hides and skin, textiles, cement, chemicals, plastics, fertilizer, printing, ceramics	40	18,7
Rwanda	Cement, plastic , textiles	20	0.132
Sao Tome& Principe	Textiles, timber	19	0.017
Senegal	Fertilizer production, petroleum refining, cement	20	1.27

Seychelles	Boat building, printing	26.3	0.16
Sierra Leone	Mining, textiles, petroleum refining	26	0.24
Somalia	Textiles, Petroleum refining	10	0.26
South Africa	Mining, Automobile assembly, metal work, machinery, textiles, iron and steel making, chemicals food stuffs, plastic, cement, paper	30	186.903
Sudan	Textiles, cement, petroleum refining, pharmaceutical	17	1.76
Swaziland	Mining, wood products	46	0.375
Tanzania	Mining, oil refining, cement, textiles, wood products, fertilizer , machine building	17	2.248
Togo	Mining, cement, textiles	21	0.092
Uganda	Cement	17	1.326
Zambia	Mining and processing, Chemicals, textiles, fertilizer, cement	27	7.642
Zimbabwe	Mining, steel, wood products, cement, chemicals, fertilizer.	32	5.78

**APPENDIX 2.1: The Estimated Industrial Production Growth Rate for Africa, 2008**

<b>RANK</b>	<b>COUNTRY</b>	<b>PERCENTAGE</b>
1	Congo	15
2	Equatorial Guinea	12.5
3	Lesotho	12
3	Angola	12
4	Tanzania	10
5	Sao Tome and Principe	9.5
6	Mozambique	9
7	Burundi	8
7	Rwanda	8
7	Madagascar	8
7	Cape Verde	8
7	Guinea	8
8	Egypt	7.7
9	Zambia	7
9	Uganda	7
10	Ghana	6.5
10	Namibia	6.5
11	Ethiopia	6
11	Malawi	6
12	Gambia	5.9
13	Morocco	5.8
13	Libya	5.8
14	Benin	5.5
15	Senegal	5
15	Cote d'Ivoire	5
16	Cameroon	4.7
17	Algeria	4.5
17	Mauritius	4.5
17	Tunisia	4.5
17	Burkina Faso	4.5
18	Seychelles	4
19	South Africa	3.8
20	Kenya	3.6
21	Togo	3
22	Nigeria	2.8
23	Botswana	2.4
24	Chad	2
25	Gabon	1.5
26	Swaziland	1.1
27	Sudan	-4

### APPENDIX 3.1: Industrial Loads Estimation

Section	Load	Quantity	Rating (kW)	Pr at % load	Efficiency at % load	Pin at % load	Voltage rating	Vphase	Iphase A	Q	S	Zpu	Y	r	ii	Rpu	Xpu	Z	Ohm	Ohm	Ohm	chi	l	l	cos	o	sin	
				75%	100%	75%	100%	line		Kvar	KVA											mH						
Hammer mill		2	90	0.75	94	240	190	475/19	230 940/1	327 084/1	123 181/3	226 265/2	22 075/88	0.045/505	0.038/14	0.024/636	18 500/07	11 949/96	0.704/65	0.592/002	0.382/396	1.21/7821	0.84	32	87.6/55	0.542/586		
	1	1250	0.8	94	1310	1332	622/6	6300	3637 307	68 824/8	270 030/1	27 713/3	336/595	0.066/84	0.24/259	2 052/162	8 652/68	22 013/6	16 200/7	14 800/5	14 800/5	47 154/46	0.74	42	290/02	0.672/607		
	1	584	0.81	95	95	611	626	6300	3637 307	68 824/8	270 030/1	27 713/3	336/595	0.066/84	0.24/259	2 052/162	8 652/68	22 013/6	16 200/7	14 800/5	14 800/5	47 154/46	0.82	34	532/92	0.572/64		
	1	75	0.82	95	95	241	241	400	230 940/1	132 528/1	45 271/11	91 818/18	54 455/45	0.018/84	0.009/47	0.008/47	0.008/47	0.008/47	0.008/47	0.008/47	0.008/47	2 736/24	0.87	29	556/34	0.493/02		
	1	5	0.8	91	91	230.8	544/06/64	400	230 940/1	9 249/39	3 375/838	6 408/407	780 225/1	0.001/82	0.000/89	0.000/675	663 191/3	411 009/1	24 967/2	83 210/02	59 626/23	189 892/4	0.85	31	804/45	0.526/53		
		total demand at 75%		actual		R+XL=10.734-8.73 Cos39.13=0.7796		Cos		1.952+1.1		1.743																
Raw mill	ID fan	1	670	0.85	94	712.8	706	020/32	6300	3637 307	77 115/67	456 575/6	841 480/1	0.168/296	0.141/369	0.091/315	4 991/206	3 224	47 166/89	39 620/19	25 592/11	81 503/55	0.84			0.542/586		
	Boat fan	1	132	0.81	94	138	94/17	400	230 940/1	239 036/9	89 857/33	165 609/6	30 191/48	0.033/22	0.027/822	0.017/92	25 360/85	16 381/49	9 661/27	8 115/47	5 242/08	1 665/451	0.84			0.542/586		
	Kin drive	2	132	0.82	95	141.02	280	85/106	400	230 940/1	488 960/9	188 975/9	14 759/02	0.067/55	0.056/237	0.037/91	12 249/99	8 232/041	0 472/89	0 392	263/425	0 838/934	0.83			0.557/53		
	Auxiliaries	4	5	0.75	90.6	220.8	21 551/24	400	230 940/1	41 525/48	19 929/37	28 769/7	173 794	0.005/54	0.004/315	0.003/806	130 345/5	114 953/9	5 951/407	4 170/55	3 675/25	11 715/05	0.79			0.667/428		
			total demand at 75%		Actual		R+XL= 24.13-15.97		Alt Cos		754 419/3		1374 635		Y=0.2297+0.15988 Zpu= 3.0442/0.17 Cos33.48		3.645		Cos O=									
Kin	cement mill	1	1820	0.75	90	2022	2222		6300	3637 307	247 389/3	1785 547	2659 483	1 852/2	0.539/899	0.404/924	0 357/109	1 389/15	1 251/15	14 702/6	11 927/07	0 792/376	30 871/22	0.75			0.651/438	
	Compressor	1	132	0.87	94.2	138	94/17	400	230 940/1	230 784/2	78 838/45	159 899/9	31 269/75	0.031/88	0.027/822	0.017/92	25 360/85	16 381/49	9 661/27	8 115/47	5 242/08	1 665/451	0.87			0.493/032		
	Compressor	1	110	0.82	94.7	116	156/26	400	230 940/1	198 878/5	75 184/9	138 440/2	36 115/37	0.027/88	0.022/13	0.001134	368 000/9	183 409/3	12 871/84	11 456/03	5 869/007	18 691/39	0.84			0.542/586		
	Auxiliaries	1	10	0.85	89.6	90.5	228.8	375/6	400	230 940/1	17 941/36	5 667/82	14 931/4	402 248/2	0.026/89	0.022/13	0.001134	368 000/9	183 409/3	12 871/84	11 456/03	5 869/007	18 691/39	0.89			0.455/961	
			total demand at 75%		Actual		R+XL= 10.06-8.554		Alt Cos O		1945 171		3019 207		Y= 0.45827+0.389 Zpu=1.268-1.077 Cos40.36= 0.762		1.664		Cos O=		0.792/376 sinO= 0.608 0.018/89							
cement mill			Total demand at 100%		Actual		R+XL= 10.06-8.554		Alt Cos		4511 481		7259 768		Cos O total		1.664		Cos O=		0.792/376 sinO= 0.608 0.018/89							
			Total plant load		load 2+1		R= 7.46		XL= 5.68		2566 239		4248 502		Cos= 0.792/376				L		L							
			Load 2+3		R= 34.35		7.321		5.62		2699 59		4384 502		Cos= 0.783/37				L		L							
			Zk3																									

Sb= 5000  
 Sbp= 1666.6667  
 Vb1= 6.3  
 Vb1p= 3.6373067  
 Vb2= 0.4  
 Vb2p= 0.2309401  
 Zb1= 7.938  
 Zb2= 0.032 0.032

APPENDIX 5.1: Share of Electricity Generation in Africa

Share of Energy Generation in African Countries

Regions	Capacity		Net generation	
	Total GW	Hydro (%)	Total (BKWh)	Thermal (%)
Central	4.3	91	10.8	95
East	2.8	64	10.4	78
North	33	12	111.6	12
Southern	43.8	15	217.6	7
West	9.6	48	24.8	52
<b>TOTAL</b>	<b>93.5</b>	<b>22</b>	<b>375.2</b>	<b>16</b>
				<b>81</b>

Source: Energy Information and Administration.

NB: Approximately 5% of East Africa's generation is from Geo thermal and 6% of South Africa's generation is from nuclear

APPENDIX 5.2: Industrial Historical Data

S/N	MONTH	Cement Mill Output (t)	Cement Mill Power (kWh)	Cement Mill Run time (hours)	x2	y2	xy
S/N	MONTH	Production (x)	Energy (y)	time (hours)	x2	y2	xy
1	Jan-07	20745	1006372	530.5	430355025	1012784602384	20877187140
2	Feb-07	19347	998574	518.9	374306409	997150033476	19319411178
3	Mar-07	21325	1144790	586.5	454755625	1310544144100	24412646750
4	Apr-07	10071	527833	279.8	101425041	278607675889	5315806143
5	May-07	26707	1178252	647.0	713263849	138827775504	31467576164
6	Jun-07	28605	1108806	602.4	818246025	1229450745636	31717395630
7	Jul-07	29235	1160792	623.2	854685225	1347438067264	33935754120
8	Aug-07	29275	1237198	661.4	857025625	1530658891204	36218971450
9	Sep-07	28731	1194762	630.3	825470361	1427456236644	34326707022
10	Oct-07	18070	853038	384.9	326524900	727673829444	15414396660
11	Nov-07	29307	1283403	653.2	858900249	1647123260409	37612691721
12	Dec-07	27465	1367173	681.7	754326225	1869162011929	37549406445
13	Jan-08	27412	1200556	613.4	751417744	1441334709136	32909641072
14	Feb-08	24217	1162743	574.0	586463089	1351972425739	28158159120
15	Mar-08	24882	1157117	609.7	619113924	1338920424052	28791392423
16	Apr-08	25010	1189470	616.4	625500100	1414838880900	29748644700
17	May-08	27963	1092459	571.4	781929369	1193466666681	30548431017
18	Jun-08	28762	1116131	604.2	827252644	1245748409161	32102159822
19	Jul-08	27384	1169381	641.3	749883456	1367451923161	32022329304
20	Aug-08	15613	653394	358.2	243765769	426923719236	10201440522
21	Sep-08	29295	1011913	547.9	858197025	1023967919569	29643991335
22	Oct-08	26408	1037572	586.7	697382464	1076555655184	27400201376
23	Nov-08	16002	669122	375.1	256064004	447724250884	10707290244
24	Dec-08	24674	1040751	572.0	60806276	1083162644001	25679490174
Sum	24	586505	25561603	13470.1	14975060423	28178394901587	646081121532
mean		24438	1065067				

APPENDIX 7.1: Monthly Electricity Consumption, Year 2008

MONTH	Raw Mill Power (kWh)	Cement Mill Power (kWh)	Whole Site Power (kWh)	Raw Mill Eff. (kWh/t)	Budget Raw Mill Eff. (kWh/t)	Raw Mill Variance (kWh/t)	Cement Mill Eff. (kWh/t)	Budget Cement Mill Eff. (kWh/t)	Cement Mill Variance (kWh/t)	Whole Site Eff. (kWh/t)	Budget Whole Site Eff. (kWh/t)	Whole Site Variance (kWh/t)
Jan-08	767174	1200556	2876100	26.0	30.0	4.0	43.8	45.0	1.2	107.5	125.0	17.5
Feb-08	761017	1162743	2780700	26.9	30.0	3.1	48.0	45.0	-3.0	109.6	125.0	15.4
Mar-08	857259	1157117	2880600	26.8	30.0	3.2	46.5	45.0	-1.5	107.0	125.0	18.0
Apr-08	480011	1189470	2235600	27.2	30.0	2.8	47.6	45.0	-2.6	112.1	125.0	12.9
May-08	911681	1092459	3008200	23.5	30.0	6.5	39.1	45.0	5.9	95.0	125.0	30.0
Jun-08	882462	1116131	2928000	26.3	30.0	3.7	38.8	45.0	6.2	100.3	125.0	24.7
Jul-08	808059	1169381	2910300	25.3	30.0	4.7	42.7	45.0	2.3	100.9	125.0	24.1
Aug-08	800736	653394	2227400	29.2	30.0	0.8	41.8	45.0	3.2	115.2	125.0	9.8
Sep-08	898974	1011913	2888500	26.9	30.0	3.1	34.5	45.0	10.5	91.2	125.0	33.8
Oct-08	182605	1037572	1494500	38.0	30.0	-8.0	39.3	45.0	5.7	123.3	125.0	1.7
Nov-08	604869	669122	1929200	27.7	30.0	2.3	41.8	45.0	3.2	103.7	125.0	21.3
Dec-08	802803	1040751	2603400	36.7	30.0	-6.7	42.2	45.0	2.8	118.9	125.0	6.1

APPENDIX 7.2: Monthly Industrial Production, Year 2008

MONTH	Crusher Output (t)	Crusher Budget (t)	Crusher Variance (t)	Raw Mill Output (t)	Raw Mill Budget (t)	Raw Mill Variance (t)	Kiln Rate (t/hr)	Kiln Rate Budget (t/hr)	Kiln Rate Variance (t/hr)	Kiln Output (t)	Budget Kiln Output (t)	Kiln Output Variance (t)	Cement Mill Output (t)	Cement Mill Output Variance (t)	Cement Sales (t)	Budget Cement Sales (t)	Cement Sales Variance (t)
Jan-08	31706	46485	-14779	29500	36155	-6655	28.62	28.59	0.03	19021	21268	-2247	27412	-1791	24569	26611	-2042
Feb-08	27881	43403	-15522	28314	33758	-5444	29.26	28.53	0.73	18363	19858	-1495	17	-2913	23017	24861	-1844
Mar-08	35675	47127	-11452	32023	36654	-4631	29.45	29.95	-0.50	18742	21561	-2819	24882	-4537	25280	26611	-1331
Apr-08	15318	18748	-3430	17623	14582	3041	28.93	11.91	17.02	10571	8578	1993	25010	5138	26490	24711	1779
May-08	36588	46485	-9897	38765	36155	2610	34.16	28.59	5.58	24243	21268	2975	27963	-1240	28285	27411	874
Jun-08	35673	44944	-9271	33568	34956	-1388	30.77	28.56	2.21	21144	20563	581	28762	596	26596	27861	-1265
Jul-08	32410	46485	-14075	31896	36155	-4259	31.48	28.59	2.89	21560	21268	292	27384	-1819	28084	27961	123
Aug-08	33038	46485	-13447	27445	36155	-8710	29.46	28.59	0.87	16262	21268	-5006	15613	-13590	23861	29511	-5650
Sep-08	35402	24912	10490	33469	19376	14093	33.48	15.83	17.65	23039	11398	11641	29295	4844	23000	30161	-7161
Oct-08	3101	46485	-43384	4805	36155	-31350	31.99	28.59	3.40	3554	21268	-17714	26408	-2795	26065	29111	-3047
Nov-08	25664	44944	-19280	21863	34956	-13093	29.14	28.56	0.58	13893	20563	-6670	16002	-12164	21449	28761	-7312
Dec-08	25664	46485	-20821	21863	34956	-13093	25.44	28.56	-3.12	13893	20563	-6670	24674	-4529	205211	28761	176450

### APPENDIX 9.1: CUSUM Parameter Calculation

	Month	Production x	Energy y	Predicted energy	Variance	CUSUM
1	Jan-07	20745	1006372	977544.5	28828	28828
2	Feb-07	19347	998574	931270.7	67303	96131
3	Mar-07	21325	1144790	996742.5	148048	244179
4	Apr-07	10071	527833	624235.1	-96402	147777
5	May-07	26707	1178252	1174886.7	3365	151142
6	Jun-07	28605	1108806	1237710.5	-128905	22237
7	Jul-07	29235	1160792	1258563.5	-97772	-75534
8	Aug-07	29275	1237198	1259887.5	-22690	-98224
9	Sep-07	28731	1194762	1241881.1	-47119	-145343
10	Oct-07	18070	853038	889002	-35964	-181307
11	Nov-07	29307	1283403	1260946.7	22456	-158850
12	Dec-07	27465	1367173	1199976.5	167197	8346
13	Jan-08	27412	1200556	1198222.2	2334	10680
14	Feb-08	24217	1162743	1092467.7	70276	80956
15	Mar-08	24882	1157117	1114479.2	42638	123594
16	Apr-08	25010	1189470	1118716	70754	194348
17	May-08	27963	1092459	1216460.3	-124001	70347
18	Jun-08	28762	1116131	1242907.2	-126776	-56430
19	Jul-08	27384	1169381	1197295.4	-27914	-84344
20	Aug-08	15613	653394	807675.3	-154281	-238625
21	Sep-08	29295	1011913	1260549.5	-248637	-487262
22	Oct-08	26408	1037572	1164989.8	-127418	-614680
23	Nov-08	16002	669122	820551.2	-151429	-766109
24	Dec-08	24674	1040751	1107594.4	-66843	-832952

## APPENDIX 9.2: Survey Results

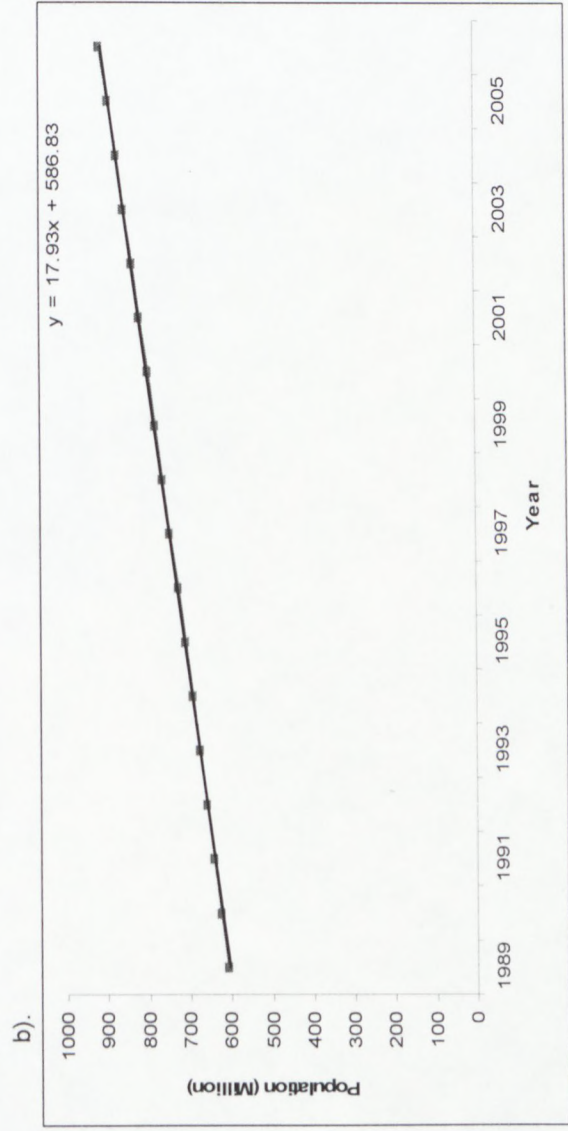
Name	Ind.1	Ind.2	Ind.3
Production	Cement	Cement	Cement
Capacity	6MVA	10MVA	12MVA
Production capacity	25,000t/month	60,000t/month	50,000t/month
Type of tariff structure	Two part	Two part	Two part
How frequency is your meter read	Monthly	Monthly	Monthly
Are you verified your bill	Yes	Yes	Yes
Have you noticed any discrepancy in your bill	Yes	Yes	Yes
Which discrepancy have you noticed	High energy charge than actual	High energy charge than actual	High energy bill
Are you aware about energy auditing?	Yes	Yes	Yes
How often are you doing and what was the motivation factor	When energy researchers did the studies	When energy researcher did the studies	It happened once
Which type of load are predominant in your industry	Motors and lightings	Motors and lightings	Motors and lightings
How are you handling energy issues in your industry	Electrical and mechanical engineers are in charge of the energy issues in the plant	Electrical and mechanical engineers are in charge of the energy issues in the plant	Electrical and mechanical engineers are in charge of the energy issues in the plant
Have you ever have/had any EM program?	Yes very small	No	Not sure
How are you rank of the involvement technical personnel in EM	3	NA	NA
Rate the potential saving achieved?	2	0	0
Do you have any energy consumption benchmark?	Yes	Yes	NA
What is value? (different section)	RM	RM	RM
	Clinker	Clinker	Clinker
	Cement	Cement	Cement
Is the target met? give the reason for each answer	Yes in some month only in kiln section	No	Yes in some month and some section
Which types of energy and demand management are implemented in your industry at the moment?	PFC , sequence starting, maintenance	PFC , sequence starting	PFC, sequence starting
Which LM technique has high return	PFC	PFC	PFC
How would you rate LM awareness in your company	3	2	2
Rate the energy saving opportunities that you might find in your industry?	2	2	2
What kind of barrier have you encountered for introduction and implementation of EM	Financial, Lack of knowledge	Financial, Lack of knowledge and technology	Financial, Lack of knowledge and technology
Rate how would be possible to overcome barrier	3	2	2
How do you rate the contribution of EEM technology Use of Variable speed drive	1	2	1

Use of Energy Efficient motor	1	1	1
Motor rewinding	2	2	2
Demand control	1	2	1
Load shedding	2	2	2
Self generation	0	0	0
Other methods are you rate more	0	0	0
How the top management support the LM idea?	3	3	3
What is the internal and external factor affecting LM	Tariff, funds, perception	Tariff, main power	Technology, main power, tariff
How worker are involved in existing energy management strategy?	2	3	2
How do you value EM program in your company	3	3	3
Is your industry having any energy management policy?	No	No	No

**APPENDIX 10.1: Trend of Population Increase, a) Individual Country, b) Overall Sub-Saharan Africa**  
a).

Region/Country	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
Angola	8.15	8.30	8.50	8.74	8.97	9.17	9.42	9.65	9.86	10.04	10.22	10.38	10.54	10.76	11.06	11.39	11.71	11.99
Benin	4.53	4.68	4.83	4.98	5.21	5.49	5.70	5.89	6.07	6.25	6.44	6.63	6.82	7.03	7.23	7.44	7.65	7.86
Botswana	1.23	1.26	1.30	1.34	1.38	1.43	1.47	1.51	1.54	1.58	1.61	1.64	1.67	1.69	1.71	1.73	1.76	1.79
Burkina Faso	8.09	8.36	8.64	8.93	9.24	9.57	9.90	10.22	10.54	10.87	11.23	11.59	12.04	12.58	13.07	13.48	13.90	14.34
Burundi	5.38	5.51	5.64	5.81	5.63	5.68	6.08	6.10	6.12	6.27	6.46	6.62	6.81	7.02	7.25	7.52	7.80	8.09
Cameroon	11.54	11.88	12.23	12.57	12.92	13.26	13.60	13.94	14.29	14.64	14.99	15.34	15.71	16.09	16.49	16.87	17.26	17.66
Cape Verde	0.34	0.35	0.35	0.36	0.37	0.37	0.38	0.38	0.39	0.39	0.40	0.40	0.41	0.41	0.41	0.42	0.42	0.42
Central African Republic	3.00	3.08	3.17	3.27	3.37	3.46	3.54	3.62	3.70	3.78	3.86	3.94	3.99	4.05	4.11	4.17	4.24	4.30
Chad	5.71	5.84	6.03	6.26	6.38	6.50	6.77	7.05	7.26	7.48	7.71	7.94	8.18	8.44	8.75	9.10	9.40	9.65
Comoros	0.42	0.43	0.44	0.45	0.47	0.48	0.50	0.51	0.53	0.54	0.56	0.58	0.60	0.61	0.63	0.65	0.67	0.69
Congo	2.20	2.26	2.34	2.41	2.49	2.57	2.65	2.73	2.80	2.88	2.97	3.10	3.24	3.33	3.41	3.50	3.60	3.70
DRC	37.80	39.05	40.37	41.65	43.03	44.49	46.30	47.20	47.74	48.76	50.28	51.85	53.50	55.20	56.89	58.63	60.47	62.38
Cote d'Ivoire	11.48	11.98	12.46	12.77	13.14	13.58	13.99	14.34	14.63	14.88	15.20	15.56	15.91	16.25	16.60	16.94	17.30	17.65
Djibouti	0.35	0.37	0.38	0.38	0.39	0.40	0.41	0.41	0.42	0.42	0.43	0.43	0.44	0.45	0.46	0.47	0.48	0.49
Equatorial Guinea	0.36	0.37	0.38	0.39	0.40	0.41	0.43	0.44	0.45	0.46	0.48	0.49	0.51	0.52	0.54	0.55	0.57	0.58
Eritrea	--	--	--	--	--	3.82	3.86	3.93	4.06	4.18	4.32	4.36	4.36	4.41	4.47	4.55	4.67	4.79
Ethiopia	49.39	51.19	53.58	55.76	57.19	54.95	56.63	58.28	59.86	61.44	63.05	64.69	66.31	67.95	69.63	71.34	73.05	74.78
Gabon	0.92	0.94	0.96	0.99	1.01	1.04	1.07	1.10	1.13	1.16	1.20	1.24	1.27	1.30	1.33	1.36	1.40	1.43
Gambia, The	0.91	0.95	0.99	1.03	1.07	1.11	1.15	1.19	1.24	1.28	1.32	1.37	1.41	1.46	1.50	1.55	1.60	1.64
Ghana	14.99	15.41	15.86	16.30	16.81	17.31	17.71	18.09	18.48	18.88	19.30	19.74	20.18	20.64	21.11	21.57	22.03	22.48
Guinea	5.96	6.28	6.73	6.99	7.20	7.43	7.68	7.95	8.05	8.17	8.43	8.64	8.71	8.81	9.02	9.23	9.45	9.69
Guinea-Bissau	0.97	1.00	1.02	1.05	1.08	1.12	1.14	1.17	1.19	1.22	1.25	1.28	1.31	1.33	1.36	1.39	1.41	1.44
Kenya	22.63	23.35	24.12	25.02	25.82	26.45	27.12	27.79	28.46	29.12	29.80	30.51	31.30	32.16	33.04	33.97	34.91	35.89
Lesotho	1.68	1.72	1.76	1.80	1.84	1.88	1.92	1.96	1.99	2.02	2.05	2.07	2.09	2.10	2.11	2.11	2.12	2.12
Liberia	2.41	2.12	1.82	1.91	1.99	1.97	1.98	2.03	2.20	2.46	2.60	2.69	2.76	2.82	2.81	2.81	2.90	3.04
Madagascar	11.29	11.63	11.99	12.36	12.74	13.13	13.53	13.95	14.38	14.82	15.27	15.74	16.23	16.73	17.24	17.77	18.31	18.87
Malawi	9.08	9.54	9.92	10.29	10.48	10.30	10.22	10.46	10.74	11.01	11.29	11.56	11.83	12.11	12.39	12.68	12.97	13.28
Mali	7.93	8.08	8.25	8.42	8.59	8.78	8.97	9.17	9.37	9.59	9.81	10.05	10.29	10.55	10.81	11.09	11.38	11.68
Mauritius	1.05	1.06	1.07	1.08	1.10	1.11	1.12	1.14	1.15	1.16	1.17	1.19	1.20	1.21	1.22	1.23	1.24	1.25
Mozambique	12.48	12.67	12.93	13.18	13.69	14.78	15.76	16.30	16.76	17.22	17.68	18.12	18.56	18.98	19.38	19.77	20.15	20.53
Namibia	--	1.47	1.51	1.55	1.60	1.64	1.68	1.72	1.77	1.81	1.85	1.89	1.94	1.96	1.98	2.01	2.03	2.05
Niger	7.73	7.95	8.16	8.39	8.63	8.88	9.14	9.40	9.67	9.94	10.22	10.52	10.82	11.14	11.47	11.81	12.16	12.53

Nigeria	86.14	88.51	90.92	93.36	95.86	98.39	100.96	103.57	106.21	108.88	111.58	114.31	117.07	119.90	122.79	125.74	128.77	131.86
Rwanda	6.80	6.98	7.12	7.27	7.56	6.26	5.46	6.51	7.58	7.96	8.12	8.28	8.47	8.69	8.90	9.13	9.38	9.64
Sao Tome and Principe	0.12	0.12	0.12	0.13	0.13	0.13	0.14	0.14	0.15	0.15	0.15	0.16	0.17	0.17	0.18	0.18	0.19	0.19
Senegal	7.62	7.85	8.08	8.31	8.54	8.78	9.02	9.27	9.53	9.79	10.06	10.33	10.62	10.91	11.22	11.53	11.86	12.19
Seychelles	0.07	0.07	0.07	0.07	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
Sierra Leone	4.06	4.23	4.34	4.27	4.22	4.32	4.39	4.45	4.58	4.68	4.71	4.82	5.09	5.37	5.57	5.74	5.87	6.01
Somalia	6.77	6.69	6.46	6.12	6.10	6.26	6.40	6.57	6.75	6.97	7.17	7.39	7.63	7.90	8.17	8.46	8.75	9.03
South Africa	38.99	38.39	39.18	39.96	40.64	41.21	41.78	42.31	42.84	43.33	43.75	44.07	44.30	44.43	44.48	44.45	44.34	44.19
Sudan	25.34	26.05	26.94	27.85	28.58	29.35	30.14	30.81	31.59	32.51	33.35	34.19	35.06	35.91	36.59	37.10	37.76	38.57
Swaziland	0.85	0.88	0.93	0.96	0.99	1.00	1.00	1.03	1.05	1.08	1.09	1.11	1.12	1.13	1.14	1.14	1.14	1.14
Tanzania	24.48	25.21	25.97	26.77	27.70	28.80	29.75	30.39	31.09	31.95	32.81	33.71	34.57	35.38	36.20	36.99	37.77	38.57
Togo	3.39	3.50	3.63	3.75	3.73	3.75	3.97	4.16	4.32	4.45	4.58	4.71	4.84	4.98	5.11	5.26	5.40	5.55
Uganda	16.83	17.46	18.08	18.73	19.42	20.13	20.69	21.25	21.86	22.50	23.23	23.96	24.69	25.47	26.32	27.23	28.20	29.21
Zambia	7.75	7.98	8.21	8.44	8.67	8.89	9.10	9.31	9.53	9.75	9.97	10.21	10.44	10.63	10.80	10.96	11.12	11.29
Zimbabwe	9.87	10.15	10.43	10.70	10.95	11.05	11.11	11.26	11.40	11.53	11.65	11.75	11.84	11.93	12.00	12.08	12.16	12.24
<b>Africa</b>	<b>607.25</b>	<b>624.23</b>	<b>642.24</b>	<b>659.96</b>	<b>677.00</b>	<b>693.39</b>	<b>710.97</b>	<b>728.53</b>	<b>745.90</b>	<b>763.64</b>	<b>781.79</b>	<b>799.99</b>	<b>818.39</b>	<b>837.15</b>	<b>855.93</b>	<b>874.75</b>	<b>894.02</b>	<b>913.71</b>



**APPENDIX 10.2: SSA Carbon Dioxide Emissions Per Capita by Country, Year-2004**  
(Metric Tonnes)

<b>RANK</b>	<b>COUNTRY</b>	<b>CARBON DIOXIDE EMISSION (In Metric Tonnes)</b>
1	Equatorial Guinea	2.86
2	South Africa	2.68
5	Mauritius	0.71
6	Botswana	0.66
10	Namibia	0.34
11	Congo	0.28
12	Gabon	0.27
13	Nigeria	0.24
14	Swaziland	0.23
15	Zimbabwe	0.22
16	Angola	0.19
17	Cape Verde	0.18
18	Sao Tome and Principe	0.14
19	Djibouti	0.13
20	Senegal	0.12
21	Togo	0.11
22	Ghana	0.09
22	Kenya	0.09
23	Sudan	0.08
23	Benin	0.08
23	Cote d'Ivoire	0.08
24	Cameroon	0.07
25	Zambia	0.05
25	Gambia	0.05
25	Eritrea	0.05
25	Sierra Leone	0.05
25	Liberia	0.05
26	Madagascar	0.04
26	Guinea	0.04
26	Comoros	0.04
27	Tanzania	0.03
27	Ethiopia	0.03
27	Mozambique	0.03
27	Niger	0.03
28	Burkina Faso	0.02
28	Malawi	0.02
28	Uganda	0.02
28	Rwanda	0.02
28	Central African Republic	0.02
29	Mali	0.01
29	Democratic Republic of Congo	0.01
29	Burundi	0.01

**APPENDIX 10.3: GDP of African Countries (2008)**

<b>RANK</b>	<b>COUNTRY</b>	<b>GDP (USD Millions)</b>
1	South Africa	506100
2	Egypt	452500
3	Nigeria	328100
4	Algeria	240200
5	Morocco	137400
6	Angola	114600
7	Libya	92010
8	Sudan	88950
9	Kenya	66480
10	Ethiopia	63440
11	Tanzania	56220
12	Cameroon	44030
13	Ghana	34520
14	Uganda	34230
15	Cote d'Ivoire	33780
16	Botswana	29170
17	Senegal	22980
18	Gabon	22160
19	Madagascar	21620
20	DRC	21080
21	Mozambique	19680
22	Burkina Faso	19340
23	Equatorial Guinea	18620
24	Zambia	17830
25	Chad	16190
26	Mauritius	15750
27	Mali	14980
28	Congo	14790
29	Benin	13150
30	Malawi	11820
31	Namibia	11590
32	Guinea	11070
33	Niger	9657
34	Rwanda	8909
35	Mauritania	6492
36	Somalia	5756
37	Swaziland	5708
38	Togo	5428
39	Sierra Leone	4418
40	Eritrea	3965
41	Lesotho	3384
42	Central African Republic	3262
43	Burundi	3215
44	Zimbabwe	2292
45	Gambia	2044
46	Djibouti	1930
47	Cape Verde	1808
48	Liberia	1741
49	Seychelles	1537
50	Comoros	779
51	Sao Tome and Principe	278



