

ENHANCED ENERGY-EFFICIENT PARALLEL PUMPING USING  
VARIABLE SPEED DRIVE (VSD) TECHNOLOGY

Onwunta Emea Kalu Onwunta

 CAPE PENINSULA  
UNIVERSITY OF TECHNOLOGY  
LIBRARIES

Doc No. THE 621.46 ON W

CAPE PENINSULA  
UNIVERSITY OF TECHNOLOGY



20131891

CAPE PENINSULA UNIVERSITY OF TECHNOLOGY  
LIBRARY SERVICES  
BELLVILLE CAMPUS

TEL: (021) 959-6210

FAX: (021) 959-6109

Renewals may be made telephonically.

This book must be returned on/before the last date shown.

Please note that fines are levied on overdue books

11 NOV 2013

14 JAN 2014

BEL THE 62146 ONW  
(Green)

**ENHANCED ENERGY- EFFICIENT PARALLEL PUMPING USING VARIABLE  
SPEED DRIVE (VSD) TECHNOLOGY**

**by**

**ONWUNTA EMEA KALU ONWUNTA**

**Thesis submitted in fulfilment of the requirements for the degree**

**Master of Technology:** Electrical Engineering

**in the Faculty of Engineering**

**at the Cape Peninsula University of Technology**

**Supervisor:** Prof MTE Kahn

**Bellville**

November 2011

**CPUT copyright information**

The dissertation/thesis may not be published either in part (in scholarly, scientific or technical journals), or as a whole (as a monograph), unless permission has been obtained from the University

## DECLARATION

I, Onwunta Emea Kalu Onwunta, declare that the contents of this dissertation/thesis represent my own unaided work, and that the dissertation/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.

---

**Signed**

---

**Date**

## ABSTRACT

Global economic meltdown appears to be a new phenomenon in this 21<sup>st</sup> century because worldwide poor financial situation seemed forgotten after the Great Depression of the 1930s. However, energy crisis has been a common worldwide issue and challenge since the October 1973 war in the Middle East which triggered the first of two waves of energy-price increases in the 1970s. That event catapulted the debate about energy and conservation, from its obscure beginnings, in academic and policy circles to sudden public prominence. The recent co-incidence of South Africa's energy crisis with the global financial crisis was a double tragedy. The main reason for the 2007 to 2008 energy crisis in South Africa was the imbalance between electricity supply and demand

Globally about 40% of industrial electricity is consumed by Electric Motor-Driven Systems (EMDS) and South African estimates are around 60%. Pumping systems are crucial industrial EMDS and their energy demand ranges from 25% to 50% of the energy usage in certain industrial plant operations. In South Africa, an estimated 15% of generated electrical power is consumed by pumping systems.

Unfortunately pump systems are often operated inefficiently especially when varying flow demand is necessitated. The most common flow control methods of pumps are throttling, bypassing, on-off switching and use of Variable Speed Drive (VSD). But pump systems with widely varying flow demand are best controlled with VSD.

Parallel operation of pumps, commonly known as parallel pumping, aims at realising a wider range of flow than would be possible with a single and fixed-speed pump for systems with widely varying flow demand. The efficiencies of electric motors in parallel pumping systems are high because they are loaded above 75% of their rating. Parallel pumping also ensures system reliability and availability. In City of Cape Town parallel pumping is currently deployed in the municipal water and wastewater schemes, and petrochemical industry.

Energy efficiency means many things to many people and remains a low hanging fruit on the energy tree. Basically energy efficiency is using less energy to provide the same level of energy service. It is often interchangeably used with energy conservation which has a starvation connotation. But conservation by nature is only used in emergencies where there is not sufficient supply of energy. While efficient use of tertiary energy leads to primary energy

conservation, intentional denial of primary energy does not necessarily result to efficient use of tertiary energy.

Non-holistic approach to energy efficiency improvement strategies of EMDS, especially pumping systems, has resulted to more attention being given to electric motors with pump and VSD receiving little or no attention. However, pumping system efficiency should be a measure of how efficiently the electric motor is controlled as it converts the purchased power into useful work and the pump transfers same efficiently to the fluid. Using an efficient equipment inefficiently leads to energy wastage.

In principle software simulation is a fictitious representation of a real life system. But technically, simulation is a virtual or software representation of a physical circuit or system. Every simulation needs a model description by mathematical equations or circuit topology. Therefore, the accuracy of simulation results depends on the accuracy of the component models. PSIM is a simulation software specifically designed for power electronics and motor drives and provides the advantage of circuit simulation hybridizing with system simulation. This explains its being a favourite for this research work in studying a truly parallel pumping system deploying a VSD in the City of Cape Town.

## ACKNOWLEDGEMENTS

The journey to this research work commenced with Rev Dr Olo Ndukwe who is endowed in exhuming the hidden potentials of his parishioners and nurturing same unto greatness. This he does in tandem with God's master plan for His people because God makes even an unyielding soul a veritable instrument in His hands for the fulfilment of His purpose for His chosen ones.

My darling wife and sponsor , Mrs Ngozi Kalu Onwunta – Medical Laboratory Scientist par excellence – your willingness and desire for the realisation of this vision portrays you as being stupid to many people. Indeed you are a rare gem. You and my son, Chidiebere Emea Onwunta, including my entire household were denied of my fatherly presence while this work lasted. What a huge sacrifice?

The following yielding souls played crucial roles for my admission namely Ms Hombakazi Portia Mbolekwa, Mrs Cyndi Engelbrecht (nee Davy) and Mr Nicholas Madonsela.

Prof MTE Kahn graciously accepted my candidature for this research work. When the work commenced he was everything for the success of this work which ranged from facilitating for industrial visits and their executions to moral and financial supports including academic guidance. I look forward to more academic endeavours with him!!!

My brother in a strange land, Mr Atanda K. Raji, your contributions to the successful completion of this work will not go unrewarded.

Mr Peter Mithamo you were a solid link with Cape Town Refinery (Caltex Refinery). Messrs Inus Basson and Kobus Stassen have the credit for all technical inputs from Caltex Refinery. Ms Jolene Hall of ZEST WEG Group ensured the feasibility of receiving the motor parameters used in the simulations. The aim of this work would have been defeated without the assistance of City of Cape Town personnel namely Messrs Mogamatjusuf Klein, Deon Lategan and Shamiel Peters.

I also wish to gratefully acknowledge the financial and moral supports of Messrs Kalu Onwukwe Uduma, Uwaoma Nwoke Kalu, Nnachi-Chi Ukpai, Okonkwo Uduka, Stephen Udo Kalu, Richmond Udo Onyeije and Drs Maxwell Ukonu Odo and Awa Eke Awa.

The CPUT financial support through CPGS bursary was of immense assistance towards this research work.

Finally I thank God Almighty for His grace and mercy, provision and protection before and during this research period.

## **DEDICATION**

This work is dedicated to my late mother Mrs Hannah Kalu Onwunta who toiled to ensure that I received proper education from primary to tertiary. She was determined to achieve the desire of my late father – Mr Jacob Emea Kalu Onwunta – who vowed to educate his children.

The dedication is also for my darling wife – Mrs Ngozi Kalu Onwunta, and son – Chidiebere Emea Onwunta. You are all I have!!!

## TABLE OF CONTENTS

DECLARATION	ii
ABSTRACT	iii
ACKNOWLEDGEMENTS	v
DEDICATION	vi
LIST OF FIGURES	xii
LIST OF TABLES	xv
GLOSSARY	xvi
CHAPTER 1: INTRODUCTION	
1.1 Background	1
1.2 Problem Statement	4
1.3 Research Objectives	5
1.4 Thesis Statement	6
1.5 Research Scope and Limitations	6
1.6 Significance of the Research	6
1.7 Organisation of the thesis	6
CHAPTER 2: LITERATURE REVIEW	
2.1 Introduction	8
2.2 Energy and Related Concepts	8
2.2.1 Energy Efficiency	10
2.2.2 Energy and Exergy Efficiency	13
2.2.3 Energy Efficiency and Conservation	15
2.2.4 Energy Efficiency and Intensity	17
2.3 Electric Motors	22
2.3.1 Historical Perspective	22
2.3.2 Classifications	24
2.3.3 Performance Parameters	30
2.3.3.1 Torque	30

2.3.3.2 Power	34
2.3.3.3 Speed	35
2.3.3.4 Efficiency	38
2.3.4 Efficiency Standards and Classifications	42
2.4 Pumps	49
2.4.1 Historical Perspective	50
2.4.2 Classifications	51
2.4.3 Performance Parameters	54
2.4.3.1 Centrifugal Pumps	55
2.4.3.1.1 Flow Rate	55
2.4.3.1.2 Head	55
2.4.3.1.3 Speed	55
2.4.3.1.4 Power	56
2.4.3.1.5 Power Efficiency	56
2.4.3.2 Positive Displacement	56
2.4.3.2.1 Flow Rate	56
2.4.3.2.2 Outlet Pressure	56
2.4.3.2.3 Shaft Power	57
2.4.3.2.4 Efficiency	57
2.4.4 Efficiency Standards and Classifications	57
2.5. Drives	58
2.5.1 Drive System Types	59
2.5.1.1 Mechanical System	59
2.5.1.2 Hydraulic System	60
2.5.1.3 Electrical System	61
2.5.2 Electrical Drives	63
2.5.2.1 Historical Perspective	64
2.5.2.2 Drive as a Device or System	64
2.5.2.3 Adjustable Speed Drive or Variable Speed Drive	67

2.5.2.4 Variable Frequency Drive or Variable Speed Drive	69
2.5.2.5 Inverter	73
2.5.2.6 Classifications	74
2.5.2.6.1 Power and Voltage Level	75
2.5.2.6.2 Semiconductor Switches	75
2.5.2.6.3 Inverter Input	76
2.5.2.6.4 Switching Strategies	78
2.5.2.6.5 Control Methods	80
2.5.2.7 Efficiency	83
2.5.2.8 Disadvantages	86
2.5.2.8.1 Harmonics	87
2.5.2.8.2 Electromagnetic Interference (EMI)	90
2.5.2.8.3 Standards	92
2.5.2.8.4 Mitigation Measures	95
2.6 Conclusion	99
CHAPTER 3: BASIC PUMPING CONCEPTS AND PARALLEL PUMPING	
3.1 Introduction	100
3.2 System Characteristics	100
3.3 Pump Characteristics	104
3.4 Pump Operating Point	107
3.5 Parallel Pumping	109
3.6 Pump Paralleling in the City of Cape Town	114
3.6.1 Bellville Wastewater Treatment Plant	114
3.6.2.1 Wynberg Reservoir and Pumping Station	117
3.6.2.2 Monterey Pumping Station	118
3.6.3 Cape Town Refinery	120
3.7 Conclusion	122
CHAPTER 4: PUMP FLOW CONTROLS	
4.1 Introduction	123

4.2 On-Off Control	126
4.3 Throttling	129
4.4 Variable Speed Drive (VSD) Control	133
4.5 Conclusion	139
CHAPTER 5: COMPUTER SIMULATION	
5.1 Introduction	140
5.2 Motor Data	142
5.3 System Simulation	143
5.4 Conclusion	147
CHAPTER 6: RESULT ANALYSIS	
6.1 Introduction	148
6.2 PSIM Motor Model	148
6.3 Conclusion	150
CHAPTER 7: CONCLUSION AND RECOMMENDATIONS	
7.1 Introduction	151
7.2 Conclusion	151
7.3 Recommendations	153
7.4 Publications	154
REFERENCES	155
APPENDICES	
Appendix 1: Wynberg Pumping Trend	166
Appendix 2: Monterey Pumping Trend	167
Appendix 3: Caltex Refinery Sludge feed pump PI data	168
Appendix 4: Electric motor data	171
Appendix 5: Publications	
(A) Energy Efficiency and Reliability Improvement Strategies in Industrial Electric Motor-Driven Systems (EMDS)	172

(B) Electric drive and energy efficiency: Myriad meanings	179
(C) Energy Efficiency and Conservation: South Africa's Perspective	188

## LIST OF FIGURES

Fig.1.1 Disaggregation of motor electricity consumption by end-use in the Industrial sector in EU	3
Fig.1. 2 Maximum energy demand in the industrial sector of South Africa	4
Fig. 2.1 Definition of primary, secondary and final energies	9
Fig. 2.2 Carbon Dioxide Emission per capita	13
Fig. 2.3 Final energy demand per capita	21
Fig. 2.4 Family tree of motor types	25
Fig. 2.5 Three phase squirrel-cage induction motor	29
Fig. 2.6 Three-phase induction motor torque-speed characteristic	31
Fig. 2.7 Typical torque–speed and current–speed curves	32
Fig. 2.8 Transformer model of an induction motor	33
Fig. 2.9 Typical motor part load efficiency	35
Fig. 2.10 Types of torque-speed curves	37
Fig. 2.11 Typical efficiency versus load curve bands for 2- and 4-pole three-phase, cage-induction motors	39
Fig. 2.12 Typical motor losses	41
Fig. 2.13 Efficiency classes for four-pole motors of standard IE3, IE2 and IE1 classes, and the new IE4 class	48
Figure 2.14 Classification of pumps	52
Fig. 2.15 Mechanical drive system	60
Fig. 2.16 Hydraulic drive system	61
Fig. 2.17 Electric drive system	62
Fig. 2.18 Classification of electronic drives	65
Fig. 2.19 Electrical drive system	66
Fig. 2.20 Comparison of process speed range control	68
Fig. 2.21 Topology of a VSI-PWM with dissipation resistance	77
Fig. 2.22 VSD using current-source inverter	78
Fig. 2.23 Typical circuit for synchronous motor VSD system (EC, 2000)	78
Fig 2.24 Classifications of PWM techniques	80

Fig 2.25 General classification of induction motor control methods	82
Fig. 2.26 Typical efficiency of indirect three-phase voltage source type converters with a passive front-end	83
Fig. 2.27 Typical efficiency of low-voltage PWM frequency converters at full-load	85
Fig. 2.28 Waveform with VSD harmonics	88
Fig. 2.29 Immunity and emission compatibility	92
Fig. 2.30 Harmonics reduction techniques	95
Fig. 2.31 An ac drive fitted with line-side and motor-side filters	98
Fig. 3.1 Static Head vs. Flow rate	102
Fig. 3.2 Friction Head ( $h_{loss}$ ) vs. Flow Rate	103
Fig. 3.3 System Head vs. Flow Rate	104
Fig. 3.4 Pump characteristic curves	105
Fig. 3.5 Conventional positive displacement pump curve	106
Fig. 3.6 Illustration of centrifugal pump operating point	108
Fig. 3.7 Illustration of positive displacement pump operating point	108
Fig. 3.8 Illustration of parallel operation of centrifugal pumps	110
Fig. 3.9 Final effluent pump section of Bellville Wastewater Plant	115
Fig. 3.10 Multistage centrifugal pump and its leakages	116
Fig. 3.11 The author inside Wynberg Pumping Station No 3	117
Fig. 3.12 Prof MTE Kahn and his student inside Monterey Pumping Station	119
Fig. 3.13 The author with Mr Shamiel Peters inside Monterey Pumping Station	120
Fig. 3.14 Sludge feed pumps of the effluent treatment plant	121
Fig. 4.1 Example of Pump performance curves	124
Fig. 4.2 Panel enclosing a VSD and left to the vagaries of nature	128
Fig. 4.3 Mr Deon Lategan and the author after the panel was opened	128
Fig. 4.4 Valve control of pump flow	129
Fig. 4.5 Wynberg Pump Station 3 isolation valve	132
Fig. 4.6 Delivery valve in Monterey Pumping Station	132
Fig. 4.7 Illustration of VSD pump flow control	134

Fig. 4.8 Filter press graphics	135
Fig. 4.9 Graph of speed, pressure and frequency versus process duration	136
Fig. 4.10 Load reactor connection	137
Fig. 4.11 Mr Inus Basson and author inside the Caltex Refinery sludge feed pump equipment room	139
Fig. 5.1 Motor equivalent circuit	142
Fig. 5.2 Simulation circuit diagram	144
Fig. 5.3 Individual motor and combined motor speed	145
Fig. 5.4 Motor and pump torque curves	145
Fig. 5.5 Motor and pump cumulative torques	146
Fig. 5.6 Single pump and cumulative torques	146
Fig. 6.1 Squirrel-cage induction machine snapshot	148

## LIST OF TABLES

Table 1.1 Energy usage by motor driven equipment in EU	2
Table 2.1 Loss distribution in three-phase, 4-pole, cage-induction electric motors	41
Table 2.2 Electric motor efficiency classes, testing standards and regulation over time	43
Table 2.3 Approximate estimation of comparable efficiency levels using JEC, IEC, and IEEE test methods	45
Table 2.4 List of features of IEEE 112-B and IEC 60034-2-1	46
Table 2.5 Motor efficiency classes in different countries and the corresponding international standard	49
Table 2.6 Efficiency range of positive displacement pumps	57
Table 2.7 Induction machines speed variation	71
Table 2.8 Loss distribution for low-voltage uncontrolled-converters	84
Table 2.9 Techniques used to reduce supply harmonics	96
Table 2.10 An overview of technique used as a counter measure to EMI	98
Table 3.1 Typical Wynberg Pumping House No 3 data	118
Table 3.2 Typical Monterey Pumping Station data	119
Table 5.1 Motor's parameter values in ohms at 20° C	142

## GLOSSARY

AC – Alternating Current

ANAS – American National Academy of Sciences

ASD – Adjustable Speed Drive

BEP – Best Efficiency Point

BJT – Bipolar Junction Transistor

BWTP – Bellville Wastewater Treatment Plant

CT – Carbon Trust

CCT – City of Cape Town

CEMEP – European Committee of Manufacturers of Electrical Machines and Power Electronics

CMSOGPE – China Manufacturers and Suppliers of Oil, Gas and Petrochemical Equipment

CO<sub>2</sub> – Carbon Dioxide

CPUT – Cape Peninsula University of Technology

CSI – Current Source Inverter

CSR – Current Source Rectifier

CSTBT – Carrier Stored Trench-Gate Bipolar Transistor

DC – Direct Current

DF – Distortion Factor

DSM – Demand Side Management

DSP – Digital Signal Processor

EC – European Commission

EEA – Energy Efficiency Agreement

EEA – European Economic Area

EIA – Energy Information Administration

EMC – Electromagnetic Compatibility

EMDS – Electric Motor-Driven System

EMF – Electromagnetic Force

EMI – Electromagnetic Interference  
EPAAct – US Energy Policy Act  
ESD – Electrostatic Discharge  
EST – Emitter Switched Thyristor  
EU – European Union  
FCT – Field Controlled Thyristor  
FFT – Fast Fourier Transfer  
FOC – Field Orientation Control  
GAMBICA – Automation, Instrumentation & Control Laboratory Technology  
GDP – Gross Domestic Product  
GHGs – Greenhouse Gases  
GIEEC – Green Insulated Electrical Earth Conductor  
GTO – Gate Turn Off Thyristor  
HI – Hydraulic Institute  
HVAC – Heating Ventilation and Air-Condition  
IEC – International Electrotechnical Commission  
IEEE – Institute of Electrical and Electronic Engineers  
IEGT – Injection Enhanced Gate Transistor  
IGBT – Insulated Gate Bipolar Transistor  
IGCT – Integrated Gate Commutated Thyristor  
LCI – Load Commutated Current Inverter  
LV – Low Voltage  
MCT – MOSFET Controlled Thyristor  
MER – Market Exchange Rate  
MMF – Magnetomotive Force  
MOSFET – Metal Oxide Semiconductor Field Effect Transistor  
MTO – MOS Turn Off Thyristor  
MTOE – Million Tonnes of Oil Equivalent

MV – Medium Voltage

NEMA – National Electrical Manufacturers Association

NPSHA – Net Positive Suction Head Available

NPSHR – Net Positive Suction Head Required

NPSPR – Net Positive Suction Pressure Required

OECD – Organisation for Economic Co-operation and Development

PCC – Point of Common Coupling

PCP – Progressive Cavity Pump

PDS – Power Drive System

PI – Pumping and Instrumentation

PPP – Purchasing Power Parity

PSM – Pump Systems Matter

PSRC – Power System Relaying Committee

PVCSWAPVC – Polyvinyl Chloride/Steel Wire Armour/ Polyvinyl Chloride

PWM – Pulse-Width Modulated

REMA – Rotating Electrical Machines Association

RFI – Radio Frequency Interference

RMS – Root Mean Square

RSA – Republic of South Africa

RSS – Root Sum Square

SAPMA – South African Pumps Manufacturers' Association

SCR – Silicon Controlled Rectifier

SNA – System of National Accounts

SO<sub>2</sub> – Sulphur Dioxide

SVM – Space Vector Modulation

TFC – Total final Energy Consumption

THD – Total Harmonic Distortion

TOE – Tonnes of Oil Equivalent

TPES – Total Primary Energy Supply

US-DOE – US Department of Energy

UWC – University of Western Cape

VFD – Variable Frequency Drive

VSD – Variable Speed Drive

VSI - Voltage Source Inverter

VSR – Voltage Source Rectifier

WAG – Western Australian Government

WEC – World Energy Council

# CHAPTER 1: INTRODUCTION

## 1.1 Background

Global economic recession or meltdown appears to be a new phenomenon in this 21<sup>st</sup> century because worldwide poor financial situation seemed forgotten after the Great Depression of the 1930s. It is basically a crisis in the global financial sector which economists believe was triggered by a liquidity shortfall in the United States banking system caused by the overvaluation of assets leading to diverse measures to restabilising the economy. Consequent on this volatile economic climate, organisations are increasingly adopting process improvements to gain competitive advantages. Finding ways to save money and enhance operations are currently more important than ever.

However, energy crisis has been a common and persistent global challenge with its attendant discourse since the October 1973 war in the Middle East which sparked off the first of two waves of energy-price increases in the 1970s (Jordan,1983;Hollander & Schneider,1996). According to Hollander and Schneider that event catapulted the debate about energy and conservation from its obscure beginnings in academic and policy circles to sudden public prominence. Therefore, globally nations are beginning to face up to the challenge of sustainable energy – in other words to alter the way that energy is utilised so that social, environmental and economic aims of sustainable development are supported.

The Republic of South Africa being a major developing economy of the world is not immune to this global energy challenge. Since 2007, Eskom has experienced a lack of capacity in the generation and reticulation of electricity (Inglesi & Pouris, 2010) which resulted in the first quarter of 2008 blackouts experienced in the country and the resultant South Africa's economic damage. Eskom is a South African government authority mandated to generate, transmit and in some cases, distribute power. In their view the economic growth of the first quarter of 2008 fell to 1.57% from 5.4% in the last quarter of 2007. The main reason for the 2007-2008 energy crisis was the imbalance between electricity supply and demand. This, according to Inglesi and Pouris (2010), is attributable to

- The delayed decision (in 2004) by government to fund the building of a new power station which failed to give Eskom enough time to prevent the crisis.
- The increase (50%) of electricity demand in the country between 1994 and 2007 which might have been partially a consequence of the implementation of the Free

Basic Electricity Policy in 2001. Coupled to this was the expansion of the economy after the lifting of the sanctions.

This crisis necessitated the posting of announcement in South African national news media, including radio and television, by the power utility Eskom from mid March 2008. Sebitosi (2008) vividly captured the announcement as follows:

Electricity demand has not reduced by the required 10% in order to stabilise the national power grid. Eskom has therefore instituted load shedding from the 1st of April (2008) in order to stabilise the national power grid. For more information about loading shedding schedules in your area please check in your local newspapers or visit [www.eskom.co.za](http://www.eskom.co.za).

He noted that this had been preceded by weeks of passionate appeals to industry and the public, by the Minister of Minerals and Energy as well as Eskom, to cut down on their electricity consumption by the said amount.

Ramachandra et al. (2006) share the same view with Sebitosi (2008) that improving efficiency can save vast amounts of energy. According to them two paths could be followed to have more disposable energy. The first is to increase the energy production. Supposing that the GDP will increase if the energy production expands; the country will then have an energy-intensive path. The second possibility is to increase the efficiency or to minimise the loss. That also leads to a situation where more energy is available.

Pumping systems account for nearly 20% of the world's energy used by electric motors and 25% to 50% of the total electrical energy usage in certain industrial facilities (HI & Europump, 2004) such as water and waste water treatment plants.

It is estimated that in the United Kingdom, pumps use a total of 20TWh/annum, responsible for the emission of 2.7MtC/annum (2.7 million tons of carbon). Pumps therefore represent the largest single user of motive power in industry and commerce (CT, 2002) as shown in Table 1.1.

Table 1.1 Energy usage by motor driven equipment in EU (CT, 2002)

S/No	Equipment	Energy Usage (%)
1	Pumps	31
2	Fans	23
3	Compressors	14
4	Air Compressors	8
5	Others	16

The findings of CT (2002) on the high energy consumption of pumps was corroborated by de Almeida *et al.* (2003) as shown in Fig. 1.1,

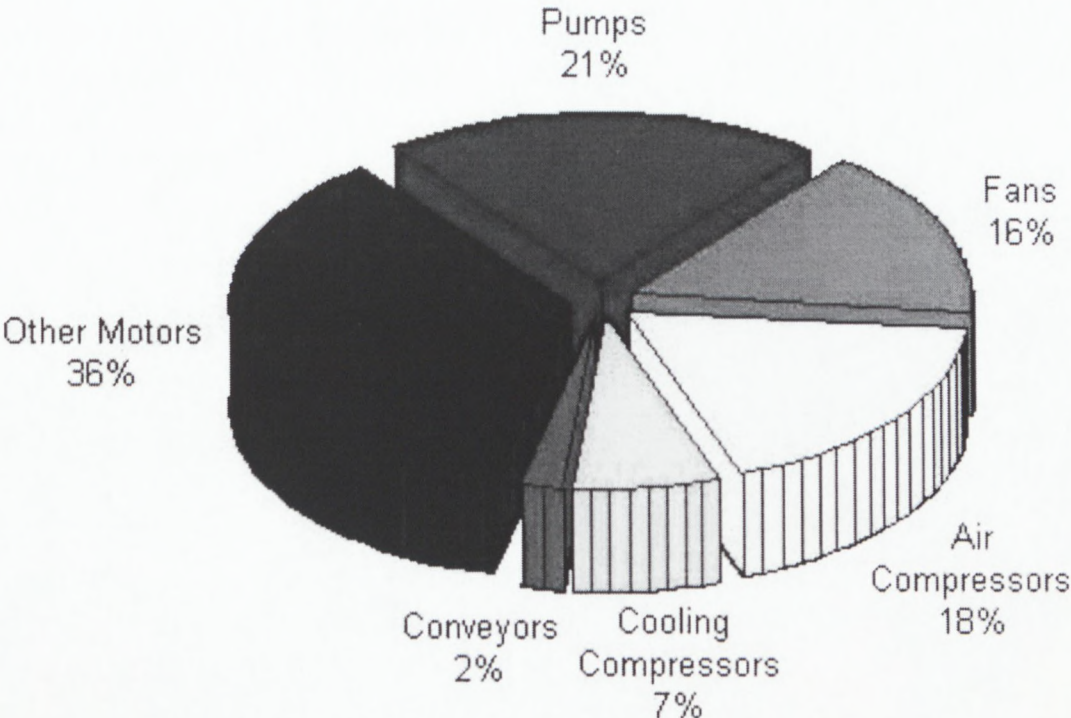


Fig.1.1.Disaggregation of motor electricity consumption by end-use in the Industrial sector in EU (de Almeida *et al.*, 2003)

Expectedly South Africa with its strong developing economy has a fair share of this high pump energy consumption. In South Africa, an estimated 15% of generated electrical power is consumed by pumping systems (Rosen, 2009). A graphical representation of the industrial energy consumption of South Africa is shown in Fig. 2. The high energy consumption of pumps is outstanding from this chart and estimated at 13%. The caption of Fig. 1.2 appears confusing because of its inclusion of Homes & Hotels as an industrial subsector. However, the author's interest is the outstanding high percentage of the pumping system energy consumption.

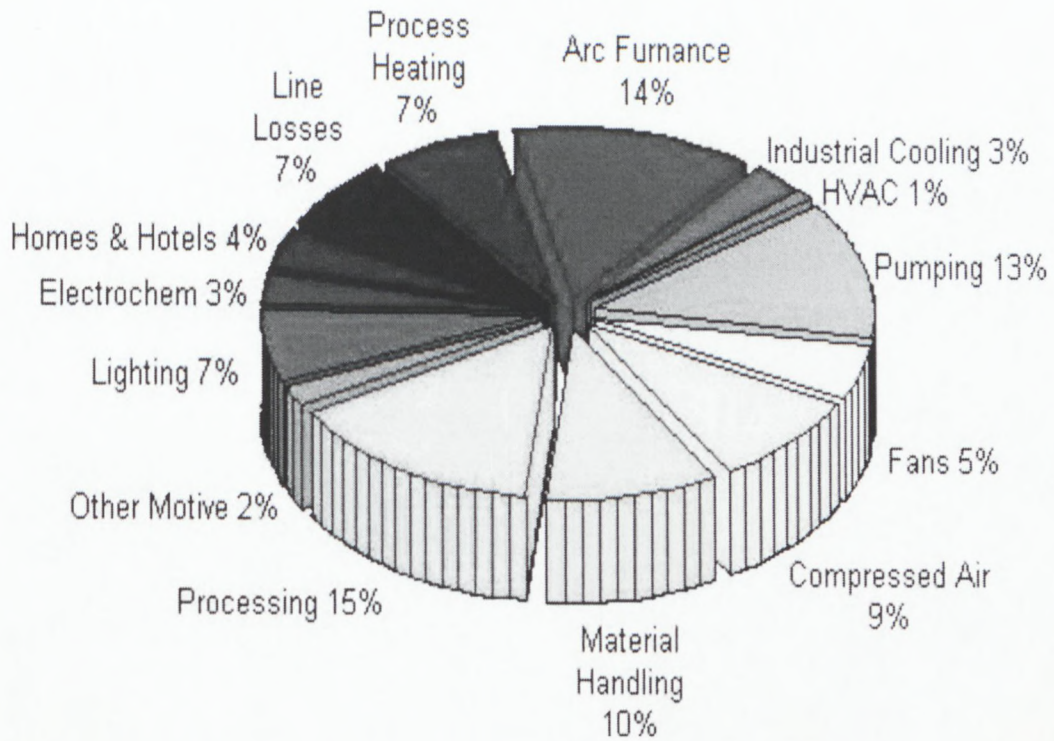


Fig.1. 2 Maximum energy demand in the industrial sector of South Africa  
(Warwick *et al.*, 2008)

## 1.2 Problem Statement

Pump systems are unfortunately often operated inefficiently irrespective of their high energy consumption ranking. Various reasons have been adduced that vary from process to process and application to application, but the constant outcome is the cost to industry through wasted energy and the cost to the environment through the generation of this wasted energy.

Along with pump speed control and multiple pump arrangements, bypass valves and throttling valves are the primary methods for controlling rates of flow in pumping systems (PSM & HI, 2008). Bypass or recycling arrangements allow fluid to flow around a system component, but at the expense of system efficiency because the power used to recycle any fluid is wasted. Throttling valves, input or output, restrict fluid flow at the expense of pressure drops across the valves. Both output pressure throttling and recycling are extremely inefficient, but, of the two, recycling is worse (Carlson, 2000). The throttling of a pump discharge to control the flow rate is not only inherently inefficient, but also in many cases destructive of the throttling device (Gibson, 1994).

Undoubtedly it is only wasted energy that could be saved (Empson,1998) and the control of pumps using variable speed control of the pump prime mover (electric motor) is basically aimed at recovering the expected wasted energy of either throttle or recycle control. Variable speed drive control achieves this feat by operating the pump system at only the necessary levels or points at a given time. Literature is replete with the assessment of both technical and economical advantages of using alternating current variable speed drive (VSD) control, instead of the former, on pumps (Rice, 1988; Rockwell Automation, 2000; Johansson, 2009; Prachyl, 2010; Saidur, 2010)

### **1.3 Research Objectives**

Parallel operation of pumps commonly known as parallel pumping is currently deployed in the municipal water supply and wastewater schemes, and petrochemical industry among others. Parallel pumping involves the connection of several pumps of same or different capacities to achieve a common discharge. The primary purpose of operating pumps in parallel is to allow a wider range of flow than would be possible with a single and fixed-speed pump for systems with widely varying flow demand (Karassik *et al.*, 2001; Volk, 2005; Viholainen *et al.*, 2009). Besides increased flow rate (capacity) at constant pressure(head),parallel pumping system according to da Costa Bortoni *et al.* (2008) brings some advantages that include, but not limited to, low energy consumption at high and low loads, ease of maintainability, quick response to disturbances such as pressure fluctuation and power glitches, reduced water hummer and cavitation effects, scalability, and expandability.

Pumps representing the largest single user of motive power in industry and commerce, this research therefore had as its core objective to identify and analyse the current deployments of parallel pumping control systems with a view to improving their energy efficiency thereby reducing their energy consumption. To realise this, the following issues were examined:

1. Evaluation and confirmation of the deployment of parallel pumping as stated earlier.
2. Evaluation of the energy efficiency standard compliance of the electric motors and pumps.
3. Assessment of the current electrical drive systems.
4. Computer simulation using PSIM software.

## **1.4 Thesis Statement**

The overall intent of this research was to evaluate existing paralleling pumping systems with emphasis on their efficient operations and subsequently propose their efficiency improvement strategies.

## **1.5 Research Scope and Limitations**

This research focused on the three major industrial sectors earlier highlighted namely municipal water supply and wastewater schemes, and petrochemical. However, this study was confined to such establishments in the City of Cape Town of South Africa.

Three phase electric motors being predominant in the industries, this study excluded the use of single phase electric motors, steam turbines, hydraulic motors, and air motors as pump prime movers.

The overall result of this research depends not just on the electric motors and their controls but also on the pumps and their ancillary equipment. Pumping systems are normally composed of pumps, drivers, piping, valves and other components necessary for system operation (Mardam-Bey, 2007). This system or integrated approach is analogous to looking at the forest and not just the trees.

## **1.6 Significance of the Research**

VSD control is acclaimed the best method of achieving variable pump flow especially in parallel pumping. The dynamic nature of Power Electronics (Bose, 2000, 2006; Wu, 2006; Shakweh, 2007; Leon & Solsona, 2010) industry has led to fast developmental strides in VSD technology. Consequently retrofitting could be contemplated upon by some industrialists. However the question to be answered remains “To what extent would that impact positively on the energy efficiency of the system?” Equally following the advances in VSD technology it has become imperative to be properly guided in making a choice given the wide range of motor speed control technologies that currently exists. Having efficient equipment such as pumps is vital but operating them efficiently according to their specifications is more important.

## **1.7 Organisation of the thesis**

This thesis is organised as follows

- Chapter 1: Introduction
- Chapter 2: Literature Review
- Chapter 3: Basic Pumping Concepts and Parallel Pumping
- Chapter 4: Pump Flow Controls
- Chapter 5: Computer Simulation
- Chapter 6: Result Analysis
- Chapter 7: Conclusion and Recommendations

## CHAPTER 2: LITERATURE REVIEW

### 2.1 Introduction

The aim of this chapter is to attempt an in-depth literature study of the basic terminologies associated with the research topic. Such terms include energy and related concepts, electric motors, pumps and drives.

### 2.2 Energy and Related Concepts

Energy is a primary entity and is difficult to define easily, as it is most correctly defined in mathematical terms. Colloquially, it is seen as the ability or capacity to do work (this could also be described as producing change or “available energy”) (EC, 2009).

Goldemberg and Lucon (2010) while chronicling the evolution of the concept of energy have noted that the existence of energy in itself may lead to profound philosophical discussions. This is because its definition is operational, allowing measurement and calculation procedures, without answering its real nature. The idea of energy has existed since antiquity; but the current concept of energy, however, took many years to develop. According to them Thomas Young (1773–1829) adopted the word Energy in 1807, from the Greek *energeia* (at work or in activity), to unify the aspects observed on heat and work. The unification was based on the works of Isaac Newton, Fahrenheit, Celsius and Thompson.

Consequently, Bhattacharyya (2011) has observed that energy is commonly defined as the ability to do work or to produce heat. Work, in turn, is the result of the action of a force on the displacement of a body. This ability to do work may represent the capability (or potential) of doing work (known as potential energy as in stored water in a dam) or its manifestation in terms of conversion to motive power (known as kinetic energy as in the case of wind or tidal waves). Thus energy manifests itself in many forms such as heat, light, motive force and chemical transformation.

Energy could be classified based on its source as primary, secondary or tertiary energy respectively. The term primary energy is used to designate an energy source that is extracted from a stock of natural resources or captured from a flow of resources and that has not undergone any transformation or conversion other than separation and cleaning. Examples of primary energy include coal, crude oil, natural gas, solar power and nuclear power.

Secondary energy on the other hand refers to any energy that is obtained from a primary energy source employing a transformation or conversion process. Thus oil products or

electricity are secondary energies as these require refining or electric generators to produce them. Both electricity and heat can be obtained as primary and secondary energies (Bhattacharyya, 2011). However, even these energy forms are not really of interest to us. What we really want are end-use energy services – things like warmth, motion, mechanical power or process heat for industrial manufacturing. These are referred to as tertiary energy (Harvey, 2010). European Commission (EC) (2009) believes that final energy is the energy that is received by the user, and may be both primary and secondary energies (e.g. natural gas as the primary energy and electricity as the secondary energy used in an installation). The relationship is shown in Fig. 2.1.

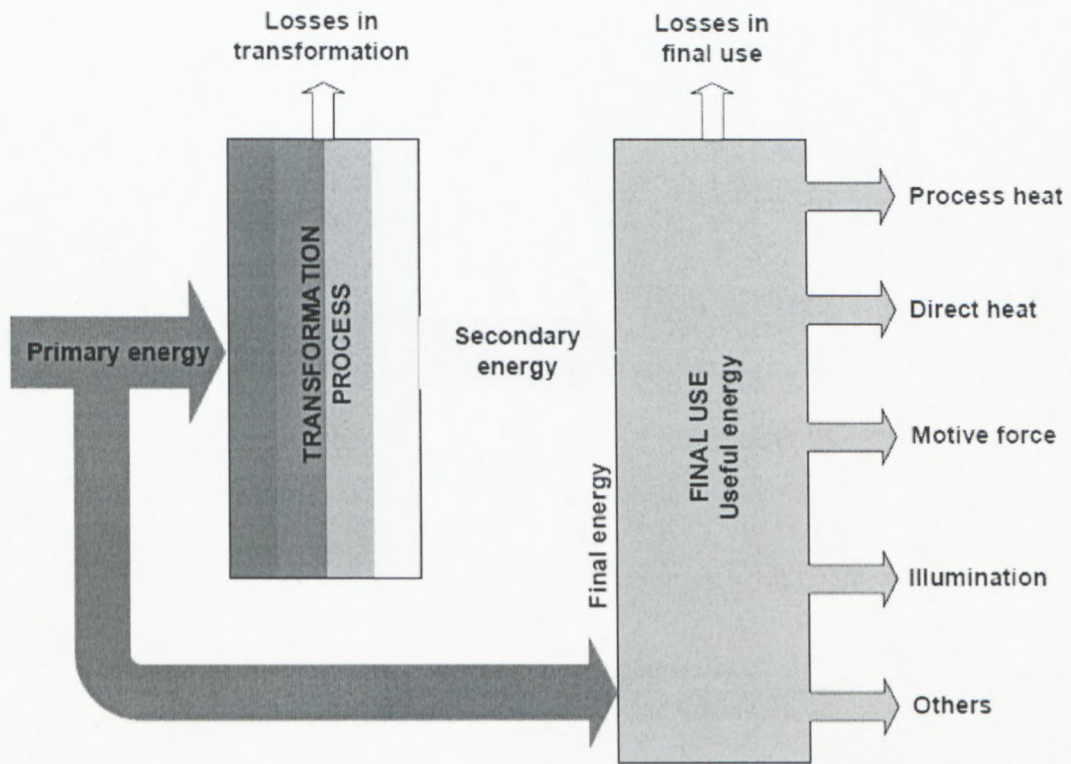


Fig. 2.1 Definition of primary, secondary and final energies (EC, 2009)

Bose (2000) in his contribution to energy and environmental issues posited that energy has been the life-blood for continual progress of human civilisation. In his view since the beginning of industrial revolution around two centuries ago, the global energy consumption has increased by leaps and bounds to accelerate the human living standard, particularly in the industrialised nations of the world. According to him, per-capita energy consumption has been a barometer of a nation's economic prosperity. By his records USA has the highest living standard in the world. With only 5% of world population, it consumes 25% of total

energy. Japan, on the hand, consumes 5% of total energy with 2% of world population. India and China together, with 38% of world population, consumes only one-tenth of that of USA. Abdelaziz *et al* (2011) affirm the view of Bose (2000) having noted that huge amount of energy is needed for countries with faster economic growth which makes energy a crucial factor for economic competitiveness and employment. They have however observed that global population and energy needs are increased hand-in-hand. This concern, according to them, must be addressed by the international community to overcome any shortage of energy resources in the future.

South Africa's energy consumption per capita is high compared with the world average: 2.7 toe versus 1.8 toe. The country's electricity consumption per capita is about 60 percent higher than the world average (4,150 kWh in 2009, compared with the world average of 2,550 kWh) (ABB, 2011). According to RSA (2009), South Africa uses some 40% of the total electricity consumed within the continent. However, comparing the values of electricity consumption per capita and the total primary energy supply (TPES) per capita of South Africa with Japan, they are only about half (Matsumoto & Nakata, 2008).

### **2.2.1 Energy Efficiency**

Energy efficiency is a "low hanging fruit" on the "energy tree" which can help address a number of objectives at the same time and at a low or negative cost: security of supply, environmental impacts, competitiveness, balance of trade, investment requirements, social implications and others (WEC, 2010).

EC (2009) has observed that initially or ordinarily '*energy efficiency*' appears to be simple to understand. However, it is not usually defined where it is used, so '*energy efficiency can mean different things at different times, and in different places or circumstances*'. This lack of clarity, according to it, has been described as '*elusive and variable*', leading to '*inconsistency and muddle*' and where energy savings need to be presented in quantitative terms, the lack of adequate definitions is '*embarrassing especially when comparisons are made between major industries or between industry sectors*'.

The view of EC (2009) is in agreement with US-EIA (1995) who had noted that the words "energy efficient" and "energy efficiency" are in common use qualitatively, but are difficult to define or even to conceptualise. In its view, an engineer may define energy efficiency in a

very restrictive equipment sense, whereas an environmentalist may have a broader view of energy efficiency. Also an economist, politician, sociologist, etc., may each have a different concept of energy efficiency. It therefore believes that increases in energy efficiency occur when either energy inputs are reduced for a given level of service or there are increased or enhanced services for a given amount of energy inputs.

Efficient energy use, sometimes simply called energy efficiency, is using less energy to provide the same level of energy service (Wikipedia, 5 March 2010). In other words, energy efficiency means gaining the greatest energy output from every unit of energy consumed (Solmes, 2009). For example, insulating a home allows a building to use less heating and cooling energy to achieve and maintain a comfortable temperature. Another example would be installing fluorescent lights or skylights instead of incandescent lights to attain the same level of illumination. The illumination produced by a 13W fluorescent light bulb could be comparable to that of a 60W incandescent bulb which implies getting more light for less energy. ANAS *et al* (2009) have also reported that sales and use of compact fluorescent lamps, which consume about 75% less electricity per unit of light output than incandescent lamps consume, have greatly increased in the past decade. In commercial buildings, according to them, energy-efficient fluorescent lighting fixtures containing T8 fluorescent lamps and high-frequency electronic lamp ballasts use 15–30% less energy per unit of light output than do older fixtures with T12 lamps and electromagnetic ballasts.

According to WEC (2008) energy efficiency improvements refer to a reduction in the energy used for a given service, such as heating and lighting, or level of activity. The reduction in the energy consumption is usually associated with technological changes, but not always since it can also result from better organisation and management or improved economic conditions in the sector (“non-technical factors”). Sola and de Paula Xavier (2007) defined technology as a grouping of techno-scientific knowledge applied to production, for new product and for improved product and processes. They further defined useful energy as the difference between the final energy (energy supplied to the equipment) and the conversion losses. Earlier Kosow (1986) had submitted that in energy conversion the concept of energy efficiency corresponds to the minimum loss of energy when the primary energy is converted to useful energy.

The energy efficiency improvement can therefore be expressed as (EC, 2009):

- Obtaining an unchanged output value at a reduced energy consumption level, or
- Obtaining an increased output value with unchanged energy consumption, or

- Obtaining an output value that in relative terms surpasses the increase in energy consumption.

The reasons for more efficient energy usage that result to energy saving are very obvious: to relieve pressure on scarce energy resources, to reduce energy costs by avoiding wastefulness, and perhaps most pressing, to reduce energy related carbon dioxide (CO<sub>2</sub>) emissions which contribute to climate change (Gnacinski, 2007; Cullen & Allwood, 2010). According to WEC (2010), improving energy efficiency, for instance in electricity use, will have two benefits:

- Supply more consumers using the same electricity production capacity, which is often the main constraint in many countries of Africa and Asia
- Slow down the electricity demand growth, and reduce the investment needed for the expansion of the electricity sector; this is especially important in countries with high growth of the electricity demand such as China and many South East Asian countries.

The economic potential of even more efficient energy use will continue to grow with new technologies and with cost reduction resulting from the economy of scale because energy efficiency is beneficial to everyone. It lengthens the time for which fossil fuels will be available to meet the world's growing energy needs, for consumers – energy efficiency saves money, and for everyone – improved energy efficiency reduces environmental hazards and greenhouse gas emissions (Morvay & Gvozdenac, 2008).

According to Warwick et al (2008) relative to the leading countries in energy efficiency, South Africa is in its infancy. The government launched its Energy Efficiency Strategy in 2004 and, with the assistance of the National Business Initiative, signed a voluntary EEA with leading companies and industry associations subject to a three year review process. The Energy Efficiency Strategy set an overall target of a 12% energy saving by 2015 and an industry saving of 15%. The Accord currently includes 44 signatories comprising some of the most intensive energy users and over eight business associations. This efficiency target shows South Africa's commitment towards energy efficiency because to date only a handful of countries worldwide have set comprehensive targets for energy efficiency improvements (RSA, 2009). These countries include Slovenia, Japan, The Netherlands and New Zealand.

However, RSA (2009) has reported that in recent years especially since 2005 and the release of the first Energy Efficiency Strategy, energy efficiency has significantly gained in stature in South Africa and has become recognised as one of the most cost-effective ways of meeting the demands of sustainable development. The benefits of energy efficiency upon the

environment are self-evident. These benefits are of particular relevance, as South Africa remains the largest emitter of GHGs (greenhouse gases) in Africa and one of the most carbon emission-intensive countries in the world, annually emitting some 7 tonnes of CO<sub>2</sub> per capita as shown in Fig. 2.2.

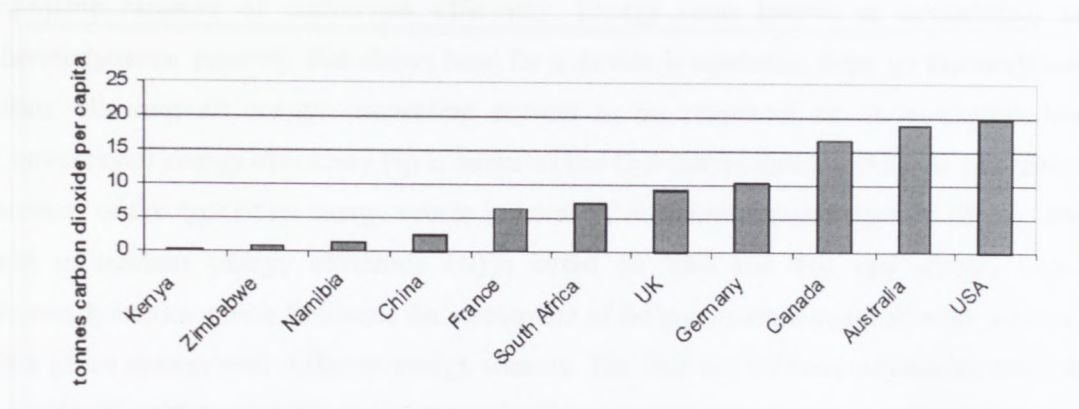


Fig. 2.2 Carbon Dioxide Emission per capita (RSA, 2009)

At a local level the problems of SO<sub>2</sub> and smoke emissions have been the focus of concern for many communities living adjacent to heavily industrialised areas. This is because such substances are known to have an adverse effect on health and are frequently a primary cause of common respiratory ailments. Energy efficiency can address both the macroscopic and microscopic aspects of atmospheric pollution.

### 2.2.2 Energy and Exergy Efficiency

While commenting on the use of energy efficiency indicators, EC (2009) has noted that to be informative and useful, energy efficiency must be comparable, e.g. to another unit or installation, or over time and for comparison there must be rules or convention. In the case of comparing energy efficiency, it is especially important to define system boundaries to ensure all users are considered equally. In other words, it is possible to affirm that a product or process is energy efficient only when compared with a standard or another similar (Sola & de Paula Xavier, 2007). This implies that a product or process is not necessarily energy efficient for consuming reduced energy. On the other hand, it does not necessarily have inefficiency for consuming much energy. A typical example is the comparison of the performance of a standard and energy efficient motor driving a centrifugal load. Given the same power rating an efficient motor runs faster than a standard motor and according to the Affinity Laws power consumption is proportional to speed cubed. Therefore while executing a similar job (driving

a centrifugal load such as centrifugal fan or pump) the energy efficient motor seems to consume more energy than the standard motor. Actually the energy efficient motor does the work faster and better because of its inherent lower energy loss.

Consequently Cullen and Allwood (2010) conceive that exergy efficiency provides a more equitable measure of conversion efficiency. Exergy (also known as availability) is a thermodynamic property that shows how far a device is operating from its thermodynamic ideal, allowing all energy conversion devices to be compared on an equivalent basis. Conventional energy efficiency ( $\eta$ ) is based on the first-law of thermodynamics and takes no account of the type of an energy source in terms of its thermodynamic quality (Wang, 2008) and in contrast exergy efficiency ( $\epsilon$ ) is based on both the first and second laws of thermodynamics which facilitates the assessment of the maximum amount of work achievable in a given system with different energy sources. The first law of thermodynamics states that energy is neither created nor destroyed. Thus, no energy is lost in the processes of transforming energy from primary to secondary and from secondary to tertiary. However, the second law of thermodynamics states that there will be an irreversible degradation of energy into unusable forms. So exergy is similar in concept to effectiveness or availability and thereby providing a more equitable measure of conversion efficiency. This is because exergy utilises mechanical work rather than energy as the basis for comparing devices with each other and their thermodynamic ideal.

Energy efficiency and exergy efficiency are typically defined for a conversion device as:

$$\eta = \frac{\text{energy output (useful)}}{\text{energy input}} \quad (2.1)$$

$$\epsilon = \frac{\text{exergy output}}{\text{exergy input}} = \frac{\text{work output}}{\text{maximum possible work output}} \quad (2.2)$$

The efficiency of an energy conversion process is the ratio of the useful output energy to the input energy. For example, the efficiency of a power plant is the ratio of electrical energy produced to the energy content of the input fuel, while the efficiency of a furnace is the ratio of heat delivered to the building to the energy content of the input fuel. The efficiency of an electric motor is the ratio of mechanical energy created by the motor to the electrical energy

input. The fuel energy not converted to electricity or useful heat, or the electrical energy not converted to mechanical energy, is lost as waste heat (Harvey, 2010).

Justifying the reason for their choice of mechanical work as a basis for comparison Cullen and Allwood (2010) are of the view that mechanical work is a high quality, low entropy form of energy. Likewise electricity, which can be perfectly converted into mechanical work, is another high quality form of energy. This implies that for a device which converts one form of mechanical energy to another (e.g. gearbox), or electrical energy to mechanical (e.g. electric motor), exergy efficiency and energy efficiency are almost the same. However, when the input or output of the device is heat (e.g. space-heater) the energy value of the heat must be downgraded into equivalent units of mechanical work.

The exact proportion of exergy in a substance depends on the amount of entropy relative to the surrounding environment as determined by the second law of thermodynamics (EC, 2009). Exergy needs the system parameters to be defined (temperature, pressure, chemical composition, entropy, enthalpy) and can be expressed according to which parameters are being held constant.

### **2.2.3 Energy Efficiency and Conservation**

Energy efficiency and energy conservation are frequently interchangeably used. It could be proper to assume that the duality of energy is responsible for energy conservation and energy efficiency being erroneously used interchangeably. According to Yanagisawa (2011) energy has duality as intermediate input to produce goods and services (or a factor of production in a wide sense) and as final goods used for space heating, water heating, travelling etc. Fig. 2.1 clearly shows this duality of energy. Therefore the distinction between these two terms is necessary at this point.

Hollander and Schneider (1996) maintain that energy conservation carries the connotation of deprivation, of doing without, of reducing amenities to save energy, for example, turning down the heat and being less comfortable or wearing a sweater indoors in cool weather: or, driving one's car fewer miles each year in order to save fuel. In contrast, a system that becomes more energy-efficient may retain, or even enhance, the level of amenities while using less energy. RSA (2009) believes that conservation by nature is only used in emergencies where there is not sufficient supply of energy and therefore will have a negative impact on production, as the only alternate for the extreme short term is to shut down activities. Whereas energy efficiency has a positive impact on production but takes place over

input. The fuel energy not converted to electricity or useful heat, or the electrical energy not converted to mechanical energy, is lost as waste heat (Harvey, 2010).

Justifying the reason for their choice of mechanical work as a basis for comparison Cullen and Allwood (2010) are of the view that mechanical work is a high quality, low entropy form of energy. Likewise electricity, which can be perfectly converted into mechanical work, is another high quality form of energy. This implies that for a device which converts one form of mechanical energy to another (e.g. gearbox), or electrical energy to mechanical (e.g. electric motor), exergy efficiency and energy efficiency are almost the same. However, when the input or output of the device is heat (e.g. space-heater) the energy value of the heat must be downgraded into equivalent units of mechanical work.

The exact proportion of exergy in a substance depends on the amount of entropy relative to the surrounding environment as determined by the second law of thermodynamics (EC, 2009). Exergy needs the system parameters to be defined (temperature, pressure, chemical composition, entropy, enthalpy) and can be expressed according to which parameters are being held constant.

### **2.2.3 Energy Efficiency and Conservation**

Energy efficiency and energy conservation are frequently interchangeably used. It could be proper to assume that the duality of energy is responsible for energy conservation and energy efficiency being erroneously used interchangeably. According to Yanagisawa (2011) energy has duality as intermediate input to produce goods and services (or a factor of production in a wide sense) and as final goods used for space heating, water heating, travelling etc. Fig. 2.1 clearly shows this duality of energy. Therefore the distinction between these two terms is necessary at this point.

Hollander and Schneider (1996) maintain that energy conservation carries the connotation of deprivation, of doing without, of reducing amenities to save energy, for example, turning down the heat and being less comfortable or wearing a sweater indoors in cool weather: or, driving one's car fewer miles each year in order to save fuel. In contrast, a system that becomes more energy-efficient may retain, or even enhance, the level of amenities while using less energy. RSA (2009) believes that conservation by nature is only used in emergencies where there is not sufficient supply of energy and therefore will have a negative impact on production, as the only alternate for the extreme short term is to shut down activities. Whereas energy efficiency has a positive impact on production but takes place over

a certain time period, more or less a 3 year cycle is followed to plan, implement and measure the implementation of energy efficiency project.

This view is also shared by Solmes (2009) according to whom the U.S. has spent decades requesting that households, businesses, and institutional consumers use less energy. Conservation – initially, turning down the thermostat and turning off the lights – largely translated into being uncomfortable and potential health hazards unless these consumers had the money to purchase, install, and maintain more efficient light bulbs, appliances, heating, ventilation, air conditioning equipment, pumps, motors, controls, insulation, thermal windows, and other investments. Incentive programs run by electric utilities were intended to help their customers reduce their energy use – again putting the responsibility for energy efficiency on the end-user.

WEC (2010) has adduced a reason for this deprived energy strategy. According to it, in some cases because of financial constraints imposed by high energy prices, consumers may decrease their energy consumption through a reduction in their energy services such as reduction of comfort temperature; in car mileage. It further notes that such reductions do not necessarily result in increased overall energy efficiency of the economy, and are easily reversible. Consequently, concludes that they should not be associated with energy efficiency.

The political and social dimension of energy conservation is worthy of note. For instance, according to Kreith (2008), conservation and energy use efficiency received support politically in the United States when U.S. President Carter in 1977 referred to “conservation as the moral equivalent of war”. However, the social acceptability of energy conservation varies widely around the world. In some countries, such as Germany, energy conservationists and environmentalists are a political force (the Green Party). In other countries, people may espouse conservation measures but be unwilling to participate in or pay for energy conservation practices, such as recycling or driving energy efficient vehicles. Some governments, especially in energy importing nations, are encouraging or requiring the development of energy conserving technologies (Fanchi, 2004).

A technical aspect to energy conservation is based on the law of conservation of energy which is a law of physics. In the view of Wikipedia (4 June 2011), this law states that the total amount of energy in a system remains constant over time – it is said to be conserved over time. A consequence of this law is that energy can neither be created nor destroyed: it can only be transformed from one state to another. The only thing that can happen to energy in a

system is that it can change form: for instance chemical energy can become kinetic energy. In other words, the conservation of energy is a law of nonrelativistic physics. Energy conservation requires that there be a balance between the energy input to a process and the sum of energy output by the process plus energy loss. One of the goals of energy conservation is to increase energy conversion efficiency by reducing energy loss (Fanchi, 2004).

The foregoing shows that efficient tertiary energy usage will ensure lower demand for energy production from the primary energy sources. This implies the conservation of the primary energy sources – reduction of the rate at which primary energy sources are depleted or converted. However, arbitrary reduction of the rate of depletion of the primary energy sources does not necessarily result to efficient usage of tertiary energy. A resultant conclusion from this is that energy efficiency leads to energy conservation but not vice versa.

#### **2.2.4 Energy Efficiency and Intensity**

The measure of energy efficiency will always depend upon how ‘useful’ is defined and how inputs and outputs are measured (Herring & Sorrell, 2009). The options include:

- Thermodynamic measures: where the outputs are defined in terms of either heat content or the capacity to perform useful work;
- Physical measures: where the outputs are defined in physical terms, such as vehicle kilometres or tonnes of steel; or
- Economic measures: where the outputs (and sometimes also the inputs) are defined in economic terms, such as value-added or GDP.

When outputs are measured in thermodynamic or physical terms, the term ‘energy efficiency’ tends to be used, but when outputs are measured in economic terms it is more common to use the term ‘energy productivity’. This is because economists are primarily interested in energy-efficiency improvements that are consistent with the best use of all economic resources.

The inverse of each measure (physical or economic measure) is termed ‘energy intensity’.

According to Yanagisawa (2011) energy efficiencies of countries are focused frequently on issues relating to energy conservation, climate change and energy security. There, however, are number of macro indicators for energy efficiency. Among them are energy consumption per gross domestic product or GDP – GDP intensity – and energy consumption per capita. He further observes that although both of them are calculated without considering factors determining energy consumption such as economic structure, climate, geographical features,

etc, they have advantages including clearness, possibility of broad application and data availability.

Initially, the energy use per capita was used as an index of a region's development: it is quite low for developing countries and high for developed nations (Ramachandra *et al.*, 2006). In their view, this approach does not reveal any picture of development or efficiency of usage. However, they assert that to achieve this goal, it is necessary to look at the energy intensity, that is, the energy consumed per unit of output, which is the inverse of the energy efficiency of any process (output per unit of energy consumed). Energy needed per unit of production (referred to as energy intensity or specific energy consumption) shows the sensitivity of products or sectors to changes in energy prices. According to them, energy intensity is directly related to price signals, whereas energy efficiency depends more on the diffusion of the most cost effective technologies. It is therefore important to point out where the losses of energy are the highest in order to reduce them.

GDP shows the amount of money and energy as a physical quantity in the same measure (Suehiro, 2007). He has noted that it is difficult to show the "amount of work" of the whole country as a physical quantity. But GDP is a popular index reflecting a country's economy and is easy to obtain because many countries estimate it. He has suggested that one way to interpret the "amount of work" gained by using energy quantity is to regard it as the amount of production. So GDP is a country's total value of production and in economics, the amount of labour or capital is often used as the necessary input factor for production. Similarly, energy is considered an input factor for production, and this is the concept of energy productivity. According to him, the idea of energy efficiency and energy intensity of GDP show how production could efficiently be increased from the view point of energy.

Therefore energy intensity which shows how much energy is used to produce one unit of GDP in a country (Matsumoto & Nakata, 2008) is mathematically expressed as

$$\text{Energy intensity} = \frac{\text{Total primary energy consumption (Mtoe)}}{\text{GDP (billionUSD2000)}} \quad (2.3)$$

where Mtoe = million tonnes of oil equivalent, and the GDP is based on US dollar exchange rate of 2000.

Concerning the problems in the estimation of energy intensity of GDP, Suehiro (2007) has cautioned on the need to be careful about GDP conversion which is a denominator of energy intensity. According to him the OECD points out that there are four necessary conditions when numerically comparing GDP among countries:

- The definition of GDP must be the same,
- Measuring methodologies must be the same,
- The currency units used must be the same, and
- The evaluated levels of prices must be the same.

He further noted that there are basically no problems regarding the first and second conditions because GDP is calculated in accordance with the SNA proposed by the United Nations, except data from developing countries and other countries where statistics are not well developed. The third condition shows that because GDP generally is calculated in each country's currency, currency units have to be converted to one unit. U.S dollars are often used. The fourth condition indicates that the currency conversion rate has to be set so that each currency is equivalent in terms of quality of goods or services it can buy. Summarily, the third and fourth conditions require the use of a proper exchange rate. In the real world, the MER is used when exchanging a country's currency for another currency and it is also often used when converting GDP to U.S dollars. Another rate to translate the currency of a country into a common unit is PPP, which is a currency exchange rate taking each country's level of prices into consideration and estimated by OECD and the World Bank.

According to Goldemberg and Lucon (2010) as a country develops, its energy intensity initially grows for the greater consumption and for the greater presence of primary goods industries for export, such as ores and metals. After that, capital goods industries – such as machinery and equipment, as well as petrochemicals – start to predominate. Later, there are more specialised industries (such as *software* and fine chemistry) and the service sector, which consume less energy and generate a larger economic product. Generally industrial energy demand varies across regions and countries of the world, based on levels and mixes of economic activity and technological development, among other factors (EIA, 2010).

Despite being acknowledged as a very rough indicator, energy intensity has some attractive characteristics. Whereas energy and the GDP per capita vary by more than one order of magnitude among the developed and developing countries, energy intensity does not change by more than a factor of two (Goldemberg & Lucon, 2010). According to them the factors determining the evolution of energy intensity are:

- Dematerialization;
- Fuel use intensity; and
- Recycling.

Goldemberg and Prado (2011) have reported that as it is well known the energy intensity of TFC of OECD countries had declined by a third between 1973 and 1998. Their assertion is based on an IEA report of 2004. This decline, according to them, is due to improvements in energy efficiency in the end-use devices as well as structural changes in the economy: changes in levels of energy needed from different sectors. In OECD countries, there was a significant growth of electricity demand as more computers, air conditioners and other electric devices were installed. Electricity driven machinery and devices during this period proved to be more efficient and more convenient to use than other energy sources. The report indicates that declines in sub-sectorial energy intensities (manufacturing, households, transportation and services) accounted for approximately 80% of the reduction in energy intensity; the remaining 20% was due to structural changes in consumption.

The level of economic development requires proper attention when comparing energy intensity of GDP internationally. This is because according to Suehiro (2007) manufacturing productivity in economically developing countries is generally inefficient while their living standard is lower and energy consumption is smaller. In other words, they have energy-intensive production systems and a non-energy-intensive lifestyle (different from energy conservation) at the same time. Meanwhile, economically mature countries have high manufacturing productivity but the convenient lifestyle results from the possession of many electrical appliances and automobiles. This means that they simultaneously have non-energy-intensive production systems and an energy-intensive lifestyle based on large-scale energy consumption. As a result of this he posits that, there is a tendency for energy efficiency of the production system to increase and that of the lifestyle to decrease as the economy develops. According to him this suggests that even if a country is small in energy intensity, it does not necessarily mean that the country is advanced in energy conservation; it can mean that they only have a non-energy-intensive lifestyle because of the low level of living.

Based on IEA, “Energy Balances” and World Bank, “World Development Indicators” Yanagisawa (2011) believes that the most energy efficient countries are India, Indonesia, Turkey, Brazil, Argentina, Italy and Japan.

Compared with developed countries, South African economy uses a lot of energy for every Rand of value added (RSA, 2009). For instance, in 2006 South Africa had the 42<sup>nd</sup> biggest GDP in the world but was the world's 21<sup>st</sup> largest consumer of energy. Indeed, by international standards the South African economy uses a relatively high amount of energy per unit of national economic output, or GDP (4.96 MJ per million Rand in 2004). Two reasons have been adduced for this and the first being the nature of the activities which dominate the economy. Mining, minerals processing, metal smelting and synfuel (synthetic fuel) production are inherently intensive users of energy. According to RSA (2009), South African gold mines are very deep with low ore concentrations, so it necessarily requires much energy per ounce (28.349g) of gold. It maintains that the process used by Sasol to convert coal into liquid fuels is such that only about a third of the energy in the coal ends up in the liquid fuel. Even though South Africa's aluminium smelters are among the most efficient in the world, they still require large amounts of electricity to produce one ton of aluminium. The second reason for the high energy intensity is that South Africa is sometimes wasteful in the use of energy. Low energy costs have not encouraged industry, commerce, transport and households to adopt energy efficiency measures.

Fig. 2.3 below gives an indication of the energy consumption in Petajoules ( $10^{15}$ J) per capita of some selected developed and developing countries. It is clear that South Africa is closer to the developed countries in terms of energy intensity than to the developing countries when the Market Exchange Rate (MER) is used rather than the Purchase Power Parity (PPP).

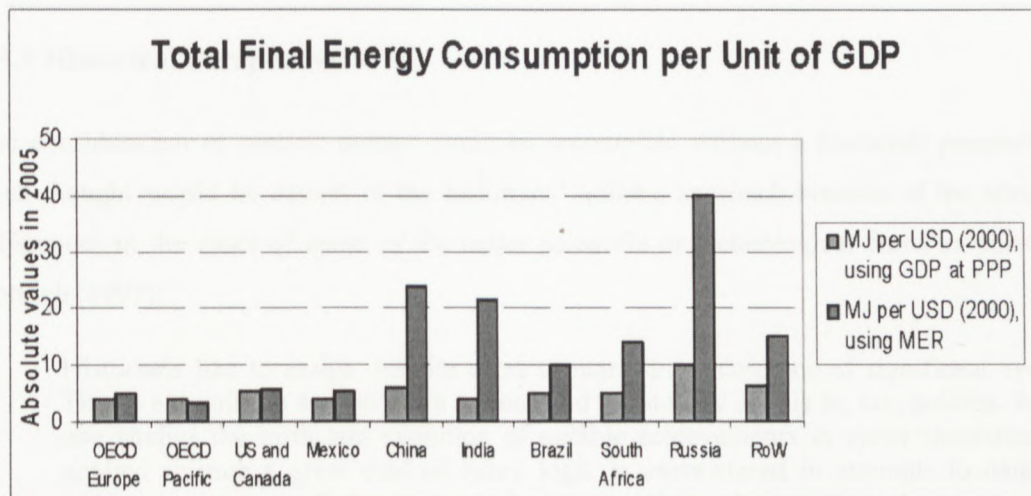


Fig. 2.3 Final energy demand per capita (2005) (RSA, 2009)

The forgoing indicates that energy intensity (energy per unit wealth) is decreased when energy is used more efficiently.

## **2.3 Electric Motors**

Electric machines as energy converters are very important in energy conversion systems. While generators basically convert mechanical energy into electrical energy, motors play a crucial role of being a good prime mover by their ability to convert electrical energy into mechanical energy. This common function of electric motors has resulted to EMDS, a term that describes the motor, its control and the load it drives.

Globally, EMDS consume at least 7000 TWh/yr, roughly equivalent to 45% of all end-use electricity consumption (Falkner & Holt, 2011) making it the largest end-user of electricity. Also global estimates are that 40% of industrial electricity is consumed by electric motor systems, and South African estimates are around 60% (Mthombeni & Sebitosi, 2008).

The realisation of energy efficiency and its concomitant energy saving in the industrial sector demands a closer attention on the electric motor. Electric motors consume more than 60% of the electric energy used by the industry sector (Vaez-Zadeh & Hendi 2005) which has necessitated the considerable interest given to motor energy saving solutions during the last three decades due to the increase in energy cost (Emadi, 2005).

### **2.3.1 Historical Perspective**

The consideration of electric motors could be incomplete without a historical perspective. Such thought would be devoid of the historians' holistic approach because of the seeming differences in the dates of some of the major scientific or technological feats, as noted by Gottlieb (1997):

Historians like to assign definite dates to mark the occurrence of significant events. This is not quite so easy to do in science and technology as it is in, say, politics. When one studies the birth and evolution of notable achievements in either theoretical or applied science a great deal of fuzzy logic is encountered in attempts to date the sudden emergence of the event, and more 'originators', inventors, discoverers and improvers are usually involved than given deserved credit. Moreover, there are inevitably earlier workers in the field who laid down the basic intellectual tools for demonstrable ideas and devices.

He added that science history can, of course, be telescoped backwards to ancient times, but these pioneers namely Hans Christian Oersted, Michael Faraday, Joseph Henry and Heinrich Lenz were notably active in ushering in our modern era.

Gottlieb's view of the applicability of history in science and technology is a reasonable premise that takes care of the chronicle of electric motor as contained in several literatures. For instance, according to Sul (2011), after Jacobic invented a direct current (dc) machine in 1830 and Ferraris and Tesla invented an induction machine, the electric machine has been a prime source of mechanical power for the past 150 years. This implies that the induction machine was invented about 1860.

However, Bose (2000) has noted that the existence of commercial dc machine received a challenge in 1888 when Nikola Tesla invented commercial induction motor. The induction machine was followed by the arrival of synchronous machine. In his view, Thomas Edison, the inventing wizard of the nineteenth century who had only three months of formal schooling and believed that "genius is 99% perspiration and only 1% inspiration", was a fervent advocate of dc machines with a firm belief that alternating current (ac) machines had no future. Thomas Edison's pessimism explains his blatant refusal to attend any discussion related to ac machines which he could have considered time wasting. Gradually these colleagues – Edison and Tesla – became fierce enemies because of their diagonally opposite viewpoints.

Boldea and Nasar (2010) maintain that Faraday discovered the electromagnetic induction law around 1831 and Maxwell formulated the laws of electricity (or Maxwell's equations) around 1860. According to them, the knowledge was ripe for the invention of the induction machine which has two fathers: Galileo Ferraris (1885) and Nicola Tesla (1886). In Ferrari's patent the rotor was made of a copper cylinder, while in Tesla's patent the rotor was made of a ferromagnetic cylinder provided with a short-circuited winding.

Further development as reported by Boldea and Nasar (2010) was the three-phase a.c. power grid capable of delivering energy at a distance to induction motors and other consumers which was put forward by Dolivo-Dobrovolsky around 1880. In 1889, Dolivo-Dobrovolsky invented the induction motor with the wound rotor and subsequently the cage rotor in a topology very similar to that used today. He also invented the double-cage rotor. Thus, according to them, around 1900 the induction motor was ready for wide industrial use. No wonder that before

1910, in Europe, locomotives provided with induction motor propulsion, were capable of delivering 200km/h.

These three sources among many others vividly attest to Gottlieb's (1997) view on history, and science and technology. Another important observation is the two different options of writing Tesla's first name: Nikola or Nicola. Perhaps this could also be part of the failure to accord a holistic consideration of history in the field of science and technology. However, it is a general consensus that dc machines precede ac machines in accordance with the available power supply system.

Subsequent reference to machines means motors because this research focuses on EMDS.

### 2.3.2 Classifications

Salon (2004) agrees that the classification of electric machines results to various configurations. Electric machines are classified generally by the type of electrical system to which the machine is connected: direct current (dc) machines or alternating current (ac) machines. In addition electric machines are classified based on their principle of operation. According to Petruzella (2010) the "family tree" of motor types is quite extensive, as depicted in Fig. 2.4.

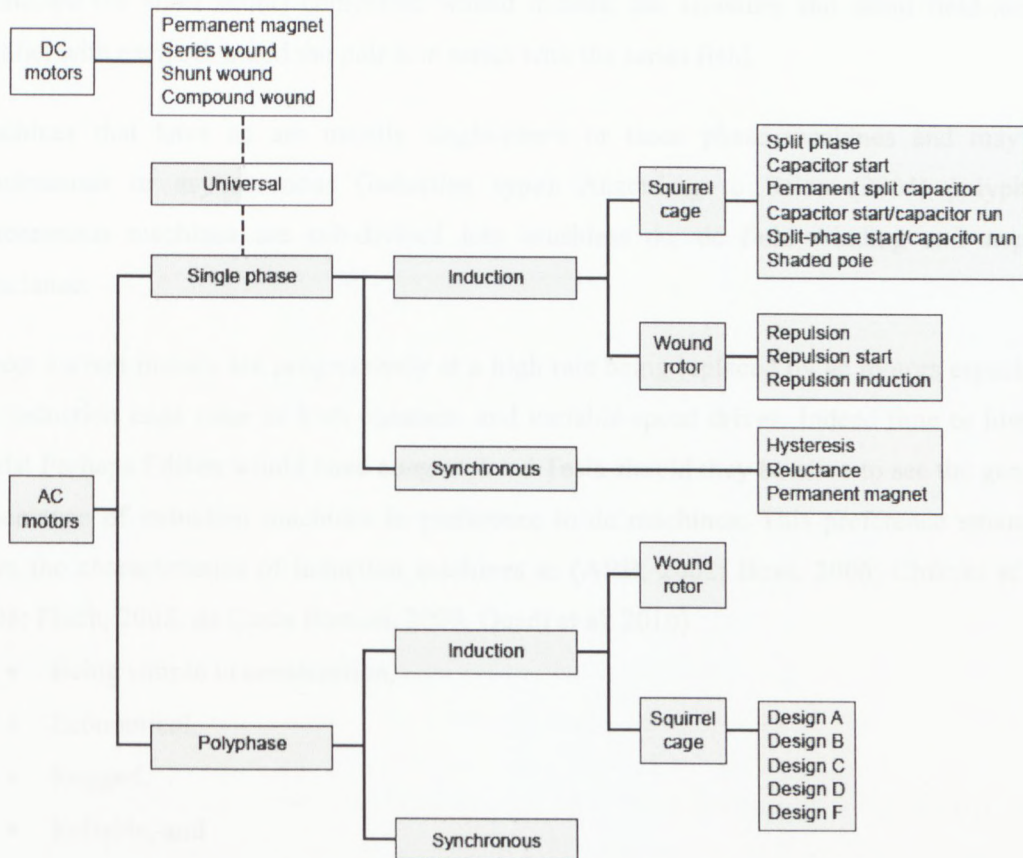


Fig. 2.4 Family tree of motor types (Petruzella, 2010)

Machines with a dc supply are divided into permanent magnet and wound field types, as shown in Fig. 2.4. The wound motors are further classified according to the connections used. The field and armature may have separate sources (separately excited), they may be connected in parallel (shunt connected), or they may be series (series connected).

A compound wound dc motor has both shunt and series field coils (Gupta, 2005) with the shunt field being normally the stronger of the two which means that it has more ampere turns. Compound wound dc motors are of two types namely cumulative compound and differential compound wound motors. In a cumulative compound wound motor the field windings are connected such that the direction of current flow is same in both field windings. But in a differential compound wound motor the field windings are connected in such a way that the direction of current flow is opposite to each other in the two field windings. Compound wound dc motors may also be either long shunt connected or short shunt connected. In long shunt connected (or long shunt) compound wound motors, series field and armature are connected in series with each other and in parallel with the shunt field. In short shunt

connected (or short shunt) compound wound motors, the armature and shunt field are in parallel with each other and the pair is in series with the series field.

Machines that have ac are usually single-phase or three phase machines and may be synchronous or asynchronous (induction type). According to Salon (2004) polyphase synchronous machines are sub-divided into brushless dc, dc field winding and stepper reluctance.

Direct current motors are progressively at a high rate being replaced by ac motors especially the induction cage rotor in both constant- and variable-speed drives. Indeed time or history heals! Perhaps Edison would have congratulated Tesla should they be alive to see the general acceptance of induction machines in preference to dc machines. This preference emanates from the characteristics of induction machines as (ABB, 2002; Bose, 2006; Chikuni *et al.*, 2008; Finch, 2008; da Costa Bortoni, 2009; Ouadi et al, 2010)

- Being simple in construction,
- Economical,
- Rugged,
- Reliable, and
- Available in wide power ranges.

Induction motors also called asynchronous motors exist in all ranges of power, except very low or very high (de Keulenaer *et al.*, 2004). These properties coupled with technological advancements justify the effective replacement of dc motors by ac induction motors. Following its wide patronage in industrial processes, ac induction motor has been dubbed the *workhorse* of industrial processes. Trzynadlowski (2001) in acknowledging this predominance of three-phase induction motors in industries remembers his conversation with a maintenance supervisor in a manufacturing facility who, when asked what types of motors they had on the factory floor, replied: "Electric motors, of course. What else?" As it turned out, all the motors, hundreds of them, were of the induction, *squirrel-cage* type. Mainly due to power electronics and digital control, the induction motor may add to its old nickname of "the workhorse of industry" the label of "the racehorse of high-tech" (Boldea & Nasar, 2002).

However, these induction motor advantages over dc motor are superseded by control problems when using an induction motor in industrial drives with high performance demands (Mohanty *et al.*, 2009). This is because of the two inherent limitations associated with induction motor (Sarhan & Issa, 2006):

- The standard motor is not a true constant-speed machine, its full-load slip varies from less than 1% (in high-horsepower motors)
- It is not inherently capable of providing variable-speed operation.

According to Kaiser *et al.* (2008), since squirrel cage induction motor has only one electrical input port, the drive must control both flux and torque simultaneously through this single input. As there is no access to the rotor, the power dissipation there raises its temperature and therefore very low-slip operation is essential. They note that this is in contrast to dc motor which could be controlled through either its armature or field.

Metwally *et al.* (2002) accept that the disadvantages of using induction motors lie mostly in the difficult controllability due to their complex mathematical model, the nonlinear behaviour during saturation and the electrical parameters variation, which depend on the physical influence of temperature. Also in the view of Kirtley (2010) the difficulty with using induction machines in servomechanisms and variable speed drives is that they are 'hard to control', since their torque–speed relationship is complex and non-linear.

Interestingly these perceived disadvantages of induction machines are continuously being successfully challenged by power electronics advancements through relevant and effective control systems.

Though the contemporary induction motors have more elaborated topologies and their performance is much better, the principle has remained basically the same (Boldea & Nasar, 2010). An induction motor consists of the stator (stationary part) which has windings spaced at 120 electrical degrees apart to realise the three phase configuration. This multiphase ac stator winding produces a travelling field which induces voltages that produce currents in the short-circuited (or closed) windings of the rotor. The rotor (rotating part) could either be of the squirrel cage or wound type. The production of a revolving magnetic field by the three-phase stator winding constitutes an important property of not only induction motors but also synchronous machines (Trzynadlowski, 2001). The interaction between the stator produced field and the rotor induced currents produces torque and thus operates the induction motor. As the torque at zero rotor speed is nonzero, the induction motor is self-starting. This self starting capability is a fundamental reason for the preference of three phase motors to single phase motors in most industrial EMDS.

A comparison of squirrel cage and wound- or slip-ring rotors (Hughes, 2008) shows that the squirrel cage rotor possesses the following advantages:

- Cheaper and more robust.
- Slightly higher efficiency and power factor.
- Explosion-proof since the absence of slip-rings and brushes eliminates the risk of sparking.

The advantages of the slip-ring rotor are:

- The starting torque is much higher and the starting current much lower.
- The speed can be varied especially by means of solid-switching.

Fig. 2.5 is an illustration of a three phase squirrel-cage induction motor showing its vital components. It shows the main parts of any induction motor which are:

- The stator slotted magnetic core
- The stator electric winding
- The rotor slotted magnetic core
- The rotor electric winding
- The rotor shaft
- The stator frame (housing) with bearings
- The cooling system
- The terminal box

The induction machine has a rather uniform airgap of 0.2 to 3mm. The largest values correspond to large powers, 1MW or more (Boldea & Nasar, 2010).

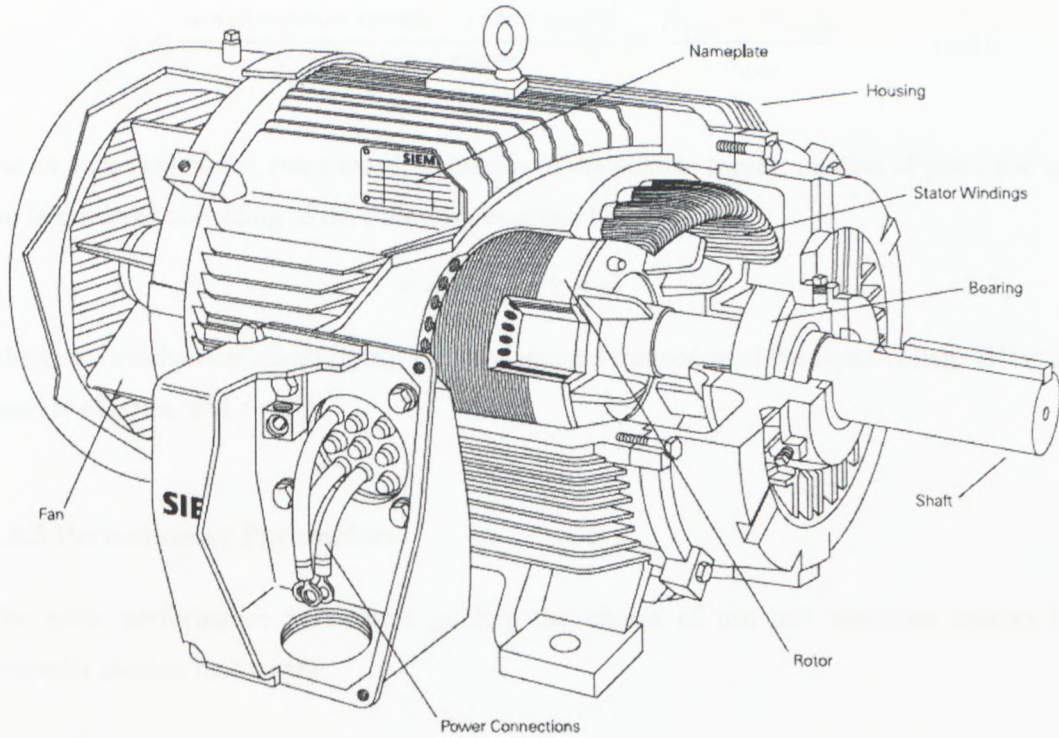


Fig. 2.5 Three phase squirrel-cage induction motor (Courtesy of Siemens)

As stated earlier, the application of balanced three-phase currents to the three-phase winding of a machine stator sets up a magnetic flux in the air gap. According to Lander (1993), this magnetic flux pattern remains constant in form throughout the alternating cycle, rotating one pole pair in one cycle. The speed of rotation of the flux is known as the synchronous speed given by

$$N_{syn} = \frac{f}{p} \text{ rev/s} \quad (2.4)$$

where:  $f$  is the frequency in Hz, and  $p$  the number of pole pairs.

When expressed in radian measure, the synchronous speed is

$$\omega_{syn} = \frac{2\pi f}{p} \text{ rad/s} \quad (2.5)$$

However, the rotor of our industrial workhorse (cage induction motor) must always rotate at a different speed from the synchronous speed for a voltage, and hence current and torque to be induced in the rotor. The relative speed of the rotor to the synchronous speed of the rotor flux is known as the slip  $s$ :

$$s = \frac{\text{synchronous speed} - \text{rotor speed}}{\text{synchronous speed}} = \frac{N_{syn} - N_{rotor}}{N_{syn}} \quad (2.6)$$

For an induction motor, rotor speed, frequency of the voltage source, number of poles and slip are interrelated according to the following equation (WEG, 2010):

$$n = \frac{120f_1}{p}(1 - s) \quad (2.7)$$

where:  $n$  : mechanical speed (rpm);  $f$  : fundamental frequency of the input voltage (Hz);  $p$  : number of poles, and  $s$  : slip

### 2.3.3 Performance Parameters

The basic performance parameters guiding the choice of not just induction motors but generally electric motors are:

- Torque
- Power
- Speed
- Efficiency

#### 2.3.3.1 Torque

Torque is the rotational force that a motor applies to its driven equipment, and a fundamental factor in motor performance. The torque capacity of a motor depends on many design characteristics.

The resultant effect of starting a three-phase induction motor with full voltage applied is shown in Fig. 2.6. The motor is initially stationary and develops locked-rotor torque. As the motor accelerates, some motor designs produce a slight dip in torque, the lowest point being called the pull-in or pull-up torque. As the speed increases further, the torque reaches the highest point on the curve, the pull-out or breakdown torque. Finally, when the motor is loaded to its full-load torque, the motor speed stabilises. If the motor is not driving anything, the speed increases to the no-load or synchronous speed (Hughes, 2008).

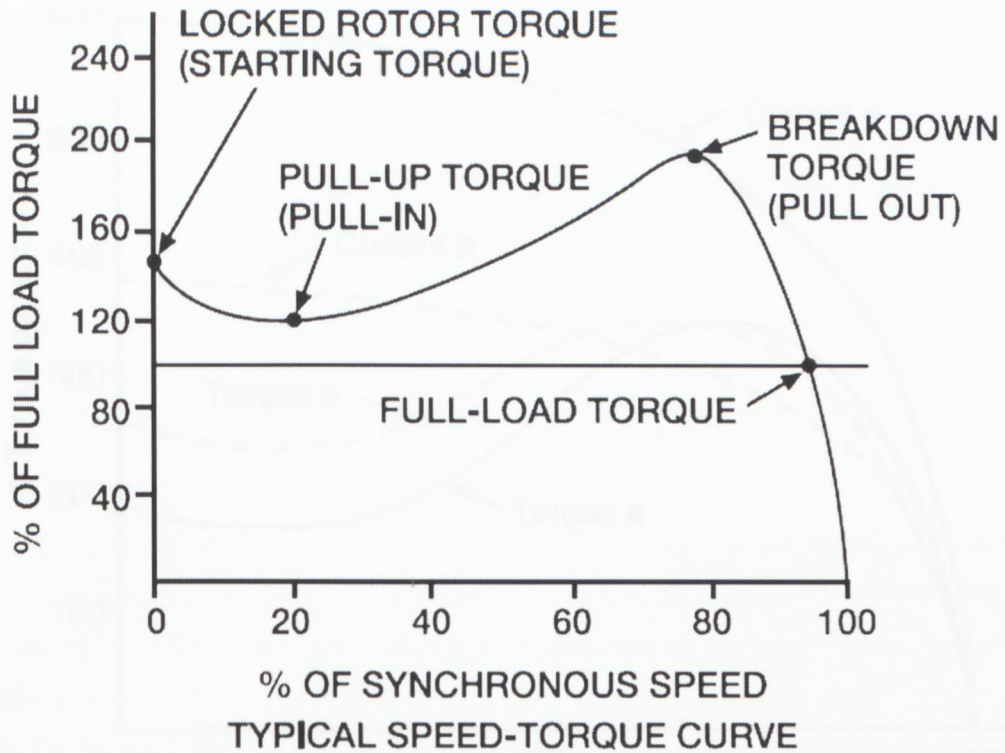


Fig. 2.6 Three-phase induction motor torque-speed characteristic (de Almeida et al., 2008)

Drury (2005) has noted that one of the disadvantages of the squirrel cage machine is its fixed rotor characteristic. The starting torque is directly related to the rotor circuit impedance, as is the percentage slip when running at load, and speed. Ideally, a relatively high rotor impedance is required for good starting performance (torque against current) and a low rotor impedance provides low full-load speed slip and high efficiency.

The curves in Fig. 2.7 are typical squirrel cage motor characteristics showing torque-speed and current-speed relationships. In the general case, the higher the starting torque the greater the full load slip. This is one of the important parameters of squirrel cage design as it influences the operating efficiency (Drury, 2005).

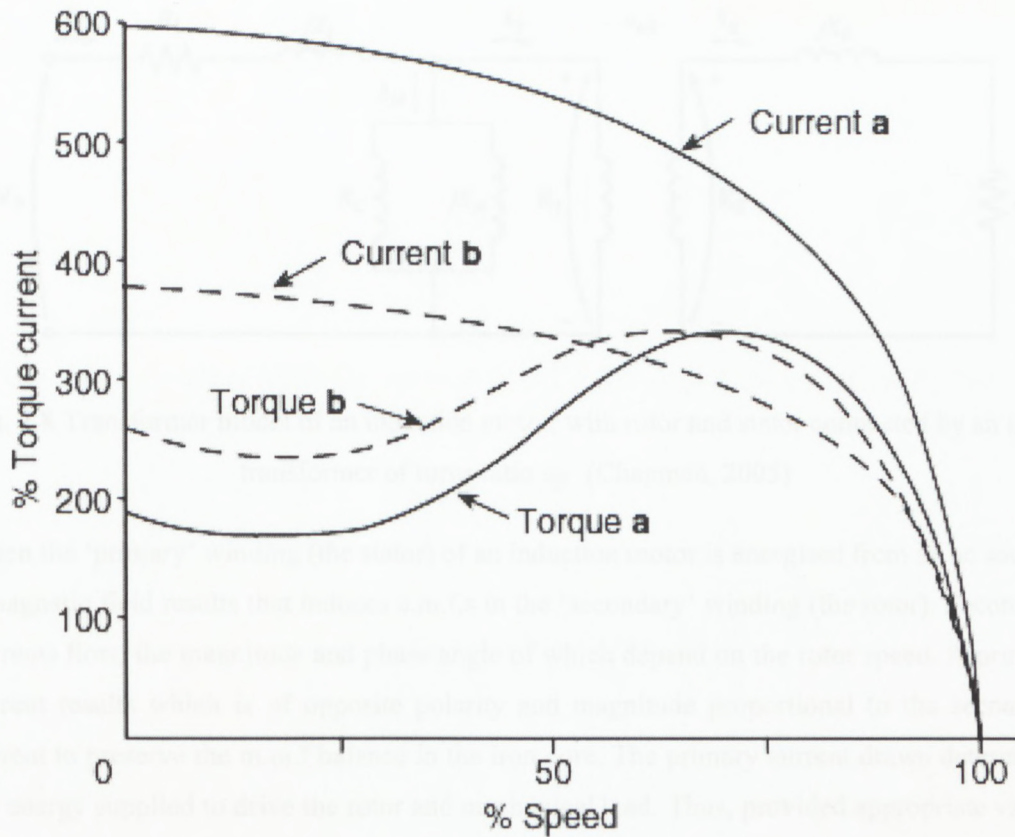


Fig. 2.7 Typical torque–speed and current–speed curves (a - standard motor, b - high torque motor (6 per cent slip)) (Drury, 2005)

Torque is produced by the interaction of a stator-bound flux wave and an induced rotor-bound current wave. Since the flux and current waves are internal to the machine, it is very difficult to measure them on load and use them for machine performance calculations. However, the similarities between the induction motor and the transformer permit the adaptation of the equivalent circuit model of the transformer to represent an induction motor. Such an electrical equivalent circuit model can be used to predict the torque-speed characteristics and efficiency of the motor, in terms of machine currents, voltage, resistances and reactances – instead of flux and current waves.

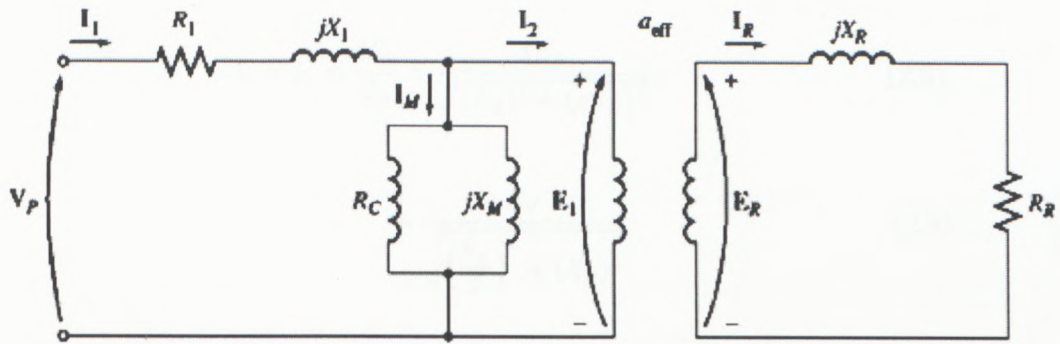


Fig. 2.8 Transformer model of an induction motor, with rotor and stator connected by an ideal transformer of turns ratio  $a_{eff}$  (Chapman, 2005)

When the ‘primary’ winding (the stator) of an induction motor is energised from an ac source, a magnetic field results that induces e.m.f.s in the ‘secondary’ winding (the rotor). Secondary currents flow, the magnitude and phase angle of which depend on the rotor speed. A primary current results which is of opposite polarity and magnitude proportional to the secondary current to preserve the m.m.f balance in the iron core. The primary current drawn determines the energy supplied to drive the rotor and mechanical load. Thus, provided appropriate values are assigned to the impedances, the circuit of Fig. 2.8 will behave electrically like an induction motor, drawing the same current and power from the source and predicting the mechanical power produced by the machine.  $R_1$  represents the per-phase resistance of the stator winding;  $X_1$  represents the per-phase leakage reactance of the stator because not all the flux produced by the stator winding links the rotor or airgap of the machine;  $X_M$  represents the magnetising reactance and the current flowing through it being the exciting current required to set up the machine flux;  $R_C$  allows the hysteresis and eddy-current losses (iron loss) in the magnetic circuit to be calculated. The rotor winding has series resistance  $R_R$  and reactance  $X_R$ . This reactance has an effective value given by  $sX_R$  which varies with the frequency of the induced rotor e.m.f.s,  $X_R$  being the value when the rotor is stationary (when  $s=1$ ). As the motor speeds up, the slip is reduced and the effective reactance of the rotor cage is reduced. The magnitude of the e.m.f induced in the rotor is also a function of slip and its value when the rotor is at standstill is  $sE_R - E_R$ .

Two assumptions guiding the simplification of this equivalent circuit are (Hughes, 2008):

- That the stator and rotor windings have the same number of turns per phase.
- That the air-gap flux has a constant amplitude and speed.

Consequently it can be deduced from Fig. 2.8 that

$$I_1 = I_2 = \frac{sE_R}{Z_R} = \frac{sE_R}{\sqrt{(R_R)^2 + (sX_R)^2}} \quad (2.8)$$

$$= \frac{E_R}{\sqrt{\left(\frac{R_R}{s}\right)^2 + (X_R)^2}} \quad (2.9)$$

Assuming  $\phi$  is the phase difference between the rotor current and voltage,  $I_2$  and  $E_2$ , then

$$\tan \phi = \frac{sX_R}{R_R} \quad (2.10)$$

And

$$\cos \phi = \frac{R_R}{\sqrt{(R_R)^2 + (sX_R)^2}} \quad (2.11)$$

### 2.3.3.2 Power

The power rating of an electric motor shows the rate at which it converts the input electrical energy into output mechanical energy. The rating is dependent on the ability of the motor to dissipate waste heat – the heat which comes from the  $I^2R$  losses in the windings, the eddy-current losses in the rotor and stator cores and windage and friction. The losses cause the windings to become warmer, and if the insulation gets too warm it will break down. Therefore, the rating depends on limiting the load such that it will not overheat the winding insulation. In an EMDS it is important that the motor power rating be able to support the power requirement of the load without being oversized. Oversized motors tend to incur higher purchase, maintenance, and operating costs (including costs for power factor correction). However, da Costa Bortoni (2009) believes that over-sizing accounts for a considerable share of the efficiency problems often found in motor applications. To buttress his claim, he made reference to a US Department of Energy study which shows that 44% of motor in industrial facilities operate at 40% or less of their full load capacity thereby being operated inefficiently. According to Vaez-Zadeh and Hendi (2005) a well known solution has been the substitution of multiple smaller motors instead of a single large one to utilize the motors close to their power ratings, thus increasing the system efficiency at partial load in addition to full load.

According to US-DOE (2008), the motor's power rating should ensure that the motor does not operate below 40% of full load for long periods to avoid poor efficiency. Fig. 2.9 is a typical motor part load efficiency curve.

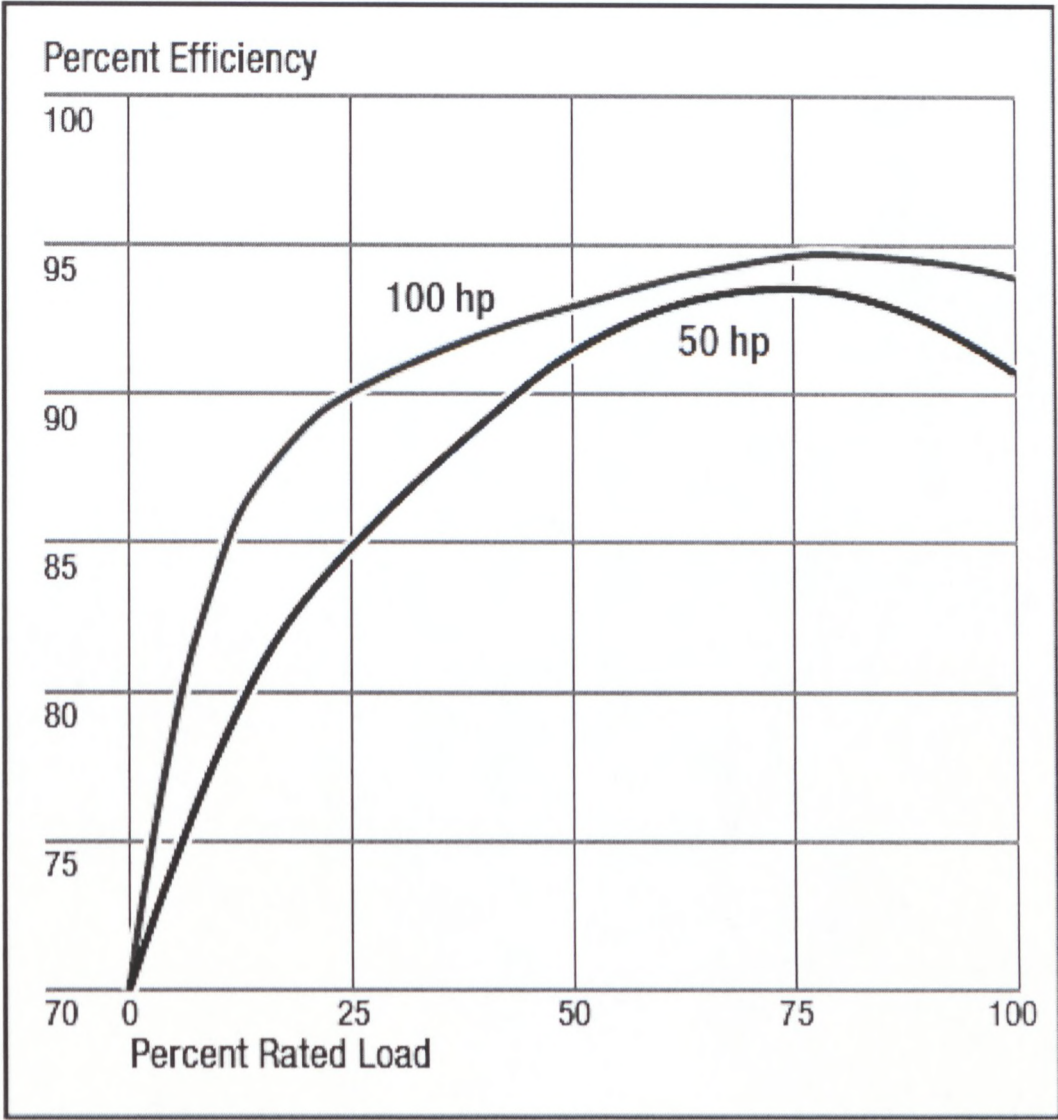


Fig. 2.9 Typical motor part load efficiency (US-DOE, 2008)

### 2.3.3.3 Speed

The speed of an electric motor is an important element that depends on many factors. For instance, operating speed of a dc motor depends on the type of motor (series, shunt or compound), the strength of the magnetic field, and the load. But the operating speed of an ac

motor depends on the rotor type, the number of poles, the frequency of the power supply, and slip characteristics. Synchronous ac motors operate at the speed of the rotating magnetic field; most induction motors operate within 1% to 3% of this speed, depending on the motor's slip characteristics (US-DOE, 2008). Common synchronous speeds for 50Hz utility are 3000, 1500, 1000, 750, and 600 rpm. Many applications require speeds different from these resulting to motors being usually combined with various types of speed adjustment devices. These devices include gears, belts, eddy-current couplings, hydraulic couplings and VSDs. Motors can also operate at multiple speeds by using separate windings within the same motor or by using a single winding with an external switch that changes the number of poles. An important consideration is whether the speed must be constant or variable. In constant speed applications, gears or belts can provide fixed speed ratios between the motor and the driven equipment. Variable speed applications can be served by multiple-speed motors or drive systems with adjustable speed ratios.

Torque, power and speed of an electric motor are related as shown in Eqn. 2.12

$$Torque[N.m] = \frac{Power[W]}{Speed[rad/s]} \quad (2.12)$$

$$= \frac{P[kW] \times 9550}{Speed[rpm]} \quad (2.13)$$

The essence of these parameters is outstanding in EMDS. Motor-driven loads can be classified into three main groups according to whether the torque required increases, remains constant, or decreases as the speed increases (EC, 2000) as shown in Fig. 2.10.

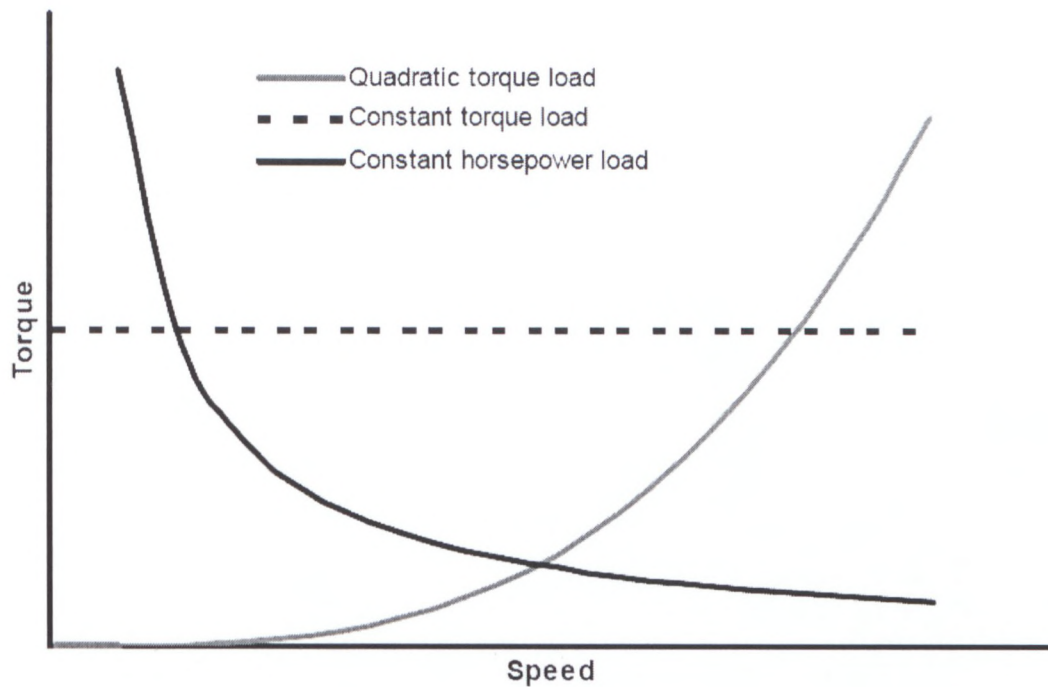


Fig. 2.10 Types of torque-speed curves (EC, 2000)

The most common type of load has variable torque characteristics, in which power and torque are proportional to speed. For example, in centrifugal pumps and fans, torque varies according to the square of speed. This means that the torque varies at a rate proportional to the square of the speed and the power varies as the cube of the speed, reaching 100 percent load torque and power at a defined speed.

In a constant torque load, the torque is independent of speed. So the load torque remains constant throughout the speed range and the power changes linearly with speed for constant torque loads. Common applications include conveyor systems, positive displacement pumps, hoists, and cranes. For example, conveying a 230kg load along an assembly line requires the same amount of torque whether it is moving at a constant speed of 1.5 metre per minute or 3.0 metre per minute. Although power varies according to speed, torque is constant.

In a constant power load, the torque increases with decreasing speed and vice versa. A good example of this type of load is a winding machine in which the torque increases as the roll thickness builds up but the rotational speed slows down. Machine tools such as lathes and cutting machines display these operating characteristics.

### 2.3.3.4 Efficiency

Motor efficiency is a measure of the effectiveness with which electrical energy is converted to mechanical energy, and is expressed as the ratio of power output to power input:

$$\text{Efficiency} = \frac{\text{Output Power}}{\text{Input Power}} = \frac{\text{Output Power}}{\text{Output Power} + \text{Losses}} \quad (2.14)$$

Motor efficiencies are usually given for rated load, although 75% load and 50% load may also be provided. The efficiency of a motor is primarily a function of load, rated power, and speed (IEC, 2009) as follows:

- A change in efficiency as a function of load is an inherent characteristic of motors. Operation of the motor at loads substantially different from rated load may result in a change in motor efficiency as shown in Fig. 2.11.
- Generally, the full-load efficiency of motors increases with physical size and rated output of motors.
- For the same power rating, motors with higher speeds generally, but not always, have a higher efficiency at rated load than motors with lower rated speeds. This does not imply, however, that all apparatus should be driven by high-speed motors. Where speed-changing mechanisms, such as pulleys or gears, are required to obtain the necessary lower speed, the additional power losses could reduce the efficiency of the system to a value lower than that provided by a direct-drive lower-speed motor.

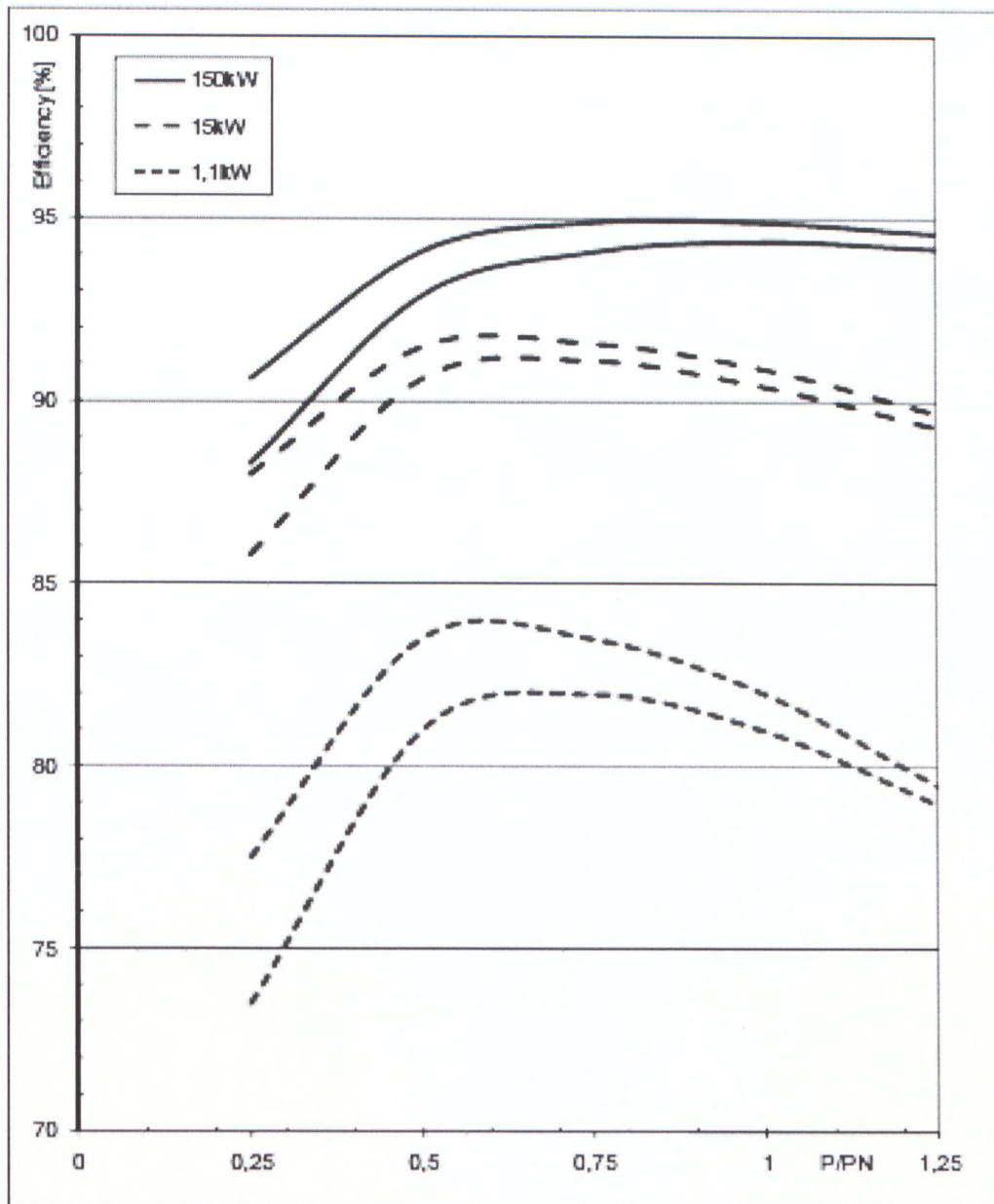


Fig. 2.11 Typical efficiency versus load curve bands for 2- and 4-pole three-phase, cage-induction motors (IEC, 2009).

It further posits that a definite relationship exists between the rated speed and the efficiency of a polyphase induction motor. That is the lower the rated speed, the lower is the efficiency, for slip (the difference between synchronous speed and operating speed) is a measure of the losses in the rotor winding.

The efficiency of an electric motor as an energy converter is adversely affected by the losses it incurs while in operation. These losses are generally described as follows (Jordan, 1983; Tripathy, 1995; Emadi, 2005; IEC, 2009):

- Electrical (stator and rotor) losses (vary with load) – Current flowing through the motor windings produces losses which are proportional to the current squared times the winding resistance ( $I^2R$ ). Rotor losses also increase with slip.
- Iron (core) losses (essentially independent of load) – These losses are confined mainly to the laminated core of the stator and to a lesser degree the rotor. The magnetic field, essential to the production of torque in the motor, causes hysteresis and eddy current losses.
- Mechanical (friction and windage) losses (essentially independent of load) – Mechanical losses occur in the bearings, fans, and seals of the motor. These losses are generally small in slow speed motors, but may be appreciable in large, high-speed or totally-enclosed motors.
- Additional load losses (stray load losses) – The additional fundamental and high-frequency losses in the iron; strand and circulating-current losses in the stator winding; and harmonic losses in the rotor conductors under load. These losses are assumed to be proportional to the torque squared.

Some authors separate the stator and rotor losses which results to having five classes of induction motor losses.

The proportion of these losses in a typical motor of 90% efficiency is illustrated in Fig. 2.12.

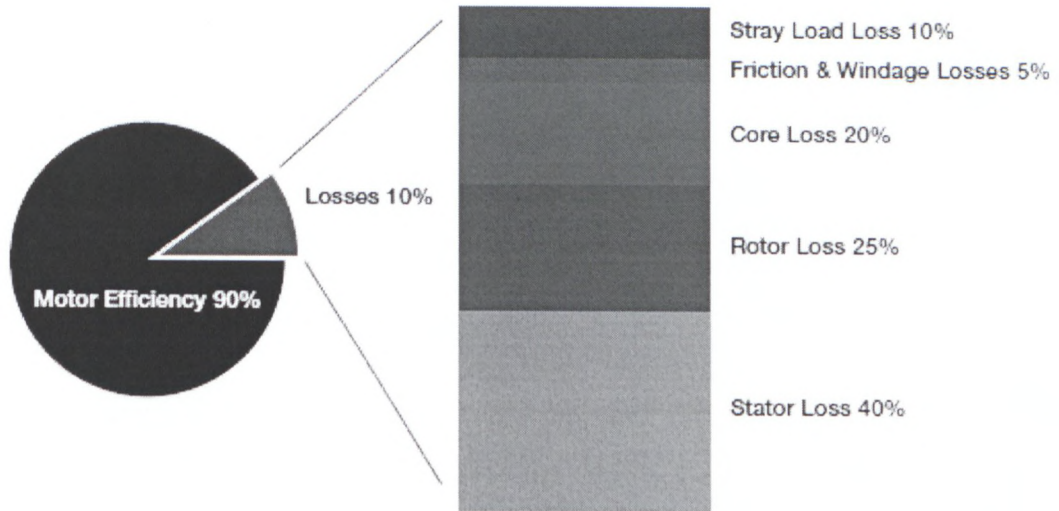


Fig. 2.12 Typical motor losses (WAG, 2002)

IEC (2009) has also disaggregated the motor loss components. Table 2.1 shows the typical percent of these losses in a 4-pole motor, and the design and construction factors which influence their magnitude.

Table 2.1 Loss distribution in three-phase, 4-pole, cage-induction electric motors (IEC, 2009)

Losses	Typical % of losses 4-pole motors	Factors affecting these losses
Stator	30 to 50	Stator conductor size and material
Rotor	20 to 25	Rotor conductor size and material
Core	20 to 25	Type and quantity of magnetic material
Additional load	5 to 15	Primarily manufacturing and design methods
Friction and windage	5 to 10	Selection/design of fan and bearings

In general, by increasing the active material in the motor, i.e., the type and volume of conductors and magnetic materials, the losses can be reduced thereby improving the efficiency. Significant efficiency improvements could be attributed to adding more copper to the windings, upgrading the laminations to premium-grade low-loss steel, enhanced lamination designs, precision airgap between rotor and stator, and reducing fan and other

losses in the motor (Manoharan *et al.*, 2009). The result of using high quality materials is the construction of high efficient motors.

Use of die-cast copper rotors is one method enabling motor efficiency to be increased as much as 1% – 2% above what is currently possible using die-cast aluminium rotors (Malinowski *et al.*, 2004). These efficiency increases are expected to be higher on smaller motors, decreasing to 0.5% on larger designs. According to them, copper bar rotors are extruded copper bars, fabricated in the rotor by brazing to copper end rings. Reasons for copper rotors are lower rotor current losses, producing higher motor efficiency and better overall performance. Copper has better conductivity than aluminium by nearly 60%; therefore, the cross section of the rotor bar for copper motors is smaller than that of an aluminium rotor motor. Less volume of copper is required, somewhat offsetting its higher cost per unit of weight.

Manoharan *et al.* (2009) believe that the cost of die-cast copper rotor (DCR) is higher by about 15% as compared to the motors of existing efficiency levels when replacing aluminium by copper die casting without any other change. But the savings in operating losses is seven or eight times the increase in price. They have also addressed some of the technical issues of DCR such as starting torque, higher start-up current and rotor inertia. In their view, the copper rotor motor has the advantage of high torque at running speed and its starting torque is lower than in aluminium rotor motors (85Nm instead of 90Nm in a 5.5kW motor). The higher conductivity of copper, i.e. its lower electrical resistance will result in a slightly higher start-up current since the slot area remains the same (7.0 times the normal current for a 7.5kW copper rotor motor, instead of 6.0 times for its aluminium counterpart). The higher rotor weight increases rotor inertia. This improves the motor's efficiency, but can be a problem in certain applications – for example motors that frequently switch direction at high speed.

### **2.3.4 Efficiency Standards and Classifications**

Until recently diverging regional or national standards for efficiency and energy classifications have been in use (Boteler *et al.*, 2009). They were a source of misunderstanding between manufacturers and users and were responsible for trade barriers between national markets. In other words there were many different worldwide definitions for energy efficient motors because there was no consensus on what really represented an energy efficient motor. The technical barriers included non harmonised testing standards and efficiency classification resulting to the unfortunate differences in terms of scope, wording and values. That was the reason for the IEC to develop and publish energy efficiency standards to replace all the national issues. This is because it is critical that motor efficiency comparisons be made using a

uniform product testing methodology. These standards are IEC 60034-2-1:27 which stipulates the testing methodology and IEC 60034-30:2008 that defines the efficiency classes. Benhaddadi and Olivier (2010) believe that this recent international harmonised standard for efficiency classes can contribute to lowering barriers in high efficient motors generalisation.

Manoharan *et al.* (2009), and Benhaddadi and Olivier (2010) among numerous authors have chronicled motor efficiency standards and highlighted the international standards for motor efficiency assessment that existed before the aforementioned harmonisation. Their accounts show that while efficiency standards became mandatory in United States of America and Canada early enough, they were voluntary in the European Union and other parts of the world until recently. According to Falkner and Holt (2011), the European Union passed efficiency legislation for electric motors for the first time in 2009, as an implementing measure under the Eco-design Directive. It is expected that between 2015 and 2017, these regulations will require the use of either an IE3 motor, or an IE2 combined with a variable speed drive. But some large motor-using economies (such as Russia and India) have not yet adopted regulations for electric motors, although they are understood to be under consideration.

Table 2.2 is a clue of current positions showing the diversity of policies – as well as the complexity this creates for global suppliers.

Table 2.2 Electric motor efficiency classes, testing standards and regulation over time  
(Falkner & Holt, 2011)

Efficiency levels	Efficiency classes	Testing standard	Performance standard
	IEC 60034-30	IEC 60034-2-1	Mandatory MEPS
Premium Efficiency	IE3	Low Uncertainty	USA 2010 Europe 2015/17
High Efficiency	IE2		USA 2001
			Canada 1997
			Australia 2006
			Korea 2008
			Brazil 2009
			Europe 2011
			Switzerland 2011
			China 2009
Standard Efficiency	IE1	Medium Uncertainty	China
			Taiwan 2003
			Switzerland 2010

US Energy Policy Act (EPAct) of October 1992 ensured strict energy efficiency compliance for electrical appliances and equipment, including certain classes of electric motors. EPAct did not create new efficiency performance levels but rather established a minimum efficiency level in US (Manoharan *et al.*, 2009). Therefore, upgrading motors from pre-EPAct level to EPAct efficiency levels increases motor efficiency by 2.3%. Some of the standards for motor efficiency assessment before 2007 were

- IEEE 112-B:1996 (United States)
- C390:98 (Canadian Standards Association)
- IEC 60034-2:1996 International Electrotechnical Commission (Europe)
- JEC-37 (Japanese Electrotechnical Committee)
- ANSI C50.20 same as IEEE 112 (United States)
- IS 12615 – 2004 read with IS 4889 – 1968 (India)

It is noteworthy that these standards differ primarily in their treatment of stray load losses. According to Malinowski et al. (2004) while the IEC 60034-2 procedure assigns stray load losses, the JEC-37 efficiency test standard for Japan ignores stray load losses altogether. Only IEEE 112-B and CSA C398-98 tests really compare measured input and output watts giving a true measurement of the motor's actual efficiency.

An approximate estimation of comparable efficiency levels based on the assumption of 0.5% of full-load input power, utter neglect and actual stray load losses measurement are shown in Table 2.3.

Table 2.3 Approximate estimation of comparable efficiency levels using JEC, IEC, and IEEE test methods (Malinowski et al., 2004)

Motor Size		Motor Efficiency		
HP	kW	IEEE 112B / C390-98	IEC 60034-2	JEC-37
1	0.75	76.8	78.8	79.6
2	1.5	81.1	83.1	83.8
3	2.2	81.4	83.4	84.1
5	3.7	83.9	85.9	86.5
7.5	5.5	84.8	86.8	87.3
10	7.5	85.6	87.6	88.1
15	11	87.4	87.6	89.9
20	15	88.3	89.4	90.7
25	19	88.9	90.3	90.8
30	22	89.8	90.4	91.7
40	30	90.4	91.3	92.3
50	37	91	91.9	92.4
60	45	91.5	92	92.8
75	55	92	92.5	93.3
100	75	92	93	93.3
125	95	92.2	92.7	93
150	110	92.8	93.3	93.6
200	150	93.8	94.3	94.6

Basically the motor efficiency can be determined by measuring output and input power (Boteler *et al.*, 2009). The simplistic approach to determine efficiency directly by measuring electrical input power with a wattmeter and mechanical output power with a torque sensor plus tachometer can lead to big errors especially for high efficient motors where both powers are large compared to their difference (i.e. the motor losses). Therefore, total losses are usually determined indirectly by determining the five components independently and summing them up. Each of the components is determined by performing various tests under load and no-load conditions.

IEC 60034-2-1 and IEEE 112B/CSA 390 are the test methods predominantly used in the world today, and they all utilise similar equipment and laboratory procedures to test motor efficiency. These standards define several methods to determine the losses and efficiency of which the input–output methods with loss segregation are extensively used in industry. This has formed the basis for their comparison by Cao (2009). According to him, to determine the stator conductor loss, it is necessary to acquire either stator winding resistances or

temperatures under any testing conditions. IEEE 112 requires a stator winding resistance to be measured when the motor is cold prior to any heat run test. This serves as a reference resistance and is later used to calculate winding resistances for all load conditions, with measured winding temperatures. Clearly, some temperature sensors are needed to obtain the winding temperature, and thus, this approach is intrusive to those induction motors in service. On the contrary, in IEC 60034-2-1, the winding resistance is directly measured before the highest load and after the lowest load points by shutting down the motor, measuring the terminal resistance, and extrapolating back to zero time. The actual winding temperature is not required.

In terms of core loss determination, the two standards define similar no-load tests to segregate the friction and windage losses from the core loss. In IEEE 112, core loss should be the same for all load points, but in the IEC standard, the core loss varies with load, depending on the resistive voltage drop in the stator winding, according to Eqn. 2.15

$$U_r = \sqrt{\left(U - \frac{\sqrt{3}}{2} \times I \times R \cos \theta\right)^2 + \left(\frac{\sqrt{3}}{2} \times I \times R \sin \theta\right)^2} \quad (2.15)$$

where U, I, and R are the line voltage, current, and resistance, respectively, and  $\theta$  is the power factor angle. A summary of his comparisons are shown in Table 2.4.

Table 2.4 List of features of IEEE 112-B and IEC 60034-2-1(Cao, 2009)

Features	IEEE 112-B	IEC 60034-2-1
Segregation of losses	√	√
Temperature sensor position	√	×
Ambient temperature reference	25°C	25°C
Stator winding R connected	√	√
Slip corrected	√	√
Core loss with voltage drop compensated	×	√
Stray-loss linear regression analysis	√	√
Stray-loss correlation coefficient	0.9	0.95
Torque meter corrected	√	×
Dynamometer corrected	×	√
Output power corrected	√	√

In their assessment of IEC 60034-2-1 in determining induction machine efficiency, Cao et al. (2011) assert that an accurate knowledge of machine efficiency is highly desired by both machine

manufacturers and end-users if they are to evaluate energy savings and environmental benefits. Their assertion stems from the wide deployment of induction machines both in terms of fixed and variable speed applications. They have also noted that the improvements in the IEC 60034-2-1 are found to be: the specification of higher instrument accuracies, a more detailed definition of the test procedures to be followed, and the use of more accurate models for estimating core loss and stray-load loss. One possible problem with the new standard, according to them, is the way in which it determines stator winding which personal experience and care taken during the tests may help minimise this uncertainty.

The efficiency class system specified under IEC 60034-30 is valid for low voltage three-phase cage-induction motors with the following specifications (CEMEP, 2011):

- Rated voltage up to 1,000 V
- Rated output between 0.75 kW and 375 kW
- Either 2, 4 or 6 poles
- Rated on the basis of continuous duty (S1) or intermittent periodic duty (S3) with cyclic duration factor of 80% or higher;
- Capable of operating direct on-line
- Rated for operating conditions in accordance with IEC 60034-1 (temperature, installation altitude, etc.)

IEC 60034-30, introduced in 2008, defines an open-ended international efficiency classification scheme, using a simple progression mark of IE1 (lowest regulated efficiency) through to IE3 (most efficient motors available at the time) and IE4 (to be defined later when further information is available from North American sources) (Falkner & Holt, 2011).

A graphical representation of these efficiency classes is shown in Fig. 2.13.

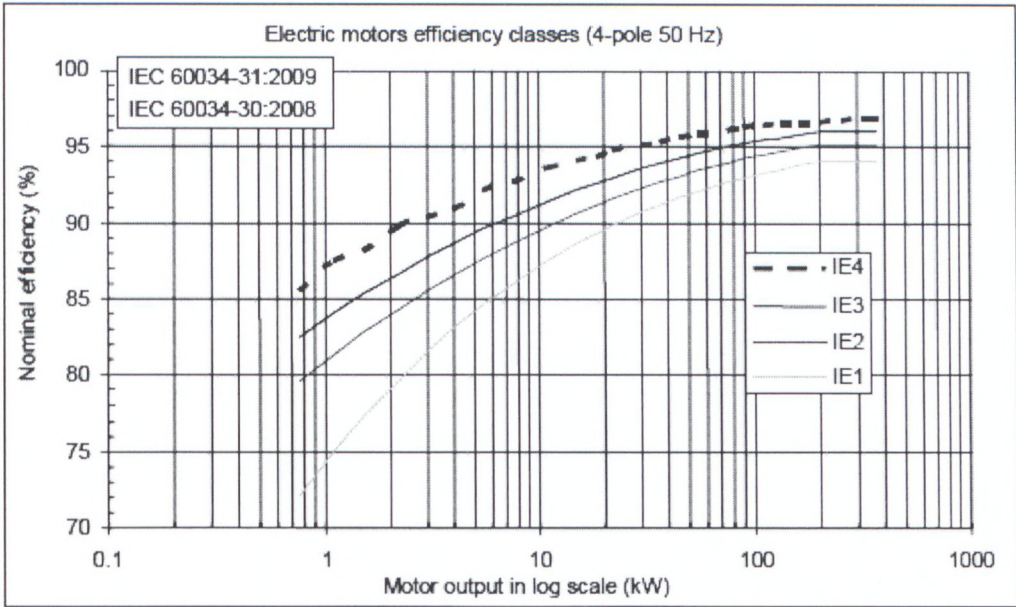


Fig. 2.13 Efficiency classes for four-pole motors of standard IE3, IE2 and IE1 classes, and the new IE4 class (Waide & Brunner, 2011)

Table 2.5 shows some of the previously existing regional classification schemes in comparison against the new globally applicable scheme.

Table 2.5 Motor efficiency classes in different countries and the corresponding international standard (Falkner & Holt, 2011)

Motor efficiency class	International	United States	European Union (old system 1998)	European Union (new system 2009)	China	Australia
Premium	IE3	NEMA Premium	-	IE3	-	-
High	IE2	EPAct	Eff1	IE2	Grade 1 (under consideration)	AU2006 MPS
Standard	IE1	-	Eff2	IE1	Grade 2	AU2002 MEPS
Below standard		-	Eff3	-	Grade 3 (current minimum)	-

Intelligent use of energy means higher productivity with lower active energy and lower losses at moderate costs. Reducing losses leads to lower environmental impact where the motor works and lower thermal and chemical impact at the electric power plant that produces the required electrical energy (Boldea & Nasar, 2010).

## 2.4 Pumps

Attempts by authors to define a pump or pumps appear to have been based on the commonest application of pumps in the field of liquid movements. In the words of Bolegh (2001), industrialisation imposed an ever increasing demand for moving liquids from one location to another far more practically than by gravity. In order to motivate the liquid to move through the pipes and channels, energy has to be imparted to the liquid. The energy, usually mechanical, provided by a prime mover is transferred to the liquid by a device called a pump.

A pump is a machine used to move liquid through a piping system and to raise the pressure of the liquid (Volk, 2005). This means that a pump is a machine that uses several energy transformations to increase the pressure of a liquid. Regardless of the driver type for a pump, the input energy is converted in the driver to a rotating mechanical energy, consisting of the driver output shaft, operating at a certain speed, and transmitting a certain torque, or power.

However it would be proper to consider pumps as machines used for the transportation of fluids because fluids include liquid, slurries and sludge.

#### **2.4.1 Historical Perspective**

Karassik *et al.* (2001) have asserted that pump stands essentially unchallenged as the earliest form of machine for substituting natural energy for human physical effort. According to them the earliest pumps are variously known, depending on which culture recorded their description, as *Persian wheels*, *waterwheels*, or *norias*. These devices were all undershot waterwheels containing buckets that filled with water when they were submerged in a stream and that automatically emptied into a collecting trough as they were carried to their highest point by the rotating wheel. Similar waterwheels have continued in existence in parts of the Orient even into the twentieth century. They have equally noted that the best-known of the early pumps, the Archimedean screw, has also persisted into modern times. It is still being manufactured for low-head applications where the liquid is frequently laden with trash or other solids. Perhaps most interesting, in their view, is the fact that with all the technological development that has occurred since ancient times, including the transformation from water power through other forms of energy all the way to nuclear fission, the pump remains probably the second most common machine in use, exceeded in numbers only by the electric motor.

The Archimedean screw pump can certainly claim to be the oldest pump as far as the transport of liquids is concerned (Ritz-Atro, 2005). In the third century before Christ Archimedes, the Greek mathematician and scientist from Syracuse (287 - 211 BC) invented the “Archimedean screw” which was used at that time to lift water. World Pumps (2009) believes that Egyptian ‘shadoof’ predates Archimedean screw pump and that in 200BC Ctesibius invented the reciprocating pump while Archimedean screw pump was described (but not invented) by Archimedes.

The credit for the design of the first centrifugal pump, although of a crude type, seems to be due to the great mathematician, Euler; it was not until about the year 1850 that the centrifugal pump came into commercial use (Cameron, 2006).

Lehman (2004) asserts that the history of the progressing cavity pump can be traced back to the late 1920's, when aeroplane designer René Moineau was searching for a compressor to increase engine power. In 1930 the University of Paris awarded Moineau a doctorate of science for his thesis on “new capsulism” and it was this pioneering dissertation that laid the

foundations for the progressing cavity pump. In 1932, he teamed up with mechanical engineer Robert Bienaimé to found PCM Pompes, which became the first company to produce progressing cavity pumps. However, most authors prefer to state that Moineau invented this pump type and applied it as a supercharger for an airplane engine. A supercharger is basically an air compressor used for forced induction of an internal combustion engine.

Pump developments from 200BC to 2008 have been traced by World Pumps (2009). This account appears priceless on pump history and establishment of some pump companies although some readers have made inputs on some of the assumed conflicting or wrong information.

This brief historical perspective has concentrated only on the pumps encountered in this research and has highlighted the earliest applications of pumps being to pump water.

#### **2.4.2 Classifications**

There is no uniform pump classification because very different criteria are used to describe a pump (SAPMA, 2005). But according to Karassik *et al.* (2001) pumps may be classified on the basis of:

- the applications they serve,
- the materials from which they are constructed,
- the liquids they handle, and
- even their orientation in space.

All such classifications, however, are limited in scope and tend to substantially overlap each other. The major classifications of pumps based on their mode of operation are kinetic (dynamic) and positive displacement pumps (Bolegoh, 2001; Karassik *et al.*, 2001; Volk, 2005).

Dynamic pumps may be further subdivided into several varieties of centrifugal and other special-effect pumps. Displacement pumps are essentially divided into reciprocating and rotary types, depending on the nature of movement of the pressure-producing members. Each of these major classifications may be further subdivided into several specific types of commercial importance (Karassik *et al.*, 2001).

Fig. 2.14 illustrates the classification of pumps by general mechanical configuration based on the 14<sup>th</sup> Edition of Hydraulic Institute Standards for Centrifugal, Rotary, and Reciprocating

Pumps. This clearly shows that Hydraulic Institute classifies pumps by type and not by application. Gabus (2006) and other standard textbooks have detailed the features of the numerous pump subsets.

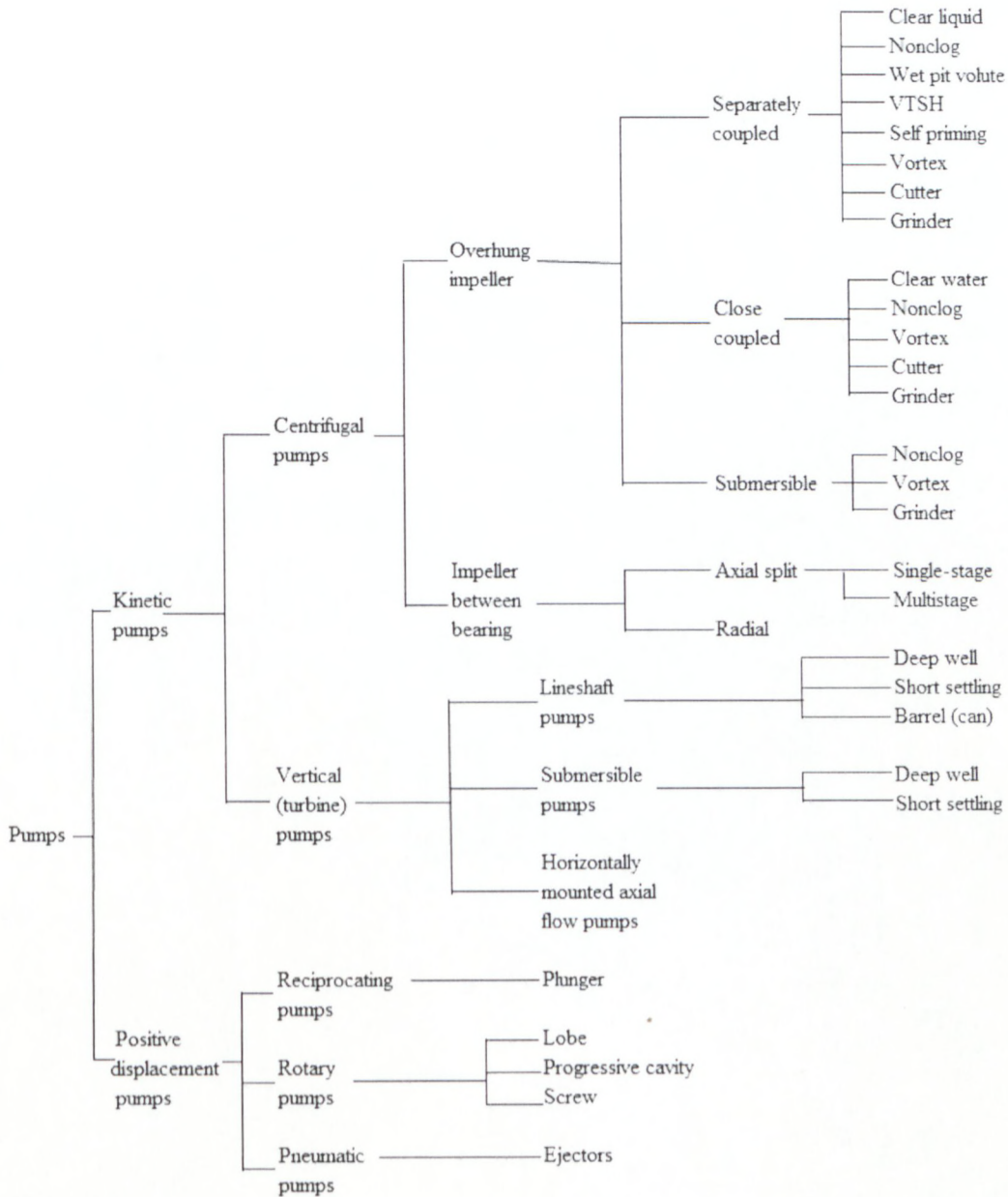


Figure 2.14 Classification of pumps (Gabus, 2006)

In a kinetic pump, energy is continuously added to the liquid to increase its velocity and this produces a pressure increase whenever the liquid velocity is subsequently reduced. But in a positive displacement pump, energy is periodically added to the liquid by the direct application of a force to one or more movable volumes of liquid. This causes an increase in pressure up to the value required to move the liquid through ports in the discharge. Volk (2005) highlights the difference between them as continuous versus periodic energy addition and indirect versus direct force application to the liquid. This classification of pumps into kinetic and positive displacement is broader than the classification by SAPMA (2005), and HI and US-DOE (2006) of pumps as positive displacement and centrifugal pumps. Presumably this is based on the strong preference of centrifugal pumps (a type of kinetic pump) by equipment engineers to a positive displacement pump given hydraulic conditions that either could be considered.

In the view of Nelik and Brennan (2005), the great majority of all pumps in the world belong to a class called *centrifugal pumps*. The other category, the *positive displacement* (PD) type, represents a smaller proportion of the total pump population. They posit that although various studies disagree somewhat, it is probably safe to estimate positive displacement designs at about one-third of the world pump population, and centrifugal at two-thirds.

According to Matthews (2002) centrifugal pumps account for perhaps 80% of fluid transfer application. Generally, higher-capacity pumps are of the centrifugal type while smaller pumps can be centrifugal or positive displacement (Rishel, 2002). An exception to these classifications is the Archimedes screw type pump for large capacities at very low static heads. Such pumps are used for lifting water over an elevation such as a lift station or a riverbank and to an open flume, tank, or reservoir. Volk (2005) explains that many reasons are given for this preference for centrifugal pumps, but most are related to the belief that centrifugal pumps are more reliable and result in lower maintenance expense. Centrifugal pumps usually

- have fewer moving parts,
- have no check valves associated with the pumps (as reciprocating positive displacement pumps do),
- produce minimal pressure pulsations,
- do not have rubbing contact with the pump rotor, and
- are not subject to the fatigue loading of bearings and seals that the periodic aspect of many positive displacement pumps produce.

He infers that centrifugal pumps should be considered first when applying a pump, but notes that they are not always suited to the application.

Nelik and Brennan (2005) have observed that despite being classified by the Hydraulic Institute as a screw-type pump, users and manufacturers (especially in North America) usually prefer the name “progressing cavity (PC) pump”, reserving the category "screw pumps" for multiple-screw types (i.e., two- [sometimes called twin-screw pumps] and three-screw pumps). According to them, there is much more similarity between applications of *multiple-screw* pumps (two- and three-screw) than *single-screw* (i.e., progressing cavity). Progressing cavity pumps are often applied to "nasty," difficult applications such as wastewater treatment, solids in suspension, highly abrasive slurries, etc., while two- and three-screw pumps are mostly used for cleaner fluids such as in oil and fuel transport. There are occasional exceptions and application boundaries are crossed at times. They have noted that in Europe (especially in Russia), PC pumps have retained their Hydraulic Institute classification and are usually referred to as screw pumps, both in Russian publications and in English translations. Overall, the term *progressing cavity pumps* is more widely accepted.

From the foregoing it is evident that although pumps could be the same based on their mode of operation yet different when their design characteristics are considered. This implies that while both municipal water supply and wastewater schemes could use centrifugal pumps, the *nonclog* impeller centrifugal pumps are designed for sewage and other waste liquids containing solids.

### **2.4.3 Performance Parameters**

To truly understand pump operation, one needs to carefully examine the specifics of each individual system in which a pump is installed and operating (Nelik, 1999). The main elements of a pumping system are:

- Supply side (suction or inlet side)
- Pump (with a driver)
- Delivery side (discharge or process)

According to him flow and pressure are the two main parameters of interest for a given application especially from the pump user’s viewpoint. Flow is a parameter that shows *how much of the fluid* needs to be moved (i.e., transferring from a large storage tank to smaller drums for distribution and sale, adding chemicals to a process, etc.). Pressure indicates *how much of the hydraulic resistance* needs to be overcome by the pumping element, in order to

move the fluid. Furthermore, he has noted that other parameters such as pump speed, fluid viscosity, specific gravity, and so on, will have an effect on flow and/or pressure, by modifying the hydraulics of a pumping system in which a given pump operates. A mechanism of such changes can be traced directly to one of the components of losses, namely the hydraulic losses.

### **2.4.3.1 Centrifugal Pumps**

CMSOGPE (2011a) posits that the performance parameters of a centrifugal pump are:

- Flow rate
- Pump head
- Speed
- Power
- Power efficiency

#### **2.4.3.1.1 Flow Rate**

The flow rate, also called capacity or discharge and designated by  $Q$ , of a pump is the volume of liquid pumped per unit of time, usually expressed in cubic meters per second ( $\text{m}^3/\text{s}$ ) for large pumps or litres per second (l/s) and cubic meters per hour ( $\text{m}^3/\text{h}$ ) for small pumps.

#### **2.4.3.1.2 Head**

The term head represented by  $h$  or  $H$  is the elevation of a free surface of water above (or below) a reference datum. For centrifugal pumps, the reference datum varies with the type of pump. Head is expressed in meters (m). Pressure can also be expressed as the equivalent head of water. Distances (heads) above the datum are considered positive and distances below the datum are considered negative. It is defined graphically as the fluid column height in meters.  $H$  is used for total head, whereas  $h$  is used for head from the datum or for head-loss.

#### **2.4.3.1.3 Speed**

This refers to the number of revolutions for the pump shaft per unit time. It is often designated by  $N$  and the unit is revolutions per minute (rpm)

#### 2.4.3.1.4 Power

Centrifugal pump power is grouped into two namely effective and shaft power respectively. Effective power also known as output power is the energy per unit time obtained by the liquid transported by the pump. It is mathematically expressed as

$$P = \frac{\rho g Q H}{1000} \quad (kW) \quad (2.16)$$

where, Q is the pump flow rate, m<sup>3</sup>/s; H is the pump head, m;  $\rho$  is the medium density, kg/m<sup>3</sup>; g is the acceleration of gravity, g = 9.81 m/s<sup>2</sup>

However the shaft power refers to the power which is passed to the pump shaft from a prime mover. The shaft power is also called the input power and measured in W or kW.

#### 2.4.3.1.5 Power Efficiency

This refers to the ratio of effective pump power to shaft power. So it is a measure of how efficient the pump utilises its shaft power in imparting the medium being pumped.

#### 2.4.3.2 Positive Displacement

Also CMSOGPE (2011b) asserts that the performance parameters of a positive displacement pump are:

- Flow rate
- Outlet pressure
- Shaft power
- Efficiency

##### 2.4.3.2.1 Flow Rate

Flow rate Q refers to the maximum pump output flow rate which is the pump flow rate listed in the sample and nameplate. In other words it is the rated flow rate.

##### 2.4.3.2.2 Outlet Pressure

This is the maximum output pressure allowed by the pump. Outlet pressure can be used for determining the pump intensity, seal and prime mover power. When the pump actually operates, the outlet pressure is determined based on back pressure of outlet pipe, which is required to be lower than the maximum allowable pump outlet pressure.

### 2.4.3.2.3 Shaft Power

The shaft power of a positive displacement pump is mathematically expressed as

$$P = \left\{ \frac{105Q(pd-ps)}{102\eta} \right\} \text{ (kW)} \quad (2.17)$$

where,  $pd$  is the pump outlet pressure, MPa;  $ps$  is the pump inlet pressure, MPa;  $Q$  is the pump flow rate,  $m^3/s$ ;  $\eta$  is the pump efficiency.

### 2.4.3.2.4 Efficiency

The efficiency remains a measure of the effectiveness of the pump in transferring the fluid from its inlet to the outlet. The efficiency range of common positive displacement pumps is shown in Table 2.6.

Table 2.6 Efficiency range of positive displacement pumps (CMSOGPE, 2011b)

Pump Type	Electric Reciprocating Pump	Steam Reciprocating Pump	Gear Pump	Three Screw Pump
Efficiency	0.65 – 0.85	0.8 – 0.9	0.6 – 0.75	0.55 – 0.8

## 2.4.4 Efficiency Standards and Classifications

Following the assertion of Karassik *et al.* (2001) that pump remains probably the second most common machine in use and exceeded in numbers only by the electric motor, it should have been expected that the same amount of attention given to electric motors should have been given to pump's efficiency classifications and improvements. An efficiency-labelling scheme for pumps is not recommended, because there would be confusion on pump sets if both the motor and pump had labels with different efficiency ratings (de Almeida *et al.*, 2003). However, according to EU (2004), efficiency values for pumps should normally be given as a range. Hence, a standard pump would have an efficiency range between 30 and 80%. A high efficiency pump would have an efficiency range of 60 to 88%.

According to Waide and Brunner (2011) in the EU, pump systems are divided into two subgroups for regulatory purposes: building circulator pumps and pump motor systems. Building circulator pumps are used to circulate heating and cooling fluids in a closed system,

typically within a building. Though circulators were regulated on 22 July 2009 under the Implementing Directive 2005/32/EC concerning Eco-design requirements, EC is still working on the test standard for circulator pumps which requires refinements to the calculation method and a means of measuring permanent magnet (PM) motors. The EuP (Eco-design Directive for Energy-Using Products 2005/32/EC) study on water pumps was completed in April 2008, and the Commission was preparing a draft regulation for stakeholder review in early 2010. Waide and Brunner (2011) have also observed that the pump industry is the largest consumer of electric motors in the United States, but there is no regulatory standard on pump systems. Instead, there is a twofold effort to encourage installation of energy-efficient pump systems:

- An aggressive efficiency regulation on electric motors, from 1 hp to 500 hp. This was originally started by EPC Act 1992 and was amended by EISA 2007. It entered into review by the US-DOE through a rule-making process for energy-conservation standards that began in 2010.
- The provision of software tools, marketing efforts and training on the specification and installation of energy-efficient pump systems, particularly Pump Systems Matter (<http://www.pumpsystemsmatter.org>) and the DOE's Pumping System Assessment Tool ([http://www1.eere.energy.gov/industry/bestpractices/software\\_psat.html](http://www1.eere.energy.gov/industry/bestpractices/software_psat.html)).

Waide and Brunner (2011) have furthermore noted the existence of voluntary pump efficiency certification and labelling in China, India and Korea; and mandatory regulations in Iran, Israel and Mexico.

The irony of this report is that the nations championing electric motor energy efficiency have relegated energy efficiency improvements of pumps through efficiency testing methodologies and classifications to the background. However, according to Falkner and Holt (2011) it is expected that European Commission will soon (Spring 2011) pass performance regulations on pumps sequel to the passage of Eco-design Directive for Energy-Using Products 2005/32/EC in June 2010.

## **2.5. Drives**

The term drive has diverse connotations with a common understanding that its application is in speed control.

There are many and diverse reasons for using variable speed drives, and the needs for speed and torque control are usually fairly obvious. In general, variable speed drives are used to (Barnes, 2003):

- Match the speed of a drive to the process requirements
- Match the torque of a drive to the process requirements
- Save energy and improve efficiency

The following sub-sections will consider the various perspectives to drives such as drive system types. However, greater emphasis is on electrical drives.

## **2.5.1 Drive System Types**

The operations of most industrial loads require wide ranges of speed. These loads could be driven by hydraulic, pneumatic or electric motors (Subrahmanyam, 1994). Polka (2003) has identified three means of achieving variable speed control in the industries namely mechanical, hydraulic, and electrical/electronic. Each of these has its strengths and weaknesses.

### **2.5.1.1 Mechanical System**

The mechanical methods were probably the first to make their way into the industrial environment. The mechanical methods operate on the principle of variable-pitch pulleys. The pulleys are usually spring-loaded and can expand or contract in diameter by means of a hand crank. The mechanical drive still gets its power source from an ac power supply – usually three-phase ac. The three phase ac power is then fed to the fixed-speed ac motor. The ability to vary the diameter of one or both pulleys gives this drive unit the ability to change its output speed. The principle of variable speed is exactly the same as the gears of a 15-speed bicycle. Shifting gears causes the chain to slip into a wider- or narrower-diameter sprocket. When that happens, a faster or slower speed is achieved with basically the same input power.

Major benefits of this type of drive as shown in Fig. 2.15 were low cost and easy maintainability because the malfunction was rather obvious.

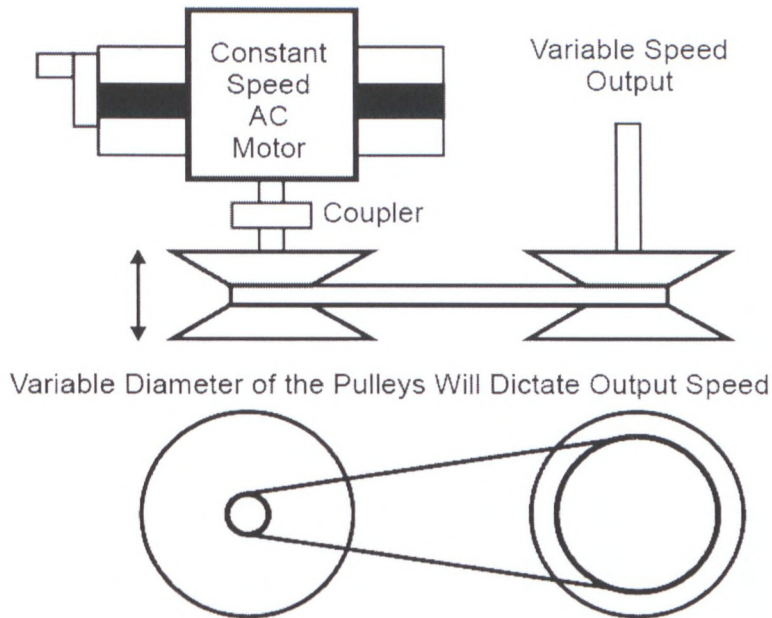


Fig. 2.15 Mechanical drive system (Polka, 2003)

However, slipping of the belt on the pulleys (sometimes called sheaves) coupled with size and weight constituted a challenge to this type of drive. The belt slippage is responsible for the efficiency of the unit ranging from 90% down to 50% or even lower. Size and weight could prohibit the use of this device in areas that would be required for mounting a drive. Equally the speed range was a limitation because of fixed diameter settings, a characteristic of the mechanics of the device.

### 2.5.1.2 Hydraulic System

Hydraulic drives have remained the workhorse of many metals processing and manufacturing applications. The hydraulic motor's small size makes it ideal for situations where high power is needed in very tight locations. The hydraulic motor's size is typically  $1/4 - 1/3$  the size of an equivalent power of an electric motor. For a drive of this type as illustrated in Fig. 2.16, a constant-speed AC motor operates a hydraulic pump. The pump builds up the necessary operating pressure in the system to allow the hydraulic motor to develop its rated power. The speed control comes from the control valve. This valve operates like a water faucet – the more the valve is open, the more fluid passes through the system and the faster the speed of the hydraulic motor. Worthy of note is that this system uses a coupler to connect the ac motor to the pump.

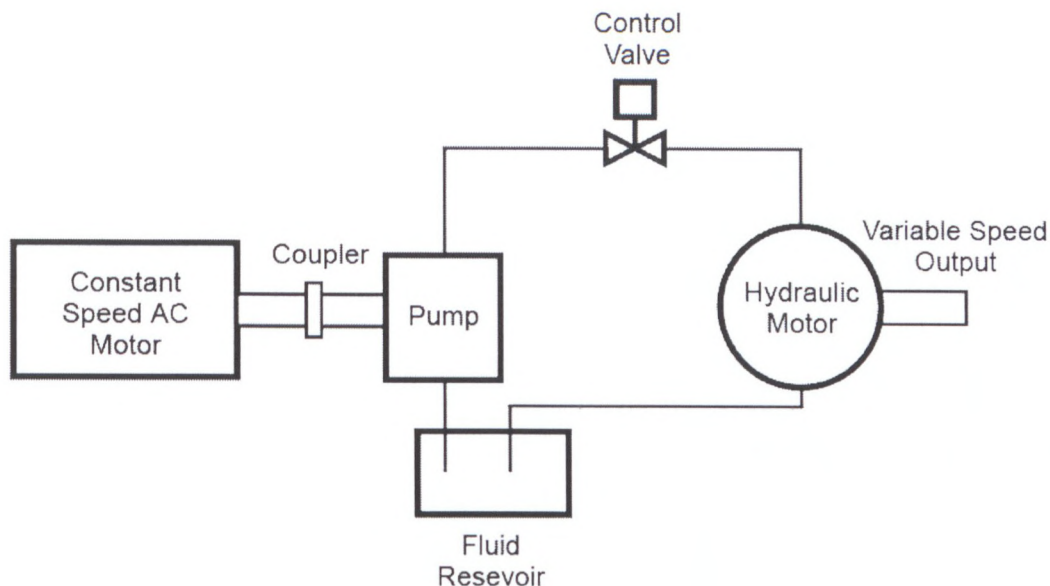


Fig. 2.16 Hydraulic drive system (Polka, 2003)

One of the benefits of this type of drive system is the ability of the hydraulic motor to develop high torque. Also, it has a fairly simple control scheme (a valve), which operates at a wide speed range and has an extremely small size compared to most ac motors of the same power. However, this type of system has several major limitations. The most limiting factor of this system is the need for hydraulic hoses, fittings, and fluid. This system is inherently prone to leaks, leading to high maintenance costs. In addition, there is virtually no way to connect this system to an electronic controller. Automatic valve-type controls have been developed, but their use is limited in today's high-speed manufacturing environment.

### 2.5.1.3 Electrical System

An electrical drive system, according to Emadi (2005),<sup>4</sup> is basically made up of five main components as shown in Fig 2.17. The input to the drive is the power source which supplies the energy for the system. This is followed by the power electronic converter. The electronic converter has the responsibility of manipulating the voltage, current, and frequency provided by the power source. The controller ensures the desired automatic control of the motor output as regards the load (output) demand relative to the input power. And the remaining two components of the system are a motor and a mechanical load. The mechanical load is the mechanical system that requires the energy from the motor drive. The mechanical load could

be the blades of a fan, the compressor of an air conditioner, the rollers in a conveyor belt, or nearly anything that can be driven by the cyclical motion of a rotating shaft. Summarily, an electrical drive system involves the control of electric motors in steady-state and dynamic operations with a consideration to the mechanical load.

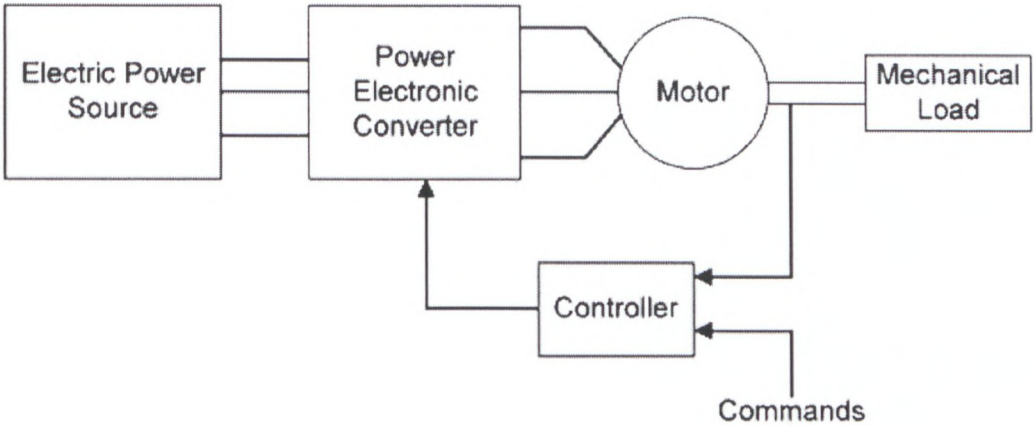


Fig. 2.17 Electric drive system (Emadi, 2005)

However, electrical drives employing electric motors are predominant in industries because electric motors enjoy some specific advantages, such as overload capacity, smooth speed control over a wide range, and capability of operating in all the four quadrants of the speed-torque plane (Subrahmanyam, 1994).

In electrical/electronic speed control method, the versatility of power electronics is deployed thereby eliminating most, if not all, of the shortfalls of the mechanical and hydraulic drive systems. One of such advantages is the location of the control equipment. In mechanical and hydraulic speed drives, the control equipment is between the motor and the working machine, which makes maintenance very difficult. But in electrical speed drives, all control systems are situated in an electrical equipment room and only the driving motor is in the process area (ABB, 2002). In mechanical and hydraulic drive systems variable speed output is achieved from a constant speed motor through ancillary equipment, whereas in electrical/electronic speed control method variable speed output is realised directly from the motor by controlling its input. This results to smooth speed control over a wide range thereby improving the control efficiency and reliability.

Today, with advancements in power electronics, control electronics, microprocessors, microcontrollers, and DSPs, electric drive systems have improved drastically (Emadi, 2005). Modern electrical VSDs can be used to accurately maintain the speed of a driven machine to

within  $\pm 0.1\%$ , independent of load, compared to the speed regulation possible with a conventional fixed speed squirrel cage induction motor, where the speed can vary by as much as 3% from no load to full load (Barnes, 2003).

The above considerations of the three means of achieving variable speed control (drive system types) in the industries agree with the drive system composition by Hanitsch (2002). He views a drive system as being composed of several subsystems such as power electronics; controller for speed or/and position; electric motor; gearbox or/and coupling; and load e.g. pump, fan, compressor.

Having examined these fundamental drive systems, and given the outstanding prominence and advantages of electrical drives attention is now focused on the electrical drive. Therefore subsequent reference to drive or drives implies electrical drive.

### **2.5.2 Electrical Drives**

In the view of Bose (2000) it is often said that solid-state electronics brought in the first electronics revolution, whereas solid-state power electronics brought in the second electronics revolution. Interestingly the perceived disadvantages of using induction machine are continuously being successfully challenged by power electronics advancements through relevant and effective control systems. These good control methods are based on physical insight into the machine characteristics (Finch, 2008). However these control methods or drive technologies and their widespread applications especially in the industrial community have resulted to different meanings to the word “electric drive” or “electrical drive”. Bose (1981) had observed a great awakening in the industrial community with an intense urge to understand the basics of ac drives technology. Unfortunately, according to him, the literature on ac drives has grown immensely and has proliferated in different directions, so that a motivated reader trying to study the literature gathers only frustration.

Part of this frustration is whether an electrical drive is a system or device. Equally confusing is its reference as VSD, ASD, VFD and Inverter. A lot of authors accept that these can be used interchangeably.

### 2.5.2.1 Historical Perspective

Bose (2006) and Shakweh (2007) have executed valuable job in chronicling the developments in the power electronics and invariably electrical drives. A comparison of the two appears to confirm the view of Gottlieb (1997) on the difficulty of assigning specific dates to scientific and or technological inventions. For instance Bose (2006) records 1891 as when Ward Leonard dc motor speed control was introduced contrary to 1886 which Shakweh (2007) documents as the birth of the electric variable speed drive system represented by Ward Leonard system. But there is no controversy on the astronomical and constant growth in the field of power electronics and electrical drives.

Historically, two of the best known electrical VSDs were the schrage motor and the Ward-Leonard system. Although these were both designed for operation from a 3-phase ac power supply system, the former is an ac commutator motor while the latter uses a dc generator and motor to effect speed control (Barnes, 2003).

### 2.5.2.2 Drive as a Device or System

In the most generic sense, a drive is a device that controls speed, torque, direction, and the resulting horsepower of a system (Polka, 2003), electric motor in particular. As a device drives interface between the utility input and control the motor speed by changing the magnitude of voltage, current or frequency, and are composed of three main components (Qureshi & Tassou, 1996; Twining & Cochrane, 1999; Deswal *et al.*, 2008; Saidur, 2010) namely a rectifier, a dc link and an inverter. According to ABB (2008) a variable-speed drive is a piece of equipment that regulates the speed and rotational force, or torque output, of an electric motor. It observes that one of the main reasons why drives save energy is because they can change the speed of an electric motor by controlling the power that is fed into the machine. In the view of Mohan *et al.* (2003) variable-frequency converters, which act as an interface between the utility power system and the induction motor, must satisfy the following basic requirements:

- Ability to adjust the frequency according to the desired output speed.
- Ability to adjust the output voltage so as to maintain a constant air gap flux in the constant-torque region.
- Ability to supply a rated current on a continuous basis at any frequency.

According to Barnes (2003) variable speed drives that control the speed of dc motors are loosely called *dc variable speed drives* or simply *dc drives* and those that control the speed of ac motors are called *ac variable speed drives* or simply *ac drives*. This means he considers a drive to be an equipment or device that controls the speed of an electric motor.

The consideration of an electric drive as a device has led to the classification of drives as shown in Fig. 2.18. The classification criteria used are the type of semiconductor switch employed, input and output circuit topology, motor type, control strategy, power and voltage level, and regeneration capability (Qureshi & Tassou, 1996). However a closer look at Fig 2.18 does not show the presence of any motor which creates some confusion based on the aforementioned criteria.

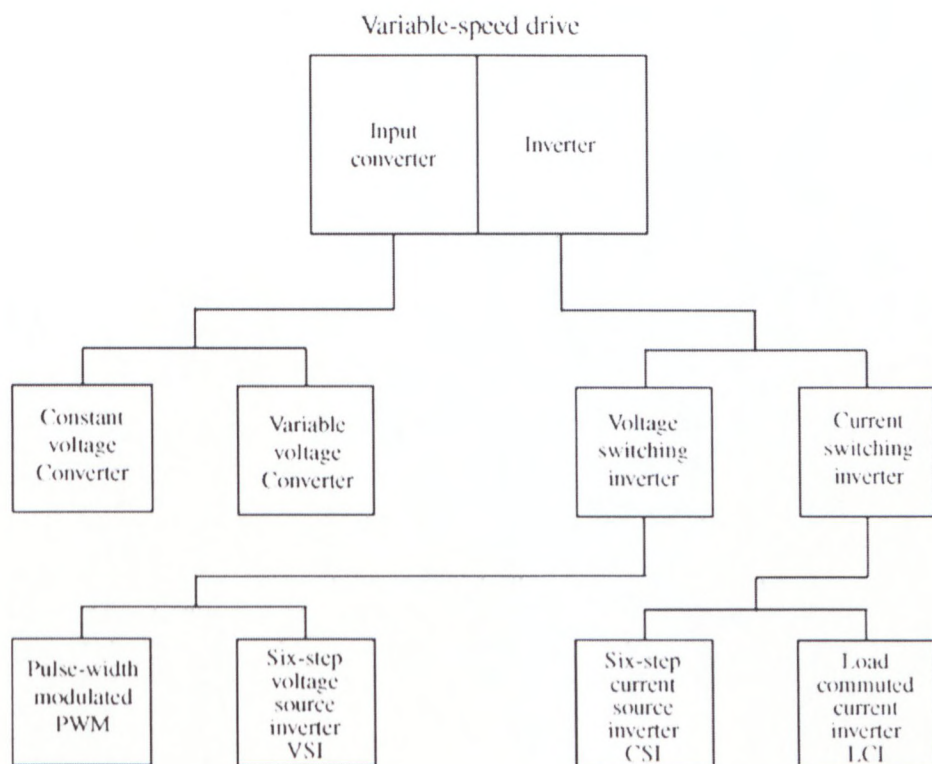


Fig. 2.18 Classification of electronic drives (Qureshi & Tassou, 1996; Saidur, 2010)

However, drives as a system are generally composed of the following (Leonhard, 1996; De Capua & Landi, 2001; ABB, 2002; Mecrow & Jack, 2008) as shown in Fig. 2.19.

- A static energy conversion group (ac/dc converter and inverter)
- An electrical motor and
- A microprocessor-based measurement and control system

Muravlev *et al.* (2005) have asserted that a modern industrial drive is a complex system consisting of a set of interconnected elements such as the actuating power mechanism (motor), power supply (converter), the drive control system. This classification differs from Fig 2.17 by assuming that the need and presence of the mechanical load are obvious because the motor must be doing some work.

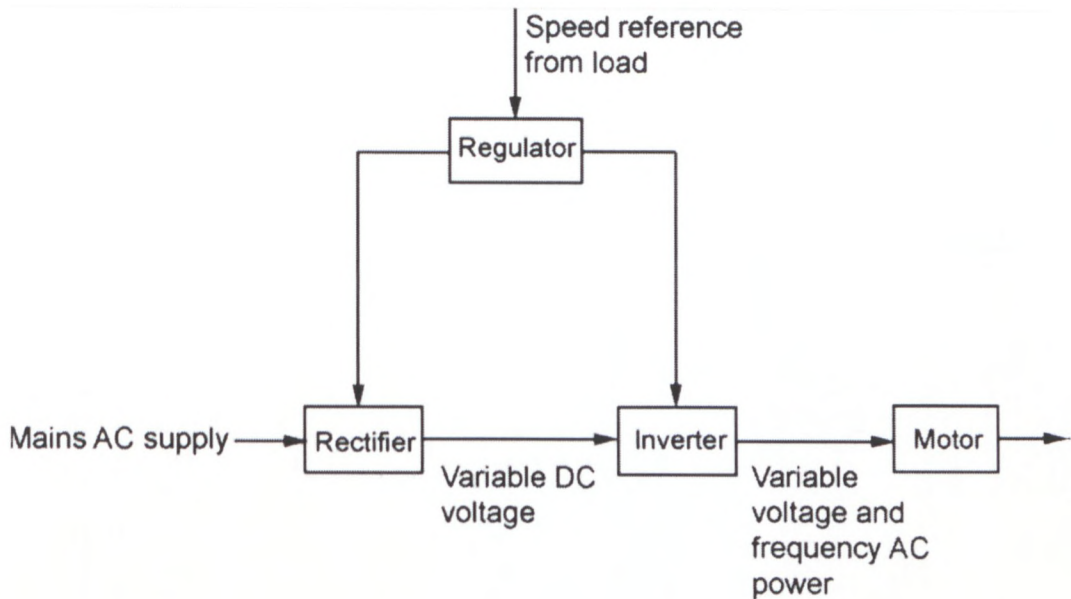


Fig. 2.19 Electrical drive system (Begg, 2002; Saidur, 2010)

NEMA (2007) and PSRC (2009) have defined drive as “the equipment used for converting electrical power into mechanical power suitable for the operation of a machine. A drive is a combination of a converter, motor, and any motor mounted auxiliary devices. Examples of motor mounted auxiliary devices are encoders, tachometers, thermal switches and detectors, air blowers, heaters, and vibration sensors”. This definition is confusing because of its combination of the meanings of a drive as a device as well as a system. The first part of this definition agrees with IEEE (2000) definition of a drive. However, IEEE (2000) further defines an electric drive as “a system consisting of one or several electric motors and of the entire electric control equipment designed to govern the performance of these motors. The control equipment may or may not include various rotating electric machines”. But NEMA (2007) holds that a drive system refers to an interconnected combination of equipment that provides a means of adjusting the speed of a mechanical load coupled to a motor. According to it a drive system typically consists of a drive and auxiliary electrical apparatus.

In the early eighties, the cost of an ac drive package had a 30% motor plus 70% power converter structure, while in the case of a dc drive the motor was worth 70% of the package cost (Lipo, 1988; Vukosavic, 1998).

One could deduce from these definitions and statistics that there is really a difference between drive as an equipment or a device and as a system. Worthy of note are the definitions of a device and system. IEEE (2000) has defined a device as a unit of an electrical system which is intended to carry but not consume electrical energy. It further defines a system as a combination of two or more sets, generally physically separated when in operation, and such other units, assemblies, and basic parts necessary to perform an operational function or functions. Obviously the power consumed by the power converter (drive as a device) is so infinitesimal that it could be ignored. Equally as noted earlier the power converter and entire control unit are located in the equipment room while the electric motor is in the process area which makes them physically separated.

These two definitions reveal the common meanings of a drive or drives as a component or system. The commonality in both meanings is the responsibility for machine speed variation.

### **2.5.2.3 Adjustable Speed Drive (ASD) or Variable Speed Drive (VSD)**

Most authors do not see any difference between ASD and VSD. According to Okrasa (1997) an ASD is a device used to provide continuous range process speed control (as compared to discrete speed control as in gearboxes or multi-speed motors) as shown in Fig 2.20.

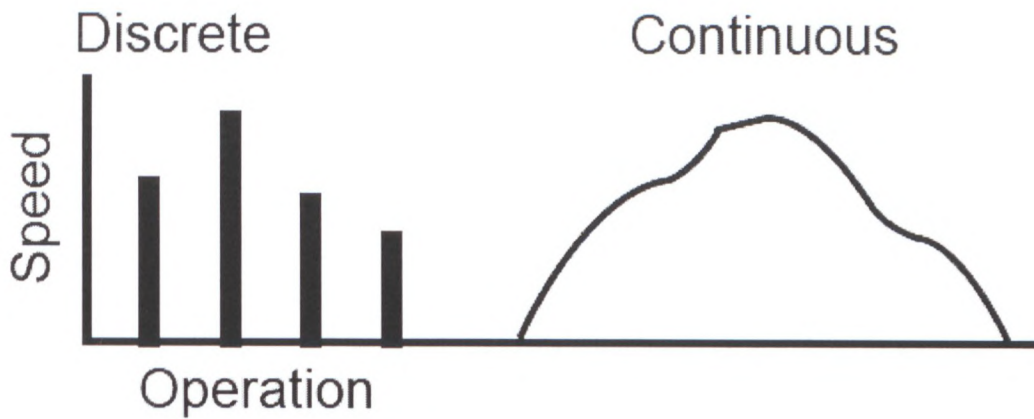


Fig. 2.20 Comparison of process speed range control (Okrasa, 1997)

However Wikipedia (12 Feb 2010) notes that where speeds may be selected from several different pre-set ranges, usually the drive is said to be “adjustable” speed. If the output speed can be changed without steps over a range, the drive is usually referred to as “variable speed”. Subrahmanyam (1994) while subscribing to the latter distinction posits that industrial loads require operation at any one of a wide range of speeds. Such loads are generally termed as variable speed drives. These drives, according to him, demand precise adjustment of speed in a stepless continuous manner over the complete speed range required. Furthermore in the view of Shakweh (2007) in every industry there are industrial processes of some form, which require adjustments either for normal operation or optimum performance. Such adjustments are usually accomplished with a VSD system.

A reference to IEEE (2000) shows a distinction between adjustable-speed drive and variable-speed drive. Adjustable-speed drive is described as an electric drive designed to provide easily operable means for speed adjustment of the motor, within a specified speed range. But a variable-speed drive refers to an electric drive so designed that the speed varies through a considerable range as a function of load.

Consequently it would be wrong to assume or accept that ASD is the same as VSD. Contrary to the assertion of Okrasa (1997), a multi-speed motor operates within a specified or already known speed range. Such a range could be low and high speed of known values which are independent of the load and this is a discrete or step speed control. A typical example of this is the speed control of wound-rotor induction motor through addition or removal of rotor resistances to realise preset speed values. Therefore adjustable-speed drive connotes an open-

loop control system as opposed to the closed-loop control connotation of a variable-speed drive.

But there is yet another perspective to ASD which is its general meaning as either a device or system. An ASD controls the speed of an induction or synchronous motor by converting fixed frequency/fixed magnitude ac mains supply voltage to a variable frequency/variable magnitude voltage at the motor terminals (Djokic *et al.*, 2005). Galceran *et al.* (2003) assert that in industry ASD now controls directly the speed of induction motor, with precision up to 1% or more depending on the control system, taking the place of mechanical systems that previously controlled the drive speed. They also acknowledged the wide applications of ASD in offices and homes and further proposed the division of ASD into four main sections namely ac/dc Rectifier, dc link and pre-charge circuit, dc/ac Inverter, and Control system. According to them this division would enable the analysis of the sensitive elements. The view of Montanari *et al.* (2006) is that for low dynamic applications such as pumps and fans the typical solution is the so-called “adjustable-speed” drive. This is a simple low-cost voltage-source inverter fed induction motor drive with scalar voltage frequency control.

In today’s industrial and commercial world, ASDs, which include alternating current (ac) VFDs, have become the accepted method of speed control for pump and other motor driven applications (Cookson *et al.*, 2008). However, the ASD and motor must be designed as a system to realise the benefits and to avoid the potential pitfalls, they noted. According to them, most ASD systems consist of three basic components:

1. A rectifier that converts the fixed ac input voltage to dc voltage;
2. An inverter that switches the dc voltage to an adjustable frequency ac output voltage;  
and
3. A controller that directs the rectifier and inverter to produce the desired ac frequency and voltage to meet the needs of the ASD system

Therefore it could be observed that ASD is an equipment of a system that includes an electric motor. But the classification of ASD as a system into the three basic units of rectifier, inverter and controller highlights the issue at stake – different meanings of electric drive.

#### **2.5.2.4 Variable Frequency Drive (VFD) or Variable Speed Drive (VSD)**

This is another set of confusing terms common in literature dealing with electric motor speed control. This apparent confusion is outstanding with the control of squirrel-cage induction

motors. As stated earlier the inherent attributes of induction machines, particularly squirrel-cage machines, make them very attractive for drive applications. They are rugged, economical to build and have no sliding contacts to wear. The difficulty with using induction machines in servomechanisms and variable speed drives is that they are ‘hard to control’, since their torque-speed relationship is complex and non-linear (Kirtley, 2010). An induction motor is essentially a constant speed motor when connected to a constant-voltage and constant-frequency power supply. The operating speed is very close to the synchronous speed. If the load torque increases, the speed drops by a very small amount. It is therefore suitable for use in substantially constant-speed drive systems (Sen, 1997). But many industrial applications require continuously variable speed range.

Part of Section 2.3.2 has been reproduced here and Eqns. 2.4 – 2.7 as Eqns. 2.18 – 2.21 to enhance understanding of the argument. In Section 2.3.2 it was pointed out that the application of balanced three-phase currents to the three-phase winding of a machine stator sets up a magnetic flux in the air gap. Equally that in the view of Lander (1993), this magnetic flux pattern remains constant in form throughout the alternating cycle, rotating one pole pair in one cycle. The speed of rotation of the flux is known as the synchronous speed given by

$$N_{syn} = \frac{f}{p} \text{ rev/s} \quad (2.18)$$

where  $f$  is the frequency in Hz, and  $p$  the number of pole pairs.

When expressed in radian measure, the synchronous speed is

$$\omega_{syn} = \frac{2\pi f}{p} \text{ rad/s} \quad (2.19)$$

However, the rotor of our industrial workhorse (cage induction motor) must always rotate at a different speed from the synchronous speed for a voltage, and hence current and torque to be induced in the rotor. The relative speed of the rotor to the synchronous speed of the rotor flux is known as the slip  $s$ :

$$s = \frac{\text{synchronous speed} - \text{rotor speed}}{\text{synchronous speed}} = \frac{N_{syn} - N_{rotor}}{N_{syn}} \quad (2.20)$$

For an induction motor, rotor speed, frequency of the voltage source, number of poles and slip are interrelated according to the following equation (WEG, 2010):

$$n = \frac{120f_1}{p}(1 - s) \quad (2.21)$$

where:  $n$  is mechanical speed (rpm);  $f_1$  is fundamental frequency of the input voltage (Hz);  $p$  is number of poles, and  $s$  is slip.

The analysis of Eqn. 2.21 shows that the mechanical speed of an induction motor is a function of three parameters. Thus the change of any of those parameters will cause the motor speed to vary as shown in Table 2.6.

Table 2.7 Induction machines speed variation (WEG, 2010)

<b>Speed Variation</b>	
<b>Parameter</b>	<b>Application characteristics</b>
Number of poles	Discrete variation
	Oversizing
Slip	Continuous variation
	Rotor losses
	Limited frequency range
Voltage frequency	Continuous variation
	Utilization of STATIC FREQUENCY Inverters!

Most authors only consider Eqn. 2.18 in their consideration of cage induction motor speed control resulting to the conclusion that frequency is the only variable for continuous variable speed control of cage induction motor. Reference to Hughes (2008) shows that controlled variable speed operation of a cage induction motor is not possible unless we can change the frequency of the three-phase supply to the stator. This in his view is not possible if the motor is connected to the 50 (or 60) Hz mains, but with modern power electronic converters it is possible to generate a variable frequency three-phase voltage using a device called a variable speed drive. VFD proponents base their arguments on this notion that only frequency variation could change the speed of cage induction motor continuously over a speed range. It should be noted that the speed being referred to here is the synchronous speed which could also be seen as the electrical speed and it is different from the rotor speed or the mechanical speed as shown in Eqns. 2.18 – 2.21 above. And this is dangerous because it ignores the crucial role of slip in the production of useful torque in an induction motor.

Chapman (2005) posits that there are really only two techniques by which the speed of an induction motor can be controlled. One is to vary the synchronous speed, which is the speed of the stator and rotor magnetic fields, since the rotor speed always remains near synchronous speed. The other technique is to vary the slip of the motor for a given load. Because synchronous speed of an induction motor is given by Eqn. 2.18 so, according to him, the only ways in which the synchronous speed of the machine can be varied are (a) by changing the electrical frequency and (b) by changing the number of poles on the machine. Slip control may be accomplished by varying either the rotor resistance or the terminal voltage of the motor. Chapman (2005) is in agreement with Bose (1981) who has noted that the speed of an induction motor is determined by the synchronous speed and slip of the rotor. Furthermore, the synchronous speed is related to the supply frequency, and the slip can be controlled by the regulation of voltage or current supplied to the motor.

The synchronous speed of an induction motor can be changed by (a) changing the number of poles or (b) varying the line frequency. The operating slip can be changed by (c) varying the line voltage, (d) varying the rotor resistance, or (e) applying voltages of the appropriate frequency to the rotor circuits (Fitzgerald *et al.*, 2003). Although these are facts, the numbering poses a challenge to comprehension. While the first two points affect the synchronous speed (electrical speed), all five methods determine the rotor speed (mechanical speed) as noted earlier. According to Singh *et al.* (1994) many strategies have been proposed for controlling the speed of the induction motor. A few of these are slip control, synchronous speed control, flux control and v/f control, angle control, and field oriented control.

The essence of these references is to show that other variables besides frequency would permit a continuous speed variation of a squirrel-cage induction motor over a certain range. It is pertinent to note that the author is aware of the limited speed range and inefficiency of some of such control methods. But his aim is to refute the notion that variable speed operation of squirrel-cage induction motor is only feasible through frequency variation of its input power.

Talking about speed control of pumps, Europump and HI (2004) maintain that speed can be controlled in a number of ways, with the most popular type of VSD being the VFD. Similarly the view of Vasquez *et al.* (2005) is that the most common VSDs used in heat pump and similar applications are VFDs controlling conventional alternating-current induction motors. Therefore it could be proper to conclude that VFDs are parts of VSDs and are not the same irrespective of their erroneous interchangeability. Perhaps the view of Carpenter and Lipo

(1988) on the terms vector control and FOC could buttress this. According to them in both the U.S. and Japan the term vector control is frequently used in lieu of FOC. Field orientation control is mechanically descriptive of the accomplished control, whereas vector control describes the technique by which it is accomplished. The technique involves a vector analysis of current which separates the magnetizing component of current from the work component of current.

Similarly VSD describes the entire system of variable speed application whereas VFD describes the technology deployed in controlling the speed of an electric motor. This reminds us of the need to properly define a drive as either a device or a system. However, various speed control techniques implemented by modern-age VFD are mainly classified in the following three categories (Swarupa *et al.*, 2009): Scalar Control (V/f Control); Vector Control (Indirect Torque Control); and Direct Torque Control (DTC). According to Laughy *et al.* (2007) VFDs provide flexibility in speed control and improve starting and operating performance of induction motors. This is because VFDs eliminate the challenge posed by the 5 to 7 times of the motor full-load current of a typical direct on-line starting of an induction motor which could cause large voltage sag during the starting transient and consequently disturb the operation of distribution network.

### **2.5.2.5 Inverter**

In Section 2.5.2.2 inverter was identified as part of the power converter unit of an electric drive. Its function remains the changing of direct-current power to alternating-current power (IEEE, 2000; NEMA, 2007). As shown in Fig. 2.18, inverters could be classified as voltage or current switching inverters respectively. While PWM and six-step VSI are subdivisions of voltage switching inverters, six-step CSI and LCI are sub-groups of current switching inverters. Literature is replete with information on inverters but the concern here is its common erroneous usage as being synonymous with an electric drive. Before the invention of variable frequency voltage and current source inverters the induction motor was never thought as continuously variable speed drive (Bocker, 2007).

Eurpump and HI (2004) have noted that the most common form of VFD is the voltage-source, PWM frequency converter (often incorrectly referred to as an inverter). This misnomer becomes very worrisome when it is rampant in reputable publications such as WEG (2010). Lipo and Novotny (1988) have noted that the three basic inverter types widely employed to

drive induction motors and thus to obtain variable speed operation are VSI, CSI and PWM. In their view the VSI and PWM inverters are most often operated essentially as open loop drives in energy conservation applications. Moreover since the CSI is not capable of open loop operation with an induction machine because of the strong dependence of inverter voltage on motor load (and the resulting inherent instability), CSI systems must employ some form of closed loop. The PWM voltage source inverter, based upon IGBTs has gained a dominant position in the ac drives market in the power range to 200kW due to its ease of application, good power factor and potential to provide good dynamic performance (Vas & Drury, 1996). Equally PWM inverters, according to them, are most commonly applied in induction motor drives, but they also form the basis of brushless ac servo drives. According to Gnacinski (2007) power losses in an induction motor can be reduced in a few different ways – by developing induction motors of high efficiency, improving the quality of supply voltage (new generations of inverters) and application of energy saving work. Undoubtedly “new generations of inverters” implies “new generations of power converters” or electric drives as a device.

The crucial role of the Inverter in an electric drive does not justify its being synonymous with the power converter or the entire drive system. A vehicle or an automobile makes a good analogy. It would be improper to address the engine as the vehicle though the vehicle is rendered useless without an engine. Likewise the engine is worthless without the other key parts of the motor such as the body, tyres and even battery in some cases.

In all, this research considers electric drive as a device or an equipment that controls the speed of an electric motor for the ultimate control of the pump flow rate or pressure. Equally this work accepts VSD as appropriate given that there are no discrete or preselected speed ranges but rather determined by the operating conditions of the entire system.

#### **2.5.2.6 Classifications**

A number of criteria are used in classifying drives such as application, power device and converter type respectively. Fig. 2.18 shows a typical classification of electronic drives based on the type of semiconductor switch employed, input and output circuit topology, motor type, control strategy, power and voltage level, and regeneration capability (Qureshi & Tassou, 1996).

### **2.5.2.6.1 Power and Voltage Level**

According to Shakweh (2007) the various power ratings of electric drives are:

- Fraction kW: power less than 1kW
- Low power: power range of 1 to 5kW
- Medium power: power greater than 5kW but less than 500kW
- Higher power: power range of 1 to 50MW

Also according to him the working voltage of electric drives are:

- Low Voltage (LV): voltage less than 600V
- Medium Voltage (MV): voltage range of 2.4 – 11kV

The MV drives cover power ratings from 0.4MW to 40MW at the medium voltage level of 2.3kV to 13.8kV (Wu, 2006). The power rating can be extended to 100MW, where synchronous motor drives with load commutated inverters are often used. However, the majority of the installed MV drives are in the 1- to 4-MW range with voltage ratings from 3.3 kV to 6.6 kV.

In the view of NEMA (2007) controls (drives) are rated to provide a defined amount of current for continuous operation at a defined maximum ambient temperature. It notes that while controls may be marked with a horsepower rating, it should be used for reference purposes only. According to it controls are generally identified as one of two basic types, distinguished by short-time overload current capabilities. The two basic control types are variable and constant torque respectively. A variable torque control is rated with a 1 minute overload capability of typically 110 – 125% of nameplate continuous rated current which is typically sufficient for variable torque loads. However, a variable torque control is not limited to variable torque load applications. A constant torque control is typically rated with a 1 minute overload capability of 150% of the nameplate continuous rated current.

### **2.5.2.6.2 Semiconductor Switches**

The semiconductor switches or power devices of electric drives are broadly divided into two groups namely Thyristors and Transistors. Thyristors also known as SCR are devices having a four-layer, three-junction monolithic structure. They are characterised by low conduction

losses and high surge and current carrying capabilities. They operate as an on-off switch. The most popular types of devices listed under this group are:

- Gate Turn Off Thyristor (GTO)
- MOSFET Controlled Thyristor (MCT)
- Field Controlled Thyristor (FCT)
- Emitter Switched Thyristor (EST)
- MOS Turn Off Thyristor (MTO)
- Integrated Gate Commutated Thyristor (IGCT).

Transistors are switches of basically three-layer two-junction structure devices, which operate in switching and linear modes. They are best recognised for ruggedness of their turn-off capabilities. The following are the most types of devices under this group namely:

- Bipolar Junction Transistor (BJT)
- Darlington Transistor
- MOSFET
- Injection Enhanced Gate Transistor (IEGT)
- Carrier Stored Trench-Gate Bipolar Transistor (CSTBT)
- Insulated Gate Bipolar Transistor (IGBT)

### **2.5.2.6.3 Inverter Input**

The nature of the supply or input from the rectifier to the inverter is also used to differentiate drives as either voltage source or current source. The rectifier whose responsibility is the conversion of the ac input into dc could be static (uncontrolled) when it is made up of diodes. Rectifiers could equally be dynamic (controlled) when it consists of thyristors or IGBTs. Drives with controlled rectifiers are also known as active front end drives.

According to EC (2000) the three-phase VSI is used to control ac-motors in the lower and medium power ranges, from small high dynamic performance servo drives with speed and position control capability (<10kW) to most auxiliary drives in industry, ranging up to several hundred kW. The VSI is suitable for supplying induction, as well as synchronous motors. The input rectifier serves to produce a dc supply, and the relatively large electrolytic capacitor is inserted to filter ("stiffen") the dc voltage which feeds the inverter. Typically, the capacitor of 2 to 20 $\mu$ F is a major cost item in the system. Additionally, it is usual to insert a reactance between the rectifier and the dc supply to limit the fault current and to reduce the harmonic distortion produced by the rectifier. The inverter module converts the dc voltage to a variable

frequency, variable voltage output. Fig. 2.21 shows a simplified diagram of the basic three-phase VSI.

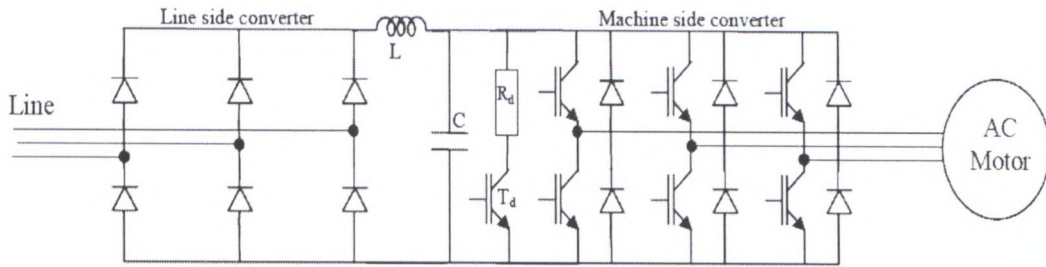


Fig. 2.21 Topology of a VSI-PWM with dissipation resistance ( $R_d$ ) (EC, 2000)

In CSI drives, the inverter switches are fed from a constant current source. While a true constant current source can never be a reality, it is reasonably approximated by a controlled rectifier (thyristor or GTO) with a current control loop with a large dc link inductor to smooth the current. Since the current is constant, there will be no voltage drop across the stator winding self-inductance and a constant voltage drop across the winding resistances. Therefore, the motor terminal voltage is not set by the drive but by the motor. Since the motor is wound with sinusoidally distributed windings, the resulting voltages that appear on the motor terminals are nearly sinusoidal. The CSI drive produces harmonic currents and voltages in the motor side, which are limited by the induction motor reactance. CSIs are used for large drives (typically above 500 kW) due to their simplicity, regeneration capabilities, reliability and low speed requirements for the power devices. The power factor is poor at low speeds, as the input stage is a phase-controlled rectifier that uses a small conduction angle at low speed, low voltage operation. The combination of a large inductor in the dc link, high voltage thyristors and components to suppress output voltage transients make this converter impractical for small size inverters. In industrial and traction applications these current source converters are robust in operation and reliable due to the insensitivity to short circuits and noisy environments. Figure 2.22 shows a typical circuit of a current source inverter drive.

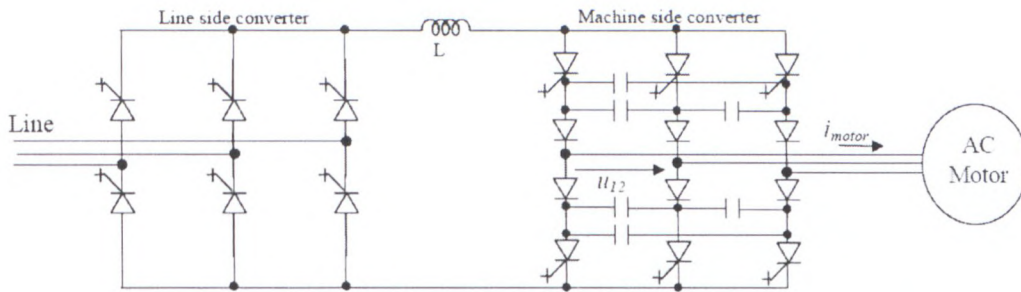


Fig. 2.22 VSD using current-source inverter (EC, 2000)

A major disadvantage of this scheme is the potential for resonance between the capacitors and the motor inductances. This possibility can be avoided by careful matching of the CSI drive with the motor. However, since the motor parameters must be known, to implement such an approach, this type of drive is presently not popular for general-purpose applications.

The LCI, a special type of CSI, drive is used in very large synchronous motor speed controls. Load commutated inverter drive uses thyristors as switching devices but avoids forced commutation because it is used only with synchronous motors. By controlling the field current, a synchronous motor can run overexcited, that is with a leading power factor which leads to natural commutation of the thyristors due to the back emf of the motor. Figure 2.23 shows the generic diagram of an LCI inverter coupled to a synchronous motor.

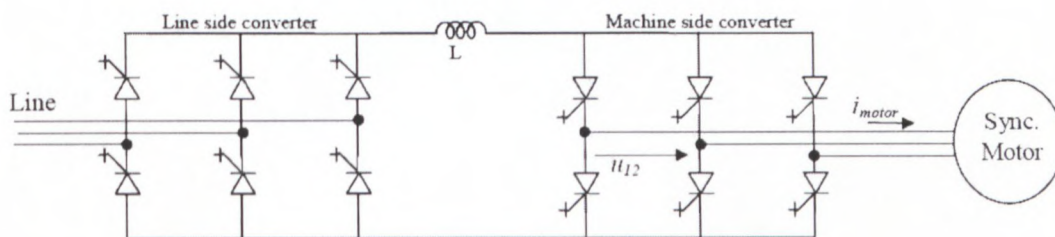


Fig. 2.23 Typical circuit for synchronous motor VSD system (EC, 2000)

The LCI drive-synchronous motor combination, although simple and efficient, is generally used only above 500 kW due to the higher cost of synchronous motors.

#### 2.5.2.6.4 Switching Strategies

Application areas of power converters still expand thanks to improvements in semiconductor technology, which offer higher voltage and current ratings as well as better switching characteristics. On the other hand, the main advantages of modern power electronic

converters, such as high efficiency, low weight, small dimensions, fast operation, and high power densities, are being achieved through the use of the so-called *switch mode operation*, in which power semiconductor devices are controlled in *ON-OFF* fashion (no operation in the active region). This leads to different types of *pulse width modulation* (PWM), which is a basic energy processing technique applied in power converter systems. In modern converters, PWM is a high-speed process ranging – depending on the rated power – from a few kilohertz (motor control) up to several megahertz (resonant converters for power supply).

Historically, the best-known triangular carrier-based (CB) sinusoidal PWM (also called sub-oscillation method) for three-phase static converter control was proposed by Schonung and Stemmler in 1964 (Kazmierkowski *et al.*, 2002). However, according to them, with microprocessor developments, the SVM proposed by Pfaff, Weschta, and Wick in 1982 and further developed by van der Broeck, Skudelny, and Stanke becomes a basic power processing technique in three-phase PWM converters. According to Wikipedia (2011) one of the early applications of PWM was in the Sinclair X10, a 10 W audio amplifier available in kit form in the 1960s. At around the same time PWM started to be used in ac motor control.

The VSI (dc/ac converter) converts the dc link voltage into variable frequency and variable magnitude ac voltage source using either sinusoidal PWM or SVM (Kazmierkowski, 2011). In his view, owing to the switch mode operation of semiconductor power switches, the PWM inverters are characterised by very high efficiency and very fast operation, creating a high-quality power amplifier.

According to NEMA (2007), the sine-triangular modulation technique is normally referred to as sine-coded PWM output of a control. This modulation technique uses a symmetrical triangular carrier wave of a higher frequency that is compared with a sinusoidal reference wave of the desired output frequency. The resultant of these two signals is a sine-coded PWM signal from an analogue comparator circuit within the control.

The different PWM techniques that have been employed in PWM-VSD converters are shown in Fig 2.24.

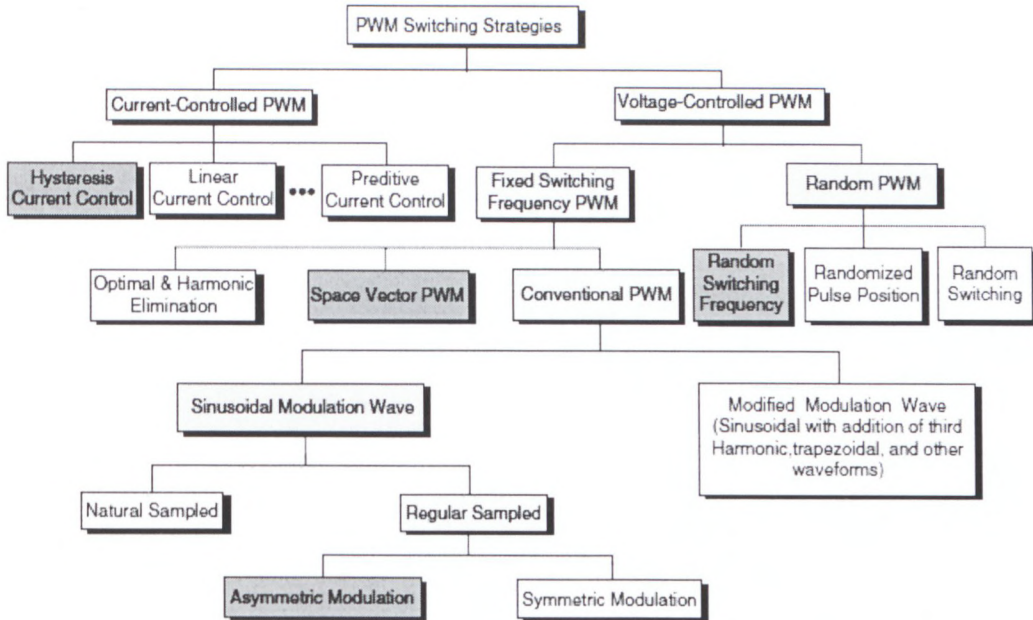


Fig 2.24 Classifications of PWM techniques (Shakweh, 2007)

Also NEMA (2007) asserts that SVM is well suited to digital implementation and produces similar PWM waveforms to those of the sine-triangular method with third harmonic injection. The main advantages of the SVM technique, according to it, are:

- Simple digital calculation of the switching times
- A 15% increase in dc link voltage utilization compared with simple sine-triangular techniques
- Possible lower harmonic content at high modulation indices, compared with simple sine-triangular techniques

The SVM technique does not offer any improved motor torque performance, however, the PWM control algorithms are much simpler to implement in digital PWM type controls (NEMA, 2007).

### 2.5.2.6.5 Control Methods

Based on the space vector description, the induction motor control methods are divided into a scalar and a vector control (Kazmierkowski, 2011).

According to WEG (2010) the scalar control is based on the original concept of a frequency converter: a signal of certain voltage/frequency ratio is imposed onto the motor terminals and

this ratio is kept constant throughout a frequency range, in order to keep the magnetising flux of the motor practically unchanged. It is generally applied when there is no need of fast responses to torque and speed commands and is particularly interesting when there are multiple motors connected to a single drive. The control is open loop and the speed precision obtained is a function of the motor slip, which depends on the load, since the frequency is imposed on the stator windings. In order to improve the performance of the motor at low speeds, some drives make use of special functions such as slip compensation (attenuation of the speed variation as function of load) and torque boost (increase of the V/f ratio to compensate for the voltage drop due to the stator resistance), so that the torque capacity of the motor is maintained. This is the most used control type owing to its simplicity and also to the fact that the majority of applications do not require high precision or fast responses of the speed control. Drives deployed in such applications such as pumps and fans are termed low performance drives.

A squirrel-cage motor is a singly excited machine fed by connection to its stator windings, unlike a dc motor that is doubly excited through its armature and field windings. Therefore ac vector control aims at realising a dc motor control benefits through an ac motor. The vector control enables fast responses and high level of precision on the motor speed and torque control. Robotics makes a good example of an application of vector control. Essentially the motor current is decoupled into two vectors, one to produce the magnetising flux and the other to produce torque, each of them regulated separately. It can be open loop (sensorless) or closed loop (feedback) (WEG, 2010):

- Speed feedback – a speed sensor (for instance, an incremental encoder) is required on the motor. This control mode provides great accuracy on both torque and speed of the motor even at very low (and zero) speeds.
- Sensorless – simpler than the closed loop control, but its action is limited particularly at very low speeds. At higher speeds this control mode is practically as good as the feedback vector control.

NEMA (2007) has classified vector control into direct and indirect vector controls. According to it, a direct field oriented control scheme is one that directly regulates the motor flux vector in order to produce controllable motor torque. Such a scheme could employ the use of Hall - effect transducers or air gap flux-sensing windings for the measurement of the motor-air-gap-flux with the necessary modifications to approximate the rotor flux. The rotor flux would then be used as the feedback in the direct vector control regulator. Conversely, an indirect field oriented control scheme is one that interprets the motor flux vector from other parameters,

such as speed or current. The two types of indirect vector drive control schemes used today are closed-loop or feedback vector control (which requires a speed feedback sensor to provide rotor position feedback) and open loop or sensorless vector (SV) control (monitors motor current instead of using a speed feedback sensor). A closed loop vector drive can provide precise speed control and maximum torque from zero speed to base speed. An open loop vector drive does not have as wide a speed range as a closed loop vector drive and cannot produce holding torque at zero speed.

The general classification of the frequency controllers is presented in Figure 2.25. The figure includes the names of some pioneers in their respective fields of variable frequency control technology.

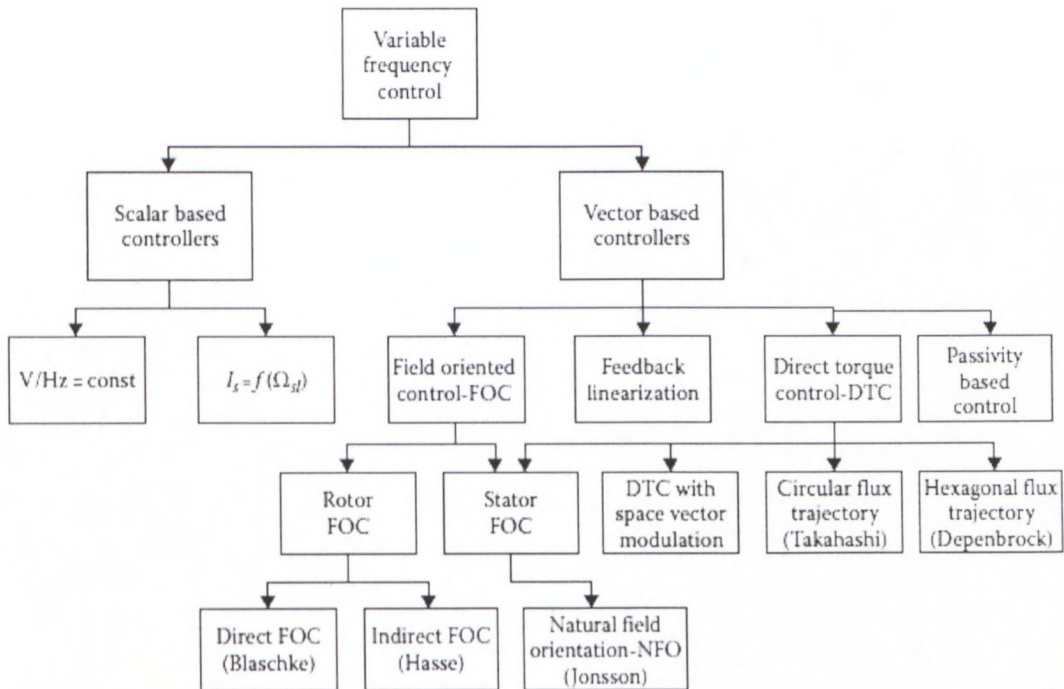


Fig 2.25 General classification of induction motor control methods (Kazmierkowski, 2011)

The main difference between the two control types is that the scalar control considers only the magnitudes of the instantaneous electrical quantities (magnetic flux, current and voltage) referred to the stator, with equations based on the equivalent electrical circuit of the motor, that is, steady state equations. On the other hand, the vector control considers the instantaneous electrical quantities referred to the rotor linkage flux as vectors and its equations are based on the spatial dynamic model of the motor. Plethora of power electronics

books exist that contain in-depth analysis of these equations. The induction motor is seen by the vector control as a dc motor, with torque and flux separately controlled.

### 2.5.2.7 Efficiency

An electric drive is considered to be highly energy efficient. According to NEMA (2007) this is as high as 98% or even higher for most control (drive) sizes. The view of de Almeida et al. (2009) is that VFD efficiency varies by manufacturer and decreases severely under partial load below 40%. Also IEC (2009) has posited that drive efficiency drops at partial load just as with motors as illustrated in Fig. 2.26.

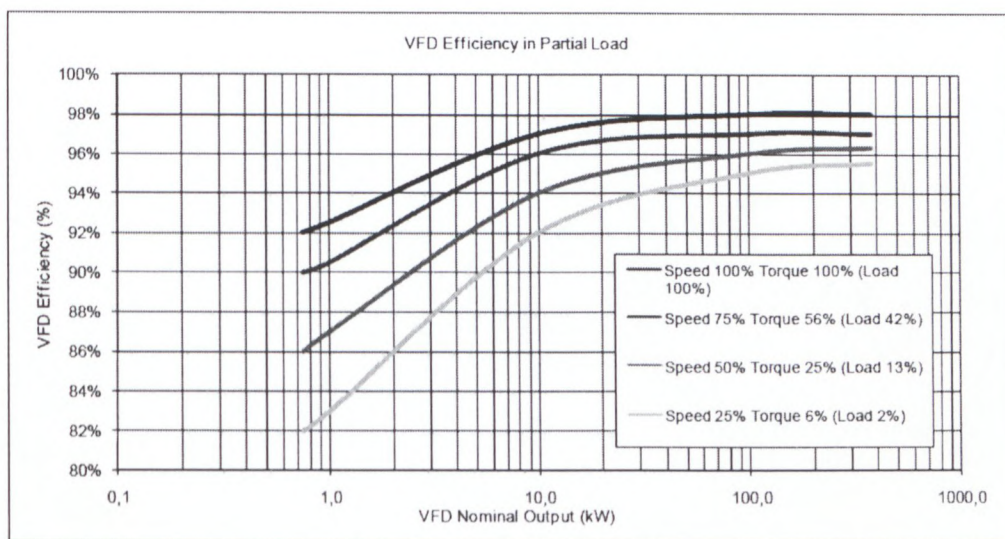


Fig. 2.26 Typical efficiency of indirect three-phase voltage source type converters with a passive front-end (IEC, 2009)

IEC (2009) has estimated drive loss components for the most common industrial converter type (low voltage indirect frequency converters of the voltage source type with uncontrolled three-phase diode rectifiers as line side converter) in the output power range from 1 to 100 kW. This is shown in Table 2.8

A decrease in converter efficiency may lead to a reduced output voltage to the motor. This may prevent the motor from reaching top speed and/or require field weakening operation which will reduce motor efficiency.

Table 2.8 Loss distribution for low-voltage uncontrolled-converters (IEC, 2009)

Losses	Typical percent of losses for passive front-end converters	Factors affecting these losses
Switching losses (output stage)	30 to 50	Motor-current and switching frequency
Line-rectifier losses	20 to 25	Line-current (nearly proportional to motor power)
Forward losses (output stage)	15 to 20	Motor current
Internal control circuit losses (microcontroller, internal power supply, display, keyboard, bus-communication, digital and analogue ins/outs ...)	5 to 20	Nearly constant
Switching losses (line-side converter/ active front-end only)	-	Line-current and switching-frequency (nearly proportional to motor power)
Compound losses (line-side converter/ active front-end only)	-	Line-current (nearly proportional to motor power)

Increasing the switching frequency allows reducing the harmonic distortion and therefore the motor losses. However, the VFD switching losses also increase when the frequency increases. Faster IGBTs allow for increased operation frequency with mitigated losses. Additional losses within the motor due to converter supply are for the most part no-load iron losses. They depend on the switching frequency (typically a user-selectable parameter) and are much different for converters with hysteresis control (de Almeida *et al.*, 2009).

According to Barnes (2003) the selection of the PWM switching frequency is a compromise between the losses in the motor and the losses in the inverter because:

- When the switching frequency is low, the losses in the motor are higher because the current waveform becomes less sinusoidal
- When the switching frequency increases, motor losses are reduced but the losses in the inverter will increase because of the increased number of commutations. Losses in the motor cable also increase due to the leakage current through the shunt capacitance of the cable.

Today, most VFDs for low-voltage (less than 1000 V) use Integrated Gate Bipolar Transistor (IGBT) switches with pulse width modulated signals and switching frequencies between 1 kHz and 20kHz (de Almeida *et al.*, 2009). They maintain that the losses of these inverters are relatively low and their efficiency is typically much better compared to cage-induction motors as shown in Fig. 2.27. The main influencing factors of the total losses are the switching frequency and the output current (which is basically related to output power and load).

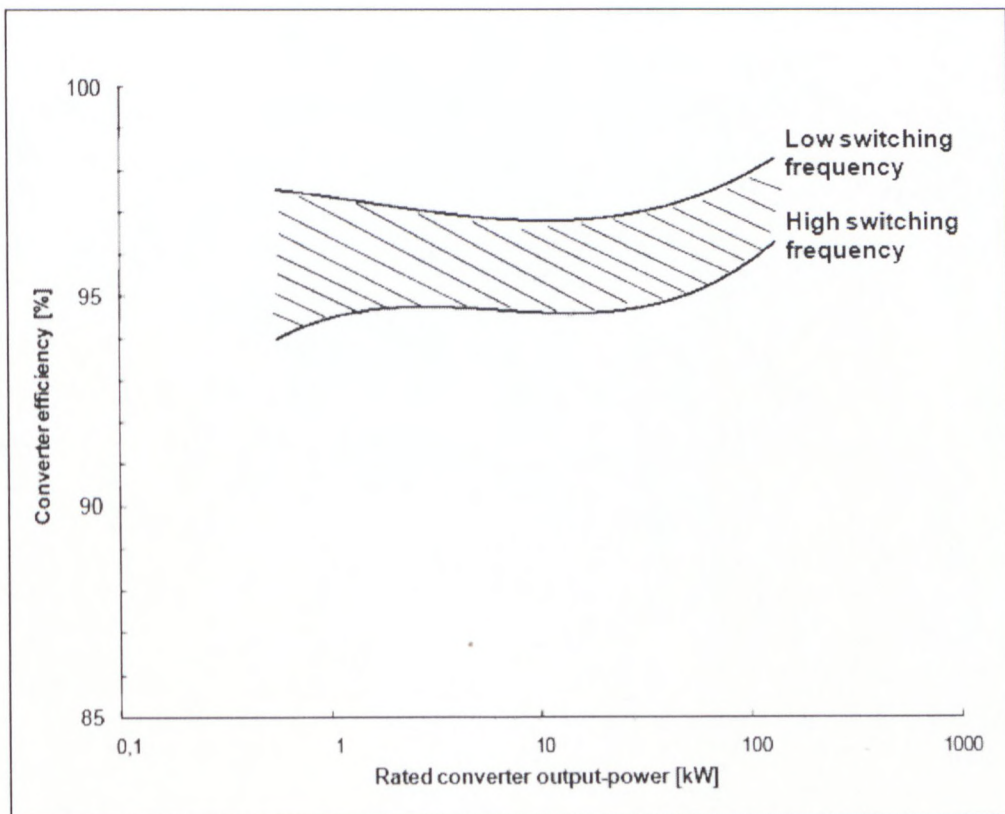


Fig. 2.27 Typical efficiency of low-voltage PWM frequency converters at full-load (de Almeida *et al.*, 2009)

Worthy of note is the definition of IGBT as Integrated Gate Bipolar Transistor by de Almeida *et al.* (2009) against its popular meaning as Insulated Gate Bipolar Transistor. This is also part of the confusion and frustration facing anyone attempting to study ac drive literatures.

According to (US-DOE, 2002) one manufacturer has provided efficiency values for pulse-width modulated VFDs as a function of operating speed for both variable torque loads (centrifugal fans and pumps) and constant torque loads (cranes, hoists). It has observed that there is no widely accepted test protocol that allows for efficiency comparisons between different drive models or brands.

This is corroborated by de Almeida *et al.* (2009) who have noted that to date there is no widely accepted test protocol that allows for efficiency comparison between VFD manufacturers and applications. They have also asserted that little reliable data exist on VFD system efficiencies and there has been no consensus yet for a standard to characterise a VFD system for efficiency at any given operating point. They have demonstrated through the results of their research that VFD efficiencies between manufacturers are comparable at 100%, 75% and 50% speed down to 50% load, although differences exist. These differences may not seem significant, but the difference between a 50hp (37kW) High Efficiency IE2 motor and a Premium Efficiency IE3 motor is only 1.5 percentage points, and therefore consideration should be made to systems that include VFDs at different speeds and loads. At lower speeds and loads, according to them, the difference is greater and depends mainly on the amount of constant losses for each unit.

However a solution is in the offing as the VSD test standard (IEC 60034-2-3) will be adopted later in 2011 (Falkner & Holt, 2011).

### **2.5.2.8 Disadvantages**

Electric drives have disadvantages or adverse effects despite their crucial roles in electric motor speed control and the resultant energy savings. These disadvantages are harmonics and electromagnetic interferences.

According to Barnes (2010) since 1896, when George Westinghouse and Nikola Tesla installed the first power-generation station at Niagara Falls, electric utility companies have developed very efficient methods for:

- Generating megawatts of alternating-current (ac) power.

- Carrying it hundreds of miles, if necessary, from generating plants to users.
- Distributing it to individual incandescent lamps, heaters, electric motors, etc., that draw current in smooth powerline frequency sine waves.

But these power distribution systems, in his view, have difficulty supplying ac power when the major or majority of loads have (switching) power supplies that draw current in short pulses at the peaks of the ac waveform. These ill-behaved loads:

- Distort the ac waveform.
- Can cause fires, from neutral wires overheating.
- Can overstress and shorten the lives of power transformers.
- Can overload ac-power generators.

Equally Arrillaga and Watson (2003) have observed that reducing voltage and current waveform distortion to acceptable levels has been a problem in power system design from the early days of alternating current. The recent growing concern results from the increasing use of power electronic devices and of waveform-sensitive load equipment.

### 2.5.2.8.1 Harmonics

Harmonic effects of drives are the consequence of their non-linearity as loads on the power system especially on the part of the rectifier. Rectifiers draw a non-sinusoidal current and thereby distort the ac voltage in the power supply system. From a harmonics point of view, it does not matter if the rectifier bridge comprises of thyristors (controlled rectifier) or diodes (uncontrolled rectifier), they both behave similarly (Barnes, 2003).

Harmonics are voltage and current frequencies in the electrical system that are multiples of the fundamental frequency (EC, 2000; Arrillaga & Watson, 2003; WEG, 2010). This fundamental frequency is 60 Hz in USA and 50 Hz in European and South African power systems. The characteristic harmonics generally produced by the rectifier on the power line are considered to be of the order given by Eqn. 2.22

$$h = np \pm 1 \quad (2.22)$$

where, h = order of the harmonics present; n = an integer (1, 2, 3, 4, 5...); p = number of pulses or rectifiers

In the view of Square (1994) the degree and magnitude of the harmonics created by the VFD is a function of the drive design and the interrelationship of the non-linear load with the connected distribution system impedance. But Barnes (2003) has posited that the level of the harmonic distortion generated by VSDs depends on a large number of variables, some of which are often difficult to quantify, such as:

- The magnitude of the current flowing through the converter
- The configuration of the power electronic circuit (6-pulse, 12-pulse, etc)
- The characteristics and impedances of the connected power supply system

In the case of a 6 diode (6 pulses) bridge, the most pronounced generated harmonics are the 5<sup>th</sup> and the 7<sup>th</sup> ones, whose magnitudes may vary from 10% to 40% of the fundamental component, depending on the power line impedance (WEG, 2010). In the case of rectifying bridges of 12 pulses (12 diodes), the most harmful harmonics generated are the 11<sup>th</sup> and the 13<sup>th</sup> ones. The higher the order of the harmonic, the lower can be considered its magnitude, so higher order harmonics can be filtered more easily.

EC (2000) has noted that other most common sources of power electronics harmonic distortion are found in computers, office equipment, electronic equipment using switch-mode power supplies, arc furnaces and high-efficiency electronic light ballasts. Furthermore, harmonics often come, too, from poor-quality line power – an increasingly important issue for many utilities. Harmonic waveforms are characterised by their amplitude and harmonic number. Fig. 2.28 shows how the 50 Hz fundamental changes when harmonics are added. The combined waveform reflects combination of fundamental frequency and harmonics.

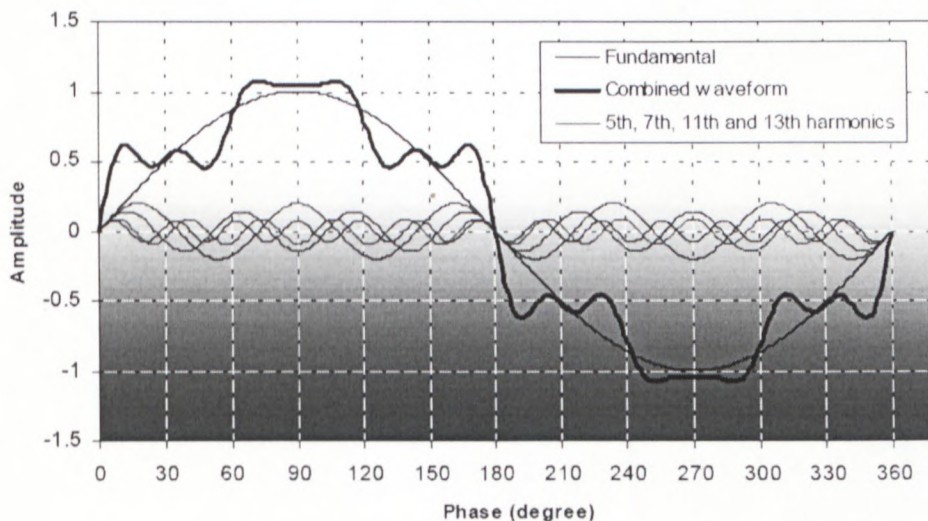


Fig. 2.28 Waveform with VSD harmonics (EC, 2000)

EC (2000) and WEG (2010) have attempted to differentiate between voltage and current harmonics. According to WEG (2010) an electric motor fed by frequency inverter sees a pulsating voltage and a practically sinusoidal current, so that the voltage harmonics generally present higher magnitudes than the current harmonics. In other words, as EC (2000) has noted, the current harmonics are one order of magnitude larger than the voltage harmonics. But Cividino (1992) while subscribing to the division of harmonic distortion into two classes – voltage distortion and current distortion – noted that since the voltage is common to all loads in a system, any voltage distortion would result in a corresponding current distortion assuming the source impedance is very low. On the other hand, current distortion results in voltage distortion only to the extent that the source impedance provides a common coupling impedance.

According to Jasinski and Kazmierkowski (2011) the recommended voltage distortion limits, usually expressed by THD index, where THD is total (RSS) harmonic voltage in percent of nominal fundamental frequency voltage. This term has come into common usage to define either voltage or current DF as shown in Eqn. 2.23. The DF is the ratio of the RSS of the harmonic content to the RMS value of the fundamental quantity, expressed as a percent of the fundamental.

$$THD = \sqrt{\frac{\sum_{h=2}^{50} U_{L(h)}^2}{U_{L(1)}^2}} 100\% \quad (2.23)$$

where:  $U_{L(h)}$  = harmonic voltage;  $U_{L(1)}$  = nominal fundamental frequency voltage

For most applications, it is sufficient to consider the harmonic range from the 2<sup>nd</sup> to the 25<sup>th</sup>, but most standards specify up to the 50<sup>th</sup> (Arrillaga & Watson, 2003).

However, Eqn. 2.24 shows a common formula for THD

$$THD = \sqrt{\sum_{h=2}^{\infty} \left(\frac{A_h}{A_1}\right)^2} \quad (2.24)$$

where:  $A_h$  = rms values of the non-fundamental harmonic components;  $A_1$  = rms value of the fundamental component

Harmonic currents cause distortion of the mains voltage waveform that affects the performance of other equipment and creates additional losses and heating. Even small power ASD can cause a THD problem for a supply line when a large number of nonlinear loads are connected to one point of common coupling (PCC) (Jasinski & Kazmierkowski, 2011). This increase in equipment losses has raised concerns about excessive currents and heating in transformers and neutral conductors (EC, 2000). For example, a total harmonic voltage distortion of 2.5% can cause an additional temperature rise of 4°C in induction motors. Consequently, Barnes (2003) has suggested that transformers, motors, cables, busbars and switchgear supplying current to converters should be de-rated (over-dimensioned) to accommodate the additional harmonic currents and the extra losses associated with the high frequency 'skin-effect'. According to him, experience has shown that the current rating of transformers, cables, etc feeding 6-pulse converters must be de-rated by roughly 10% of the converter current and those feeding 12-pulse converters by roughly 5% of the converter rated current.

Furthermore, the effects of three-phase harmonics on circuits are similar to the effects of stress and high blood pressure on the human body (Square, 1994). This is because high levels of stress or harmonic distortion can lead to problems for the utility's distribution system, plant distribution system and any other equipment serviced by that distribution system. The effects could range from spurious operation of equipment to a shutdown of important plant equipment, such as machines or assembly lines.

#### **2.5.2.8.2 Electromagnetic Interference (EMI)**

EMI owes its adverse effects on close electrical and electronic equipments to the high switching frequency of the drive inverters. EMI is sometimes also referred to as RFI. The latter is an 'old-fashioned' term and its continued use is being discouraged in the standards (Barnes, 2003). Such equipments susceptible to EMI include instrumentation, electronic control and communications devices, which operate at low voltages and high speeds.

According to ABB (2011b) the source of high-frequency emission from frequency converters is the fast switching of power components such as IGBTs and control electronics. This high-frequency emission can propagate by conduction and radiation. Barnes (2003) asserts that most modern ac converters use a VSI to generate a pulse width modulated output voltage. In his view, with the introduction of high frequency switching above 1 kHz, the harmonics on

the motor side are in the frequency spectrums from 10 kHz up to 20 MHz, which is well into the RFI spectrum (>100 kHz). In contrast to the supply side of the converter, the motor side harmonics are mainly high frequency voltages (high  $dv/dt$ ), which radiate an electric field. He further notes that the mathematical analysis of these frequencies is complex and affected by many variables, certainly not as easy as the calculation of supply side harmonics.

The interference generated by the PWM inverter on the motor side and radiated from the motor cable and the converter itself depends on (Barnes, 2003):

- The inverter output frequency range
- The PWM switching frequency (typically 2 kHz to 20 kHz)
- The architecture of the inverter, e.g. the internal screening, mechanical details, inductance in motor leads, etc

Some of these can pass through the dc link and emerge on the supply side. RFI Filters are now commonly used to prevent this interference being conducted back into the mains.

The challenge posed by the high switching frequencies of drive inverters has resulted to a measure aimed at determining how friendly a drive is to its host environment. This measure is called EMC. According to Barnes (2003) products are said to be electromagnetically compatible when they can operate together in the same environment, with limits imposed on those devices that radiate interference and higher levels of immunity for the equipment, which is susceptible being above these limits. Also ABB (2011b) defines EMC as the ability of electrical/electronic equipment to operate without problems within an electromagnetic environment. Likewise, the equipment must not disturb or interfere with any other product or system within its locality. According to it this is a legal requirement for all equipment taken into service within the European Economic Area (EEA).

Electromagnetic compatibility levels are recognised as the levels of severity of electromagnetic disturbance which can exist in any relevant environment (Arrillaga & Watson, 2003). Therefore, according to them, all equipment intended to operate in that environment is required to have immunity at least at that level of disturbance and, thus, a margin appropriate to the equipment concerned is normally provided between the compatibility and immunity levels.

The terms used to define electromagnetic compatibility are shown in Fig. 2.29.

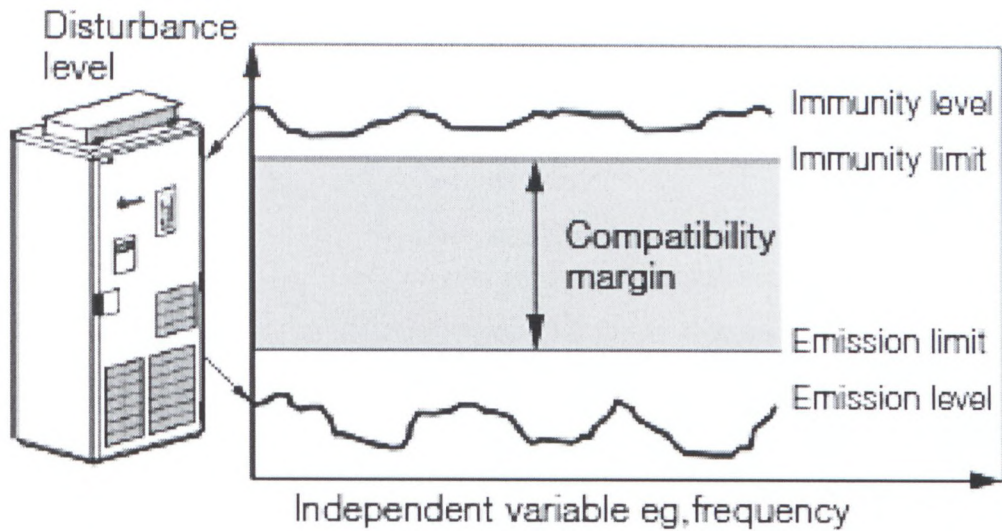


Fig. 2.29 Immunity and emission compatibility (ABB, 2011b)

ABB (2011b) has equally asserted that as variable speed drives are described as a source of interference, it is natural that all parts which are in electrical or airborne connection within the PDS are part of the EMC compliance. This assertion is hinged on the obvious concept that a system is as weak as its weakest point.

Unarguably, electrical equipment should be immune to high-frequency and low-frequency phenomena. According to ABB (2011b) high-frequency phenomena include ESD, fast transient burst, radiated electromagnetic field, conducted radio frequency disturbance and electrical surge. Typical low-frequency phenomena are mains voltage harmonics, notches and imbalance.

### 2.5.2.8.3 Standards

Most countries have in the past developed their own harmonic standards or recommendations, to suit local conditions (Arrillaga & Watson, 2003). While considering the factors that influence the development of standards, they have noted that the development of harmonic standards is centred on the following issues:

- description and characterisation of the phenomenon;
- major sources of harmonic problems;
- impact on other equipment and on the power system;

- mathematical description of the phenomenon using indices or statistical analysis to provide a quantitative assessment of its significance;
- measurement techniques and guidelines;
- emission limits for different types and classes of equipment;
- immunity or tolerance level of different types of equipment;
- testing methods and procedures for compliance with the limits;
- mitigation guidelines.

However, two standards namely IEEE 519-1992 and IEC 61000 series have received wide acceptability. To be more specific Jasinski and Kazmierkowski (2011) have observed the existence of standard regulations such as IEEE Standard 519-1992 in the United States and IEC 61000-3-2/IEC 61000-3-4 in the European Union. Arrillaga and Watson (2003) have posited that the IEC 61000 series includes harmonics and inter-harmonics as one of the conducted low-frequency electromagnetic phenomena. According to them a widespread alternative to the IEC series is the IEEE 519–1992 document, which provides guidelines on harmonics.

Halpin (2005) believes that IEEE Standard 519-1992 is a mature document at this time and contains widely-adopted recommendations for harmonic control in electric power systems. Similarly, IEC Standard 61000-3-6 is also widely recognised. In both IEEE and IEC, the ultimate goal of harmonic control is to insure voltage quality. However, according to him, IEEE and IEC approach the issue of allocating customer harmonic current production differently. A key question is whether or not the results of each approach ultimately arrive at the same conclusion. Consequently he has pointed out the importance of summarising their similarities and differences in the following major areas:

- Driving principle
- Voltage harmonic limits
- Current harmonic limits
- Even-order harmonics
- Non-characteristic harmonics
- Time-varying harmonics
- Inter-harmonics

While the international standards are used as a basis for global co-ordination, individual countries make their own adjustments to accommodate various national priorities (Arrillaga &

Watson, 2003). These are normally motivated by the special characteristics of their power system configuration and load management (e.g. the use of ripple control in some countries).

According to Rao (2008) different governments, organisations and authorities have formulated various EMC standards with a view to achieve electromagnetic compatibility in various environments or platforms with the aim of containing the ever increasing threat of electromagnetic pollution. In most of these cases compliance with these standards is mandatory. The opinion of WEG (2010) is that there is no international standardisation defining maximum acceptable values for voltage and current harmonic distortion for the drive output harmonics – electromagnetic interference. However, the international standards do consider the increase of motor losses due to the non-sinusoidal supply.

The IEC standards on EMC are mostly part of the IEC 61000 series. According to WEG (2010) the EMC Product Standard for PDSs, EN 61800-3 (or IEC 61800-3) is used as the main standard for variable speed drives. Unlike the drive input harmonics, IEEE does not have an equivalent standard for IEC 61800-3 or the like.

Consequently IEEE (2011) has proposed two standards namely IEEE P1836™ and IEEE P1837™. Proposed standard IEEE P1836™ – Standard for Electromagnetic Compatibility (EMC) - Limits for Harmonic Current Emissions Produced by Equipment Connected to Public Low-Voltage Systems with Input Current  $\leq 16$  A Per Phase – will establish limits for equipment and create methodologies for testing and simulation. Also proposed standard IEEE P1837™ – Standard for Electromagnetic Compatibility (EMC) - Limits for Harmonic Current Emissions Produced by Equipment Connected to Public Low-Voltage Systems with Input Current  $>16$  and  $\leq 75$  A Per Phase – has the same general thrust. Both standards will take the cost of corrective action into consideration and apply the principles of lowest cost solutions. Both standards, according to it, will address harmonic injection in 60Hz and 120V/240V systems such as those in use in the United States, Canada and other regions of the world. Both standards will also use the IEC SC77A and IEC 61000-3-12 standards as seed documents. In addition, the IEEE has initiated a project to revise the standard covering procedures and equipment used to measure electromagnetic emissions. The present standard, IEEE P1309™ – Standard for Calibration of Electromagnetic Field Sensors and Probes, Excluding Antennas, from 9 kHz to 40 GHz – will be revised because it has been learnt that in some situations RF probes may return values that are significantly different from the calibrated response.

According to Rao (2008) EMC standard proliferation has created problems of implementation of EMC design and EMC testing. This is particularly true for products which have multiple

applications in different environments such as industrial, automobile, ship, aircraft or military environment. He asserts that applying different standards for the same product results in escalation of cost of the product as the product has to be designed for worst case conditions and also increase in testing costs to test for compliance with different standards for the same product. Hence, there is an imperative need to reduce the number of standards and also to standardise the test methods. However, with the growth of global trade, the need for equipment manufactured in one country to comply with standards in another has prompted concerted effort in formulating international standards on harmonics and inter-harmonics (Arrillaga & Watson, 2003). The rationale is to maintain a globally acceptable electromagnetic environment that co-ordinates the setting of emission and immunity limits.

The above views of Rao (2008), and Arrillaga and Watson (2003) in addition to the proposed IEEE EMC standards using IEC 61000-3-12 as a reference material imply that sooner or later there would be a harmonisation of the harmonic and EMC standards.

**2.5.2.8.4 Mitigation Measures**

Harmonics reduction methods can be divided into two main groups (Jasinski & Kazmierkowski, 2011) as shown in Fig. 2.30 where CSR and VSR are current source and voltage source rectifier respectively. These two main groups are:

- (a) Passive filters and active filters: harmonics reduction of the already installed nonlinear loads
- (b) Multi-pulse rectifiers and VSR (active rectifiers): power-grid friendly converters (with limited THD)

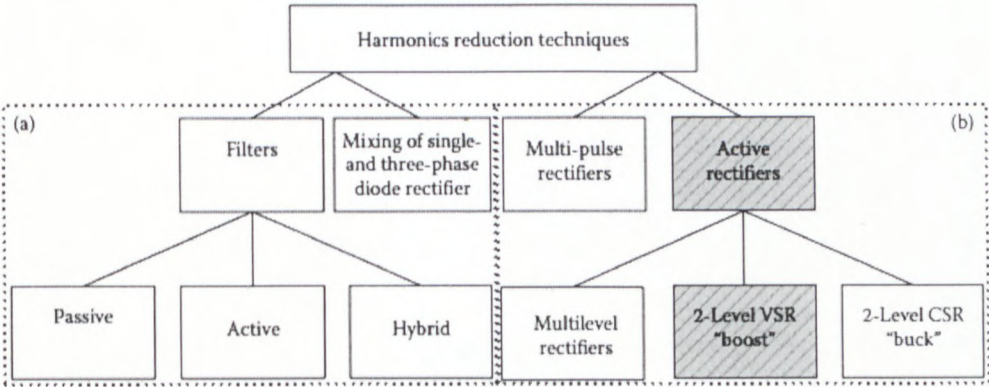


Fig. 2.30 Harmonics reduction techniques (Jasinski & Kazmierkowski, 2011)

In order to reduce supply harmonics that are generated by VSDs, equipped with a 6-pulse diode bridge rectifier, VSD equipment manufacturers adopt various techniques (Shakweh, 2007). Table 2.9 summarises the most common methods including their advantages and disadvantages.

Table 2.9 Techniques used to reduce supply harmonics (Shakweh, 2007)

<b>Topology</b>	<b>Advantage</b>	<b>Disadvantage</b>
6-pulse bridge with a choke	Least expensive – Low cost Known technology Simple to apply	Bulky Too large a value can reduce available torque  Only applies to the drive Least effective method of filtering
12-pulse bridge	Eliminate the 5,7,17,19 harmonics Known technology Simple to apply	Bulky and expensive Only applies to the drive  A lot of 12-pulse drives on one site will shift the problem to the 11 <sup>th</sup> and 13 <sup>th</sup> harmonics
6-pulse fully controlled active front-end	Commercial filtering for the drive Cancels all low order harmonics	Very expensive Not widely available New technology
Harmonic filters	Filters the installation Reduces the harmonics at the point of common coupling Least expensive filter to install	Needs a site survey Only sized to the existing load
Active filter	Intelligent filter Extremely efficient  Can be used globally or locally  More than one device can be installed on the same supply	Very expensive

According to Shakweh (2007) the techniques used to reduce the effect of VSD output harmonics include installation of output line reactor, sine-wave filter, PWM (dV/dt) filter, and RC filter at motor terminals. In his view a reactor increases the rise time but the benefit of its connection may be negated as follows:

- Beneficial connection if cable length is short enough for reflections to be superimposed within rise time, i.e. if rise time is increased beyond critical value of cable length.
- Harmful connection if cable length is too long, the reactor may have negligible effect on peak voltage (theoretically its presence is insignificant in this case) or ringing period but it will increase the duration of each overshoot, thus increasing the probability of partial discharge.

Also Shakweh (2007) views sine-wave filter as a mechanism that filters the PWM carrier frequency; thus the converter output voltages are sinusoidal. This type of filter, according to him, is best suited for low performance drives and/or retrofit applications (old or standard motors). He has noted the practical consequences of employing a filter at the inverter output to include:

- Cost and weight of filter
- Filter power losses, voltage drop
- A small de-rating of power switches due to circulating current between filter  $L$ ,  $C$ , and DC link capacitor
- Reduced torque response due to time delay in the filter, sine-wave type
- Potential oscillations which have to be electronically dampened
- Potential induction motor self excitation

Table 2.10 gives an overview of the different techniques deployed to counter the effects of electromagnetic interference.

Table 2.10 An overview of technique used as a counter measure to EMI (Shakweh, 2007).

Effect	Frequency range (f)	Counter measure	
		At source	At load
Main	$\leq 100$ Hz	Avoid circulating currents	Balanced signal circuits Avoid earth loops in signal paths Screening (electric field only)
Mains harmonics	$100 < f \leq 2.5$ kHz	Line and/or dc link reactor on rectifiers. Higher pulse number rectifier (e.g 12, 18, or 24). Low impedance supply Harmonic filters.	Balanced signal circuits  Avoid earth loops in signal paths Filtering
Intermediate	$2.5 < f \leq 150$ kHz	Filters	Filtering Screening Balanced signal circuits
Low-frequency	$150 < f \leq 30$ MHz	Filters - one per apparatus. Cable screening	Filtering Screening
High frequency	$30 \text{ MHz} < f \leq 1 \text{ GHz}$	Screening Internal filtering	Screening

The summary of some of the protection features that can be used to improve the harmonic and EMI performance of an AC variable speed drive system is shown in Fig. 2.31.

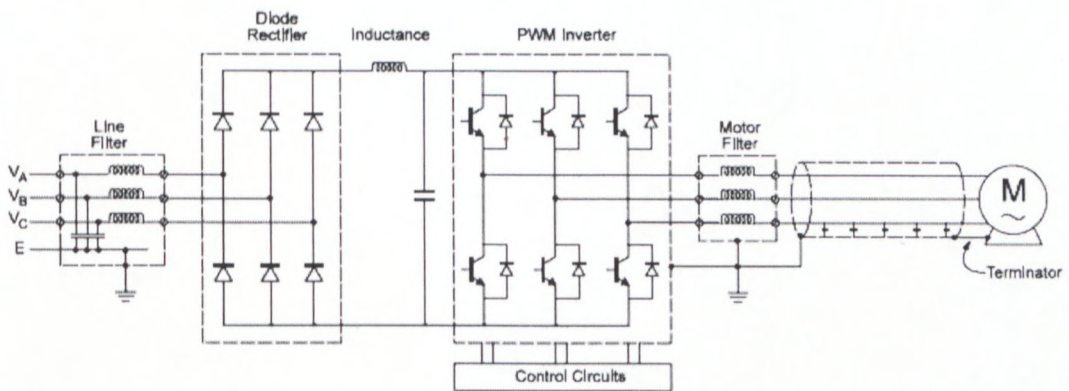


Fig. 2.31 An ac drive fitted with line-side and motor-side filters (Barnes, 2003)

## **2.6 Conclusion**

An in-depth literature study has been attempted to highlight some of the salient issues affecting energy efficiency in parallel operation of pumps deploying VSD. Among such issues are the interchangeability of energy efficiency and conservation, and the different definitions of electric drive. Also more emphasis is given to electric motor efficiency improvement (standards and classifications) to the neglect of pumps and VSD. However, a system or holistic approach to efficiency improvement of EMDS would ensure a better reward from energy efficiency improvement strategies.

The current trend in the harmonisation of different standards such as classifications and testing methodology of motor efficiency and EMC would ensure global equipment acceptability. This equally would raise the reliability of equipments from certain regions of the world.

## CHAPTER 3: BASIC PUMPING CONCEPTS AND PARALLEL PUMPING

### 3.1 Introduction

Parallel pumping is the concept of cascading and simultaneous operation of two or more pumps to achieve a common discharge (output) with or without a common suction (input). The major essence of parallel pumping is an increase in flow rate or pressure than would be possible with a single fixed-speed pump especially for systems with widely varying flow demand. Therefore, this chapter considers the prerequisite conditions for parallel pumping and also highlights some deployments of parallel pumping in the City of Cape Town.

### 3.2 System Characteristics

The obvious function of a pump is the transfer of fluid through a piping system from a source to a required destination. Examples of this are the filling of a high reservoir or the circulation of liquid around a system as a means of heat transfer. Pumps used for liquid circulation are commonly called circulators.

The realisation of a required flow rate depends on the availability of the needed increased pressure – force per unit area. Pressure and flow rate are analogous to voltage and current flow respectively. According to Volk (2005), there are actually three distinct reasons for raising the pressure of a liquid with a pump, plus another related factor:

- **Static elevation:** A liquid's pressure must be increased to raise the liquid from one elevation to a higher elevation. This might be necessary, for example, to move liquid from one floor of a building to a higher floor, or to pump liquid up a hill.
- **Friction:** It is necessary to increase the pressure of a liquid to move the liquid through a piping system and overcome frictional losses. Liquid moving through a system of pipes, valves, and fittings experiences frictional losses along the way. These losses vary with the geometry and material of the pipe, valves, and fittings, with the viscosity and density of the liquid, and with the flow rate.
- **Process:** In some systems it is necessary to increase the pressure of the liquid for process reasons. In addition to moving the liquid over changes in elevation and through a piping system, the pressure of a liquid must often be increased to move the liquid into a pressurised vessel, such as a boiler or fractioning tower, or into a

pressurised pipeline. Or, it may be necessary to overcome a vacuum in the supply vessel.

- Velocity: There is another factor to be considered here, namely that not all of the velocity energy in a pump is converted to potential or pressure energy. The outlet or discharge connection of most pumps is smaller than the inlet or suction connection. Because liquids are, practically speaking, incompressible, the velocity of the liquid leaving the pump is higher than that entering the pump. This velocity head may need to be taken into account (depending on the point of reference) when computing pump total head to meet system requirements.

A comprehension of pumping system characteristics requires proper understanding of the relationship between pressure and head. It is common for most plant engineers and those involved in operations to speak of the pressure of the fluid at various points in the process. Pressure units of measurement are kilopascal (kPa), bar, or kilogram per square centimetre ( $\text{kg}/\text{cm}^2$ ) in the SI (metric) system but it is psi (pounds per square inch, sometimes simply called “pounds”) in the United States Customary System (USCS). The head is measured in metres (m).

In the study of pump hydraulics, it is important to realise that any pressure expressed in psi (kPa) is equivalent to a static column of liquid expressed in feet (meters) of head (Volk, 2005). This is not meant to imply that pressure and head are interchangeable terms, because conceptually head is a specific energy term and pressure is a force applied to an area. When applying centrifugal pumps, pressures should be expressed in units of feet (meters) of head rather than in psi (kPa). For positive displacement pumps, the conversion to feet (meter) of head is not made, and pressures are expressed in psi (kPa).

A pumping system is commonly characterised or analysed with a graphical representation of the relationship between the pressure or head and the flow rate. As highlighted above the losses associated with the pumping system are basically static and frictional head losses. The static head is simply the difference in height of the supply and destination reservoirs. In most cases, static head is normally measured from the surface of the liquid in the supply vessel to the surface of the liquid in the vessel where the liquid is being delivered. This means that for a pump in a closed loop system, the total static head is zero. Static head accounts for the pressure changes due to gravity thereby making it independent of flow. Thus the *pure lift* system head-flow curve is a horizontal straight line as shown in Fig. 3.1. The gravity head is evaluated from the change in elevation in the system.

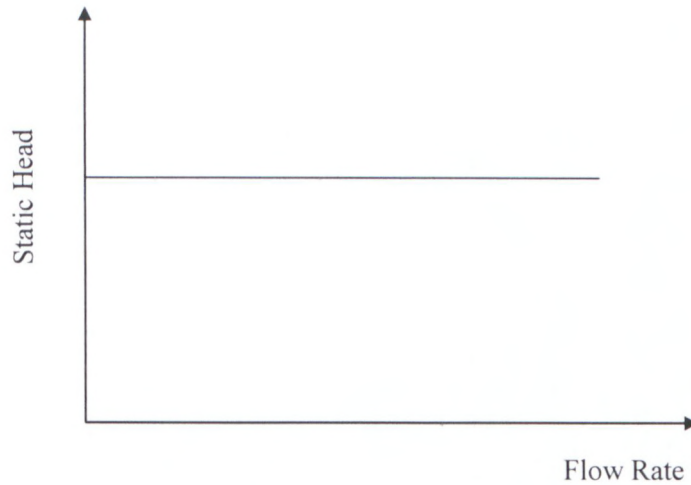


Fig. 3.1 Static Head vs. Flow rate

Friction head (sometimes called dynamic head loss) is the friction loss on the liquid being moved, in pipes, valves and equipment in the system. Essentially, any flow restriction requires a pressure gradient to overcome it. From the fundamentals of hydraulics based on the Bernoulli equation, a pressure drop (hydraulic loss) is proportional to velocity head thus (Nelik, 1999):

$$h_{loss} = K \frac{V^2}{2g} \quad (3.1)$$

where K (resistance coefficient) is a constant available in hydraulics books, V is flow velocity, and g is acceleration due to gravity.

For the flow of fluid through a duct such as pipe, the velocity is given by Eqn. 3.2

$$V = \frac{Q}{A} \quad (3.2)$$

where Q is the flow rate and A is the cross sectional area of the duct.

A comparison of Eqns. 3.1 and 3.2 shows that the pressure loss is proportional to the square of flow

$$h_{loss} \propto Q^2 \quad (3.3)$$

A plot of Eqn. 3.3 yields a parabola as shown in Fig. 3.2

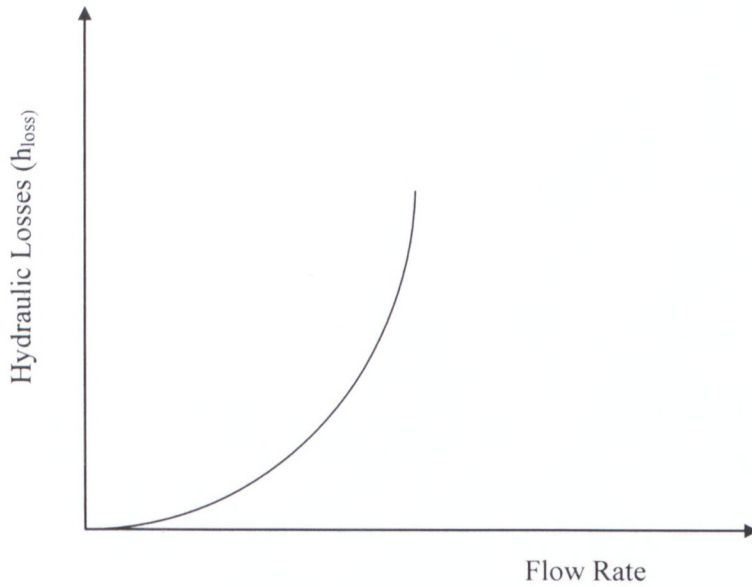


Fig. 3.2 Friction Head ( $h_{\text{loss}}$ ) vs. Flow Rate

An *all-friction* system head versus flow curve, with no static lift, starts at zero flow and head. A good example of this is a closed loop circulating system without a surface open to atmospheric pressure which exhibit the same system head loss vs. flow rate characteristic curve as Fig. 3.2. The system curve with pure friction becomes steeper as flow rate increases.

All actual flow systems have some frictional pressure drop and some elevation change. Thus all system head-flow curves may be treated as the sum of a frictional component and a static-lift component. The head for the complete system at any flow rate is the sum of the frictional and lift heads as shown in Fig. 3.3. The ratio of static to friction head over the operating range influences the benefits accruing from variable speed drive application.

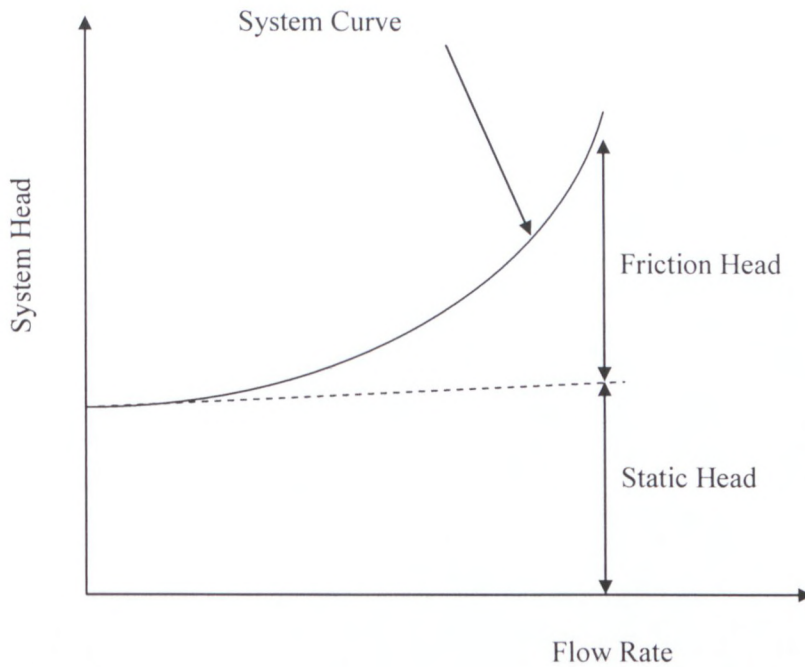


Fig. 3.3 System Head vs. Flow Rate

According to CT (2002) static head is a characteristic of the specific installation and reducing this head where this is possible, generally helps both the cost of the installation and the cost of pumping the liquid. Friction head losses must be minimised to reduce pumping cost, but after eliminating unnecessary pipe-fittings and length, further reduction in friction head will require larger pipe, which adds to installation cost.

### 3.3 Pump Characteristics

The performance of a pump can also be expressed graphically as head against flow rate. In other words a pump curve shows a relationship between its two main parameters namely pressure or head and flow rate. The shape of this curve depends on the particular pump type.

According to Rishel (2002), the pressure or head that is developed by any pump depends on the flow through that pump. This basic head-flow relationship is called the pump's head-flow curve. In the past, this was called the *head-capacity* curve. Head-Flow curve for a pump results after all of the losses are accounted for in the pump. These losses are

- mechanical,

- leakage,
- hydraulic, and
- recirculation.

Fig. 3.4 illustrates the curves of centrifugal and positive displacement pumps.

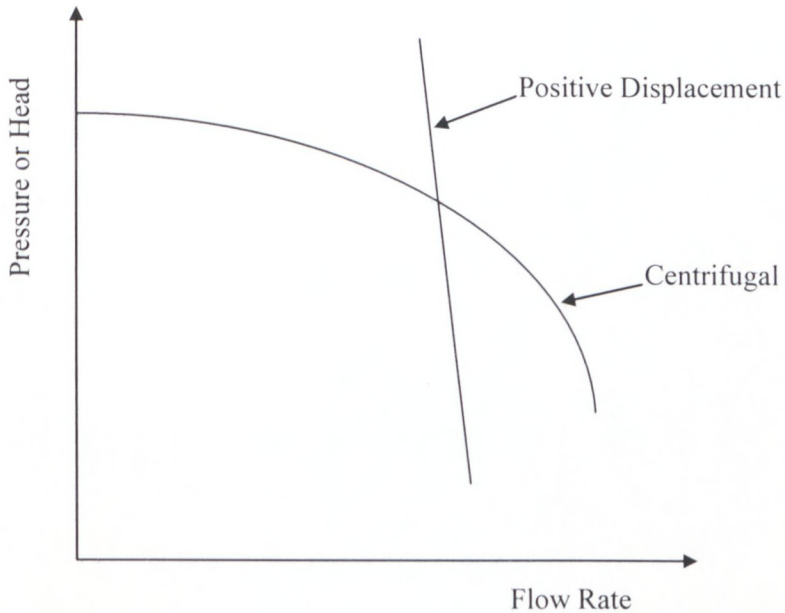


Fig. 3.4 Pump characteristic curves

The kinetic pumps represented by the centrifugal pump have curves where the head falls gradually with increasing flow, but for the positive displacement pump, the flow is almost constant irrespective of the head. There is a difference between the theoretical and actual flows in positive displacement pumps. This could be likened to the speed difference between an induction electric motor rotor speed and the speed of the electromagnetic field of the stator. This difference in flow called slip occurs because of the leakage of the fluid from the high pressure side to the low pressure side of the pump. Slip varies strongly with differential pressure and viscosity and, to some extent, with speed (Nelik, 1999). It is directly proportional to differential pressure but varies asymptotically with viscosity, approaching zero slip at high viscosities. Slip varies inversely with speed to a small extent, but this is normally ignored, and predictions are made slightly conservatively at higher speeds.

Therefore, it is customary to draw the curve for positive displacement pumps with the axes reversed as shown in Fig. 3.5.

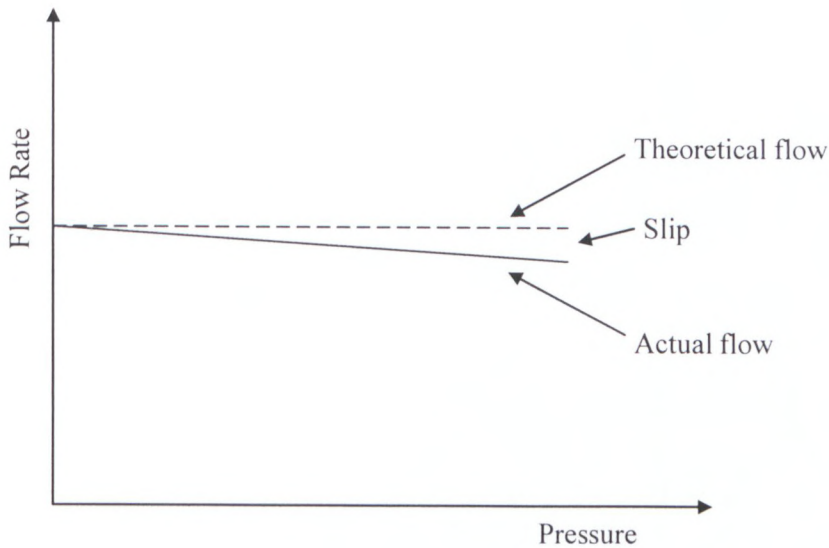


Fig. 3.5 Conventional positive displacement pump curve

If a pump has a head-flow curve that drops at lower flows, it is said to have a drooping characteristic. Therefore a centrifugal pump has a continuously rising characteristic curve, as the head increases continuously to the shutoff or no-flow condition.

A centrifugal pump performance curve may be modelled within engineering accuracy by the parabolic relationship (Fox et al., 2011):

$$H = H_0 - AQ^2 \quad (3.4)$$

where,  $H$  = total head developed;  $H_0$  = the ideal head developed by the pump for zero flow rate (i.e. the shutoff head);  $A$  = the slope of the curve of head versus square of flow rate

Rishel (2002) has noted that most pump head-flow curves provided by the pump manufacturers are for an induction motor operating fully loaded at constant speeds such as 710, 875, 1150, 1750, and 3500 rpm. According to him, the advent of high-efficiency motors has changed these traditional speeds to higher speeds for the new motors. For example, pump curves are now offered at motor speeds such as 715, 885, 1170, 1785, and 3550 rpm. He is of

the view that it is imperative for the water system designer to verify the actual full-load speed of the motor under consideration.

The shape of the pump curve was of great concern when mechanical control systems for pumps were popular (Rishel, 2002; Volk, 2005). It was desired to have relatively steep pump curves for these operations so that a minor change in system head would not make a great change in system flow. Steep curves were preferred, and flat-curved pumps were avoided. A flat-curved pump may create instability in the operation of some self-operating control valves. Such is not the case with most electronic controls for pumps. With the advent of electronic controls, there is very little need to be concerned about the shape of the pump curve. Peak efficiency is what is sought, not the shape of the curve. In fact, flat-curved pumps are desired in order to eliminate the rise to shutoff head for constant-speed pumps that are operating on variable-flow systems provided that they are equipped with electronic pressure controllers. Pumps with flat-curved, head-flow characteristics should be sought for variable-speed pumping applications provided there is no loss in pump efficiency. There is less speed reduction with a flat-curved, variable-speed pump than one with a steep curve. With this lessened speed reduction, the wire-to-shaft efficiency of the variable-speed drive and motor is greater throughout the speed range.

### **3.4 Pump Operating Point**

The superimposition of the system and pump curves gives a graphical illustration of the effect of pump installation in a system. The pump operating point is an intersection of the pump curve and system curve. This is similar to the equilibrium price established by the interaction and intersection of supply and demand curves in economics. If the actual system curve is different in reality to that calculated, the pump will operate at a flow and head different to that expected.

According to Volk (2005) pump is rather an illiterate machine and does not know what head and flow it is supposed to deliver. The pump only knows the shape of its head-capacity curve based on its speed and impeller geometry, and that it operates wherever on the H-Q curve the system tells it to operate. This may be an operating point quite different from the rated point shown on the nameplate. Furthermore, the point at which the pump operates on its H-Q curve may change as system conditions change.

An illustration of the operating point of a centrifugal pump is shown in Fig. 3.6. As can be deduced from the diagram an increasing system resistance will reduce the flow, eventually to zero, but the maximum head is limited as shown. According to CT (2002) this condition is only acceptable for a short period without causing problems.

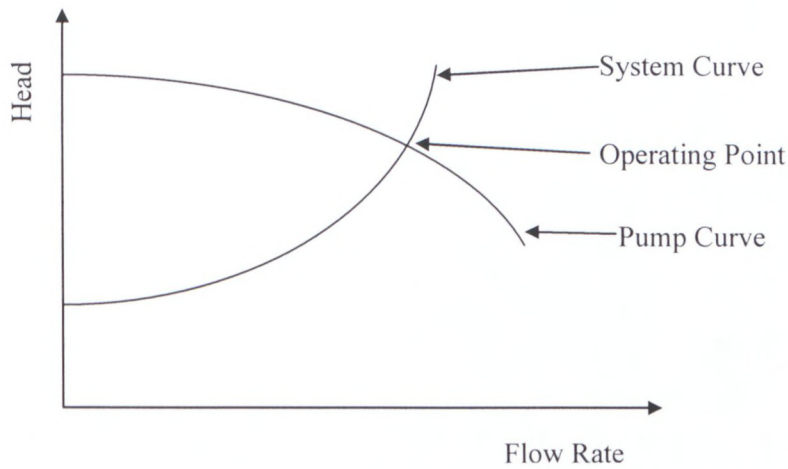


Fig. 3.6 Illustration of centrifugal pump operating point

Equally Fig. 3.7 illustrates the operating point of a typical positive displacement pump. For a pump of this type, if the system resistance increases, the pump will increase its discharge pressure and maintain a fairly constant flow rate, dependent on viscosity and pump type. This condition could result to an unsafe pressure level in the absence of a relief valve.

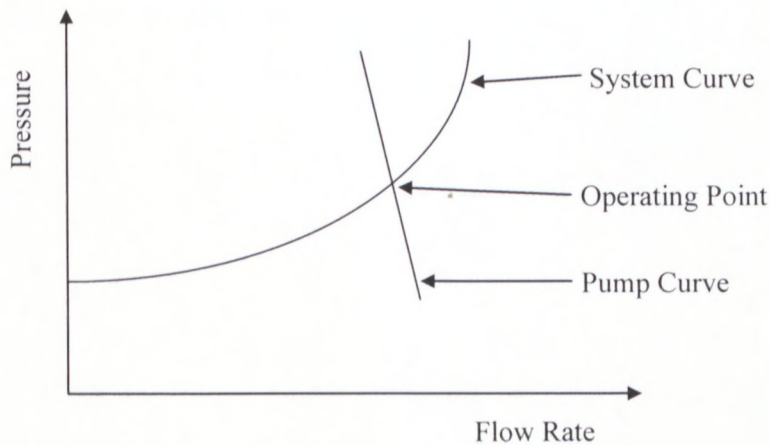


Fig. 3.7 Illustration of positive displacement pump operating point

The shapes of both the pump and the system curve can be important to system stability in certain applications. In the view of Fox et al. (2011) the original system operating point usually is chosen to coincide with the maximum efficiency by careful choice of pump size and operating speed. They assert that pump wear increases internal leakage, thus reducing delivery and lowering peak efficiency. In addition the operating point moves toward lower flow rate, away from the best efficiency point. Thus the reduced system performance may not be accompanied by reduced energy usage.

### 3.5 Parallel Pumping

Having introduced the concept of graphical representations of systems and pumps in the preceding sections of this chapter, this section analyses parallel pumping with some illustrations.

Parallel operation of two or more pumps is a common method of meeting variable-flow-rate requirements. Parallel pumping is considered as an energy efficient method of flow control, particularly for systems where static head is a high proportion of the total. According to Karassik *et al.* (2001) and Volk (2005) examples of applications for parallel pumping include municipal water supply and wastewater pumps, HVAC system chilled water pumps, main process pumps in a variable capacity process plant, and condensate pumps in a steam power plant.

When parallel pumps are being considered for a system design, the pumps must be carefully matched to each other and to the system to ensure that the pumps are always operating at a healthy point on their head-flow curves, and to ensure that the system is such that true benefits are achieved from the parallel pumping arrangement. The construction of system head curve, as explained in Section 2.2, is crucial for effective analysis of a parallel pumping arrangement. This is then followed by the development of a combined pump curve depicting the head-flow relationship for the pumps operating in parallel. According to Karassik *et al.* (2001), any number of pumps in parallel may be included on a single diagram although separate diagrams for different combinations of pumps may be preferable. The characteristic curves for one pump and for two identical centrifugal pumps in parallel are (Fox et al., 2011):

$$H = H_0 - AQ^2 \tag{3.5}$$

and

$$H_{2p} = H_0 - A \left( \frac{Q}{2} \right)^2 = H_0 - \frac{1}{4} A Q^2 \quad (3.6)$$

where,  $H$  = total head developed by each pump;  $H_{2p}$  = combined total head;  $H_0$  = the ideal head developed by the pump for zero flow rate (i.e. the shutoff head);  $A$  = the slope of the curve of head versus square of flow rate.

Once these two curves are constructed, then the total flow through the system is represented by the intersection of the system head curve with the combined pump curve. This point becomes the operating point of the parallel pumping arrangement as shown in Fig. 3.8.

If the pumps are close together, that is, in the same station, the analysis given below should be adequate to secure satisfactory operation (Karassik *et al.*, 2001). But if the pumps are widely separated, as in the case of two or more pumps at widely spaced intervals along a pipeline, serious pressure transients may be generated by improper starting or stopping procedures. According to them, the analysis of such cases may be quite complicated.

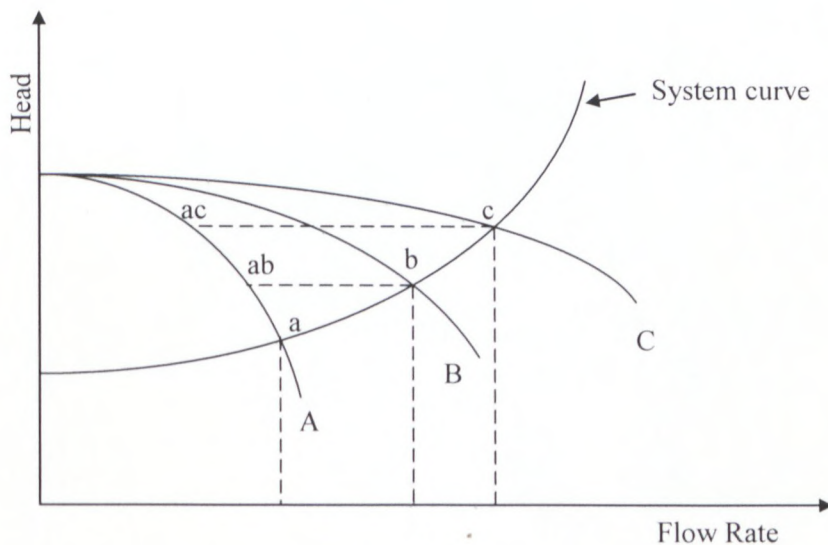


Fig. 3.8 Illustration of parallel operation of centrifugal pumps

Fig. 3.8 is an illustration of two or three identical pumps operating in parallel. Curve A represents the performance curve of any one of the pumps. Curve B is the combined pump curve, which represents two pumps operating at the same time in parallel. Similarly curve C represents the combined pump curve when all three identical pumps are operated in parallel. Points a, b and c represent the flow delivered when only one pump is operated, two pumps are operated in parallel, and all three pumps are operated in parallel respectively. Also ab

represents the point where each pump is operating on its own head-flow curve when these two identical pumps are operated in parallel. Similarly,  $ac$  represents the point where pump A would operate when these three identical pumps are operated in parallel. In general, with parallel pumping, each pump runs out the furthest on its own head-flow curve when that pump operates alone in the system or when the fewest number of pumps allowed to be operated are running (Volk, 2005). According to him, the pumps run the furthest back on their head-flow curves when the maximum number of pumps is operated in parallel in the system. This places a limitation on the number of pumps to be operated in parallel. Usually, there are no more than three or four pumps operating in parallel.

One of the often mistaken notions of parallel pumping is that when two identical pumps are operated in parallel the resultant total flow will be double the flow one pump produces when operated alone. It is based on this that there could be a tendency to measure the rate of flow of one existing pump at a certain head and install another equal pump with the aim of doubling the flow and only to discover that the two pumps do not produce twice the flow rate.

However, Fig. 3.8 clearly shows that on the contrary the resultant flow decreases with an increase in number of pumps. Theoretically, if the system curve is totally flat, absence of friction losses in the system, then the flow would double when two identical pumps are operated in parallel. In other words the flow rate is proportional to the number of pumps operating for a system with only static head. But because the system head curve curves up due to friction in the system, two identical pumps operating in parallel do not deliver twice the flow of the individual pump operating alone in the system. Generally, the parallel combination may be used most effectively to increase system capacity when the system curve is relatively flat (Fox et al., 2011).

According to Volk (2005), the benefits of paralleling two or three identical pumps are negligible if the system head curve is too steep. This situation could be caused by an undersized piping system or by some other undersized components in the system that acts as a bottleneck. He therefore believes that in such a situation it could be more profitable to flatten the system head curve, reduce bottlenecks, and increase piping sizes rather than adding additional parallel pumps to the system.

Another tendency is the parallel operation of non-identical pumps. The head-flow characteristics of the pumps need not be identical, but pumps with unstable characteristics may give trouble unless operation only on the steep portion of the characteristic can be assured (Karassik *et al.*, 2001). The operation of non-identical pumps in parallel could present

problems when these pumps are mismatched for the system in which they are working. Effects of paralleling non-identical pumps include

- operation of individual pumps at a very low flow which might be below the recommended minimum continuous flow for that pump;
- running at full speed but not delivering any flow into the system (dead headed); and
- operation of any of the pumps at shut off which is a very unhealthy point for continuous operation of most pumps.

According to Rishel (2002) there is a great danger that the pump with the lower head-flow curve can be operated at the shutoff head condition and cause heating in the pump. This will happen if these pumps are operated together at any flow rate less than 62% of the large pump. Therefore, considerable care should be exercised in trying to operate pumps in parallel that have different head-flow curves (Karassik *et al.*, 2001; Rishel, 2002).

Care must be taken when running pumps in parallel to ensure that the operating point of the pump is controlled within the region deemed as acceptable by the manufacturer (Europump & HI, 2004). Therefore, Fox *et al.* (2011) have noted that an actual system installation with parallel pumps also requires more thought to allow satisfactory operation with only one pump powered. This is because it is necessary to prevent backflow through the pump that is not powered. However, to prevent backflow and to permit pump removal, a more complex and expensive piping setup is needed.

Karassik *et al.* (2001) have posited that the overall efficiency  $\eta$  of pumps in parallel is given by

$$\eta = \frac{H(sp.gr.)}{k} \times \frac{\sum Q}{\sum P} \quad (3.7)$$

where, H = head, ft (m); sp.gr = specific gravity of the liquid; k = 3960 USCS (0.1021 SI);  $\sum Q$  = sum of the pump flow rates, gpm (l/s);  $\sum P$  = total power supply to all pumps, hp (W)

The advantages of parallel pumping include the following. Multiple pumps in a station provide spares for emergency service and therefore reduce the downtime needed for maintenance and repair. Parallel pumping offers an opportunity for the use of smaller electric motors in place of a single big electric motor to drive pumps. While the smaller electric motors will be properly loaded ( $\geq 75\%$  of rated power output), a single big electric motor tends to be under-loaded ( $\leq 50\%$  of rated power output) most times. Therefore, parallel

pumping using smaller electric motors as prime movers ensures the elimination of under-loading of electric motors and its attendant costs such as poor power factor and energy efficiency. Equally important about the parallel pumping is its increased reliability in contrast to a single big pump. For instance a parallel pumping system having three pumps keeps functioning when one or two pumps fail, perhaps at a reduced flow. But a system with just one pump is paralysed as soon as the pump fails.

The reliability of a parallel system is the complement of the system unreliability (Yang, 2007); namely

$$R = 1 - \prod_{i=1}^n (1 - R_i) \quad (3.8)$$

where,  $R$  = system reliability;  $R_i$  = component reliability

If the  $n$  components are identical, Eqn.3.8 becomes

$$R = 1 - (1 - R_0)^n \quad (3.9)$$

where  $R_0$  = component reliability

The reliability of a parallel system increases with the number of components within the system, as indicated in Eqn. 3.8. Thus, according to Yang (2007), a parallel configuration is a method of increasing system reliability and is often implemented in safety-critical systems such as aircraft and spaceships. However, he has observed that the use of the method is often restricted by other considerations, such as the extra cost and weight due to the increased number of components. For instance, parallel design is rarely used for improving automobile reliability because of its cost.

Therefore, from the reliability point of view parallel pumping offers an opportunity to add a lot of pumps into the system. But this addition is not indefinite considering the preceding issues on actual flow rate increase with additional pump in the system. Equally the economic analysis with consideration to the cost relative to the minor flow rate increase will hinder an indefinite addition of pumps in parallel.

## **3.6 Pump Paralleling in the City of Cape Town**

Parallel pumping arrangements exist within City of Cape Town in the municipal facilities and refinery. Therefore the aim of this section is to highlight their features and their controls considered in Chapter 4 (Pump Flow Controls). These highlights are based on site visits to Bellville Wastewater Treatment Plant; Wynberg Reservoir and Pumping Station, and Monterey Pumping Station; and Cape Town Refinery.

### **3.6.1 Bellville Wastewater Treatment Plant**

BWTP is among the 22 Wastewater Treatment Works of City of Cape Town. Two thirds of the City's water consumption ends up in these plants and from there the final effluent is discharged back into the environment. This treated wastewater are utilised in majority of golf courses in the City for irrigation purposes, as do parks and sport fields. A limited number of industries are also benefiting from the lower tariff.

The catchment area of BWTP is Bellville, part of Kuils River, and parts of Durbanville. In terms of its treatment capacity and usage, its design capacity is 55 Ml/day at 1160 mg/l Chemical Oxygen Demand equivalent to 580000 population equivalents (CCT, 2011a). However, it is presently treating 47 Ml/day and 495000 population equivalent which is 85% of its design capacity in dry weather. According to CCT (2011b), this plant operates at its design capacity of 55 Ml/day (100%) only in wet weather. Up to 150 Ml/month of its effluent is sand-filtered and chlorinated, and subsequently pumped into an extensive re-use reticulation system. Thereafter, the effluent or wastewater is then used for both industrial and irrigation purposes.

Besides local irrigation, BWTP's clients include CPUT, UWC, Nampak, Compose Plant, Green Farm Tissue, and Kasselsvlei Primary School. These establishments are supplied through a 300mm pipe but the individual pumps are connected to this common output through a 100mm each.

The final effluent pump system like other pumping sections of the plant such as dewatering unit has a physical parallel configuration. Fig. 3.9 shows the pump arrangement at the final effluent pump system at BWTP.

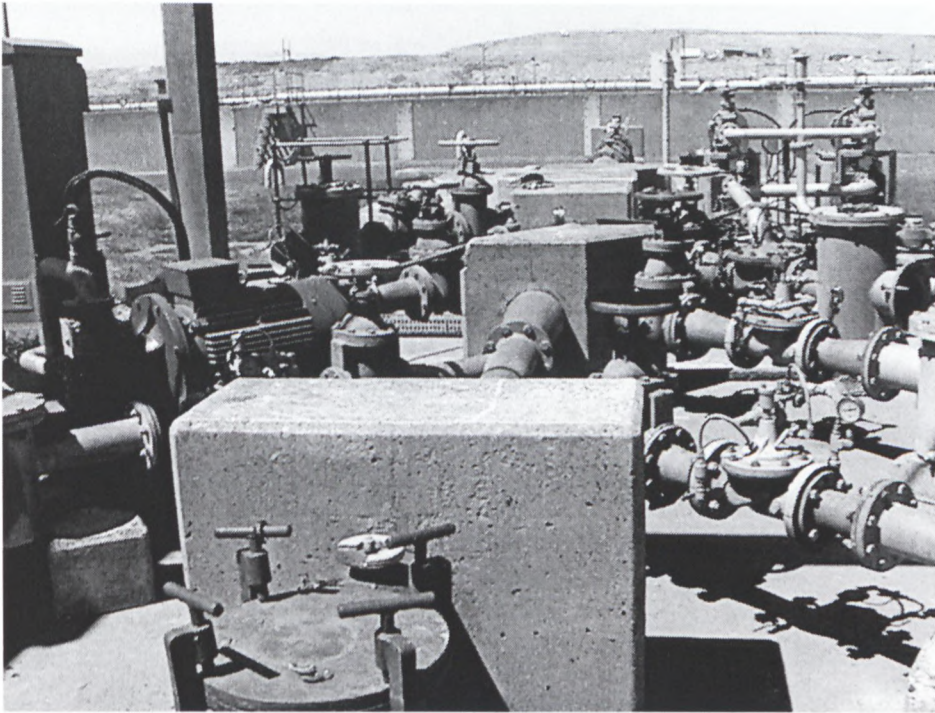


Fig. 3.9 Final effluent pump section of Bellville Wastewater Plant

They are actually operated alternately resulting to equipment redundancy. The essence of this is to ensure high system reliability and availability. Multistage centrifugal pumps remained the predominant pumps of this final effluent pump system until recently when they have started being replaced with clog (closed) impeller centrifugal pumps. This replacement is obvious because of the inherent problems associated with multistage pumps especially leakages and difficulty in maintenance. Leakages impact negatively on the overall system efficiency. Multistage centrifugal pumps owe their maintenance difficulty to their possession of so many parts and huge mass. Clog impeller centrifugal pumps develop the same flow rates and higher pressures besides their easy maintainability relative to an equivalent multistage centrifugal pump. Fig. 3.10 shows the remaining multistage centrifugal pump and its notorious leakages.



Fig. 3.10 Multistage centrifugal pump and its leakages

The multistage centrifugal pump of Fig. 3.10 is driven by a 22kW 400V 50Hz squirrel cage induction motor. This rewound electric motor runs at 2900RPM while consuming 42A. Also the prime mover for each clog impeller centrifugal pump is a 75kW 400V 50Hz squirrel cage induction motor operating at 2970RPM with a current rating of 125.6A.

BWTP also has a sludge management and disposal system. Waste activated sludge is mechanically dewatered on belt presses, deposited into skip bins and removed off-site for application to agricultural land. There is a small area on site available for emergency temporary storage.

### 3.6.2.1 Wynberg Reservoir and Pumping Station

Wynberg Pumping Station House No. 3 has two pumps each driven by 3.3kV 50Hz 400kW squirrel cage induction motor. Each of these motors consumes 87A while running at 1478RPM. The function of these pumps is the pumping of water up to Monterey reservoir situated at a distance of about 2km.

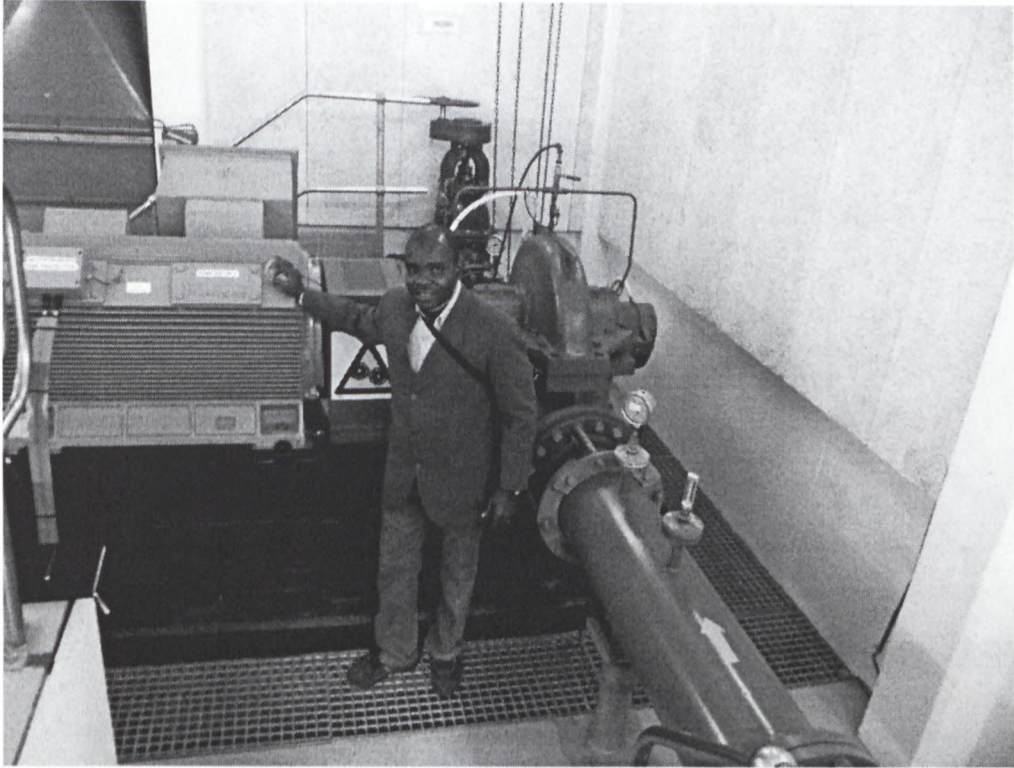


Fig. 3.11 The author inside Wynberg Pumping Station No 3

Each pump operates at a flow rate of 23Ml/day and 90m head. According to CCT (2011a) both pumps when operated simultaneously delivers 46Ml/day at the same head of 90m. This is a practical example of the assumption that the combined flow of two identical pumps is twice the flow of the individual pump flow as explained in Section 3.5. Obviously, the effect of friction cannot be ignored in pumping any fluid for a distance of 2km. However, these pumps are usually run alternately. Their water supply comes from the Wynberg Reservoir No 1 through a 460mm pipe which is reduced to 225mm through a valve. Each pump delivers into a 460mm pipe. Pressures of these pumps are monitored through pressure gauges. Both pumps have Bourdon-Haenni pressure gauges on both sides. The suction gauges range from 100 to 150 kPa. The delivery gauges range from 0 to 1000 kPa.

There is another 450mm pipeline next to this 460mm pipeline going up to Monterey Pumping Station through an x-connection. This connection is opened when there is need for simultaneous operation of these pumps thereby letting them pump on two different pipelines. The usual flow rate of these pumps of 24MI/day and the corresponding pressures are as shown in Table 3.1. The flow rate variation is achieved through valve control.

Table 3.1 Typical Wynberg Pumping House No 3 data

	<b>Suction Pressure (kPa)</b>	<b>Delivery Pressure (kPa)</b>	<b>Flow Rate (MI/day)</b>	<b>Motor Current (A)</b>
<b>Pump 1</b>	74	970	24	80
<b>Pump 2</b>	78	950	24	75

### 3.6.2.2 Monterey Pumping Station

There are two pump sets at Monterey that pump water up to Constantia Nek almost 24 hours daily during summer. But their operational durations are reduced during winter. Each pump is driven by a 3.3kV 50Hz 250kW squirrel cage induction motor whose speed and current consumption are 1485RPM and 52.9A respectively. Each pump at 80m head can deliver a maximum flow of 19MI/day with both delivering about 21.1MI/day at a head of 86m. The size of the input or suction pipe that feeds each of these pumps from the reservoir is 300mm and the delivery or discharge pipe size is 375mm. But the size of the delivery pipe from the pumping station is 460mm which can handle the combined flow rate when the need arises.

Fig. 3.12 shows Prof MTE Kahn and his student inside the Monterey Pumping Station during a visit to the station.

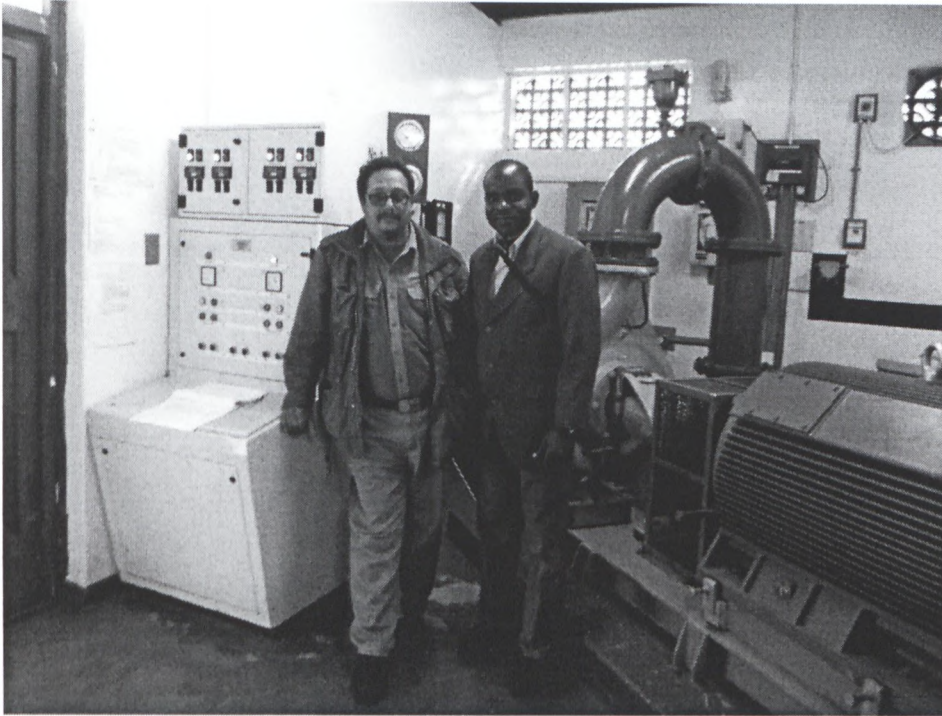


Fig. 3.12 Prof MTE Kahn and his student inside Monterey Pumping Station

During summer Monterey Pumping Station could deliver between 12MI/day and 24MI/day depending on the demand. This flow variation is realised by controlling the delivery valve, opening or closing it to the desired flow rate required of each pump. Both pump sets have their individual suction and delivery valve sets. The pressure monitoring and measurement here is the same as in Wynberg Pumping Station No 3. In other words both pumps have Bourdon-Haenni pressure gauges on both sides. While the suction gauges range from 100 to 150 kPa, the delivery gauges range from 0 to 1000 kPa. Expectedly the pressures are not constant because of the different flow rates. A typical example of this is shown in Table 3.2.

Table 3.2 Typical Monterey Pumping Station data

<b>Flow Rate (MI/day)</b>	<b>Suction Pressure (kPa)</b>	<b>Delivery Pressure (kPa)</b>	<b>Motor Current (A)</b>
15	68	910	45
17	100	930	47

Mr Shamiel Peters is the Site Superintendent for Wynberg Reservoir and Pumping Station, and Monterey Pumping Station. Fig. 3.13 shows him with the author inside Monterey Pumping Station.



Fig. 3.13 The author with Mr Shamiel Peters inside Monterey Pumping Station

### 3.6.3 Cape Town Refinery

This refinery, popularly known as Caltex Refinery, is operated by Chevron South Africa Pty Ltd.

The pump installation at its Effluent Treatment Plant is unique to this research work mainly because:

- The pumps are progressive cavity pumps (a sub-division of positive displacement pumps), unlike pumps of other sites visited which are centrifugal pumps. Centrifugal pumps are the basis for discussions on parallel pumping. Therefore this installation being a parallel configuration of progressive cavity pump was fascinating to the author as there appears to be little or no existing literature on this.

- This installation's prime movers are controlled by VSD s which are installed and operated with diligence to the adherence of the necessary regulations or requirements. This also is contrary to other sites where valve control is common.

The actual pumps that are operated in parallel at the Effluent Treatment Plant are the Sludge Feed pumps namely pumps 28G-005 A and 28G-005 B respectively as shown in Fig. 3.14

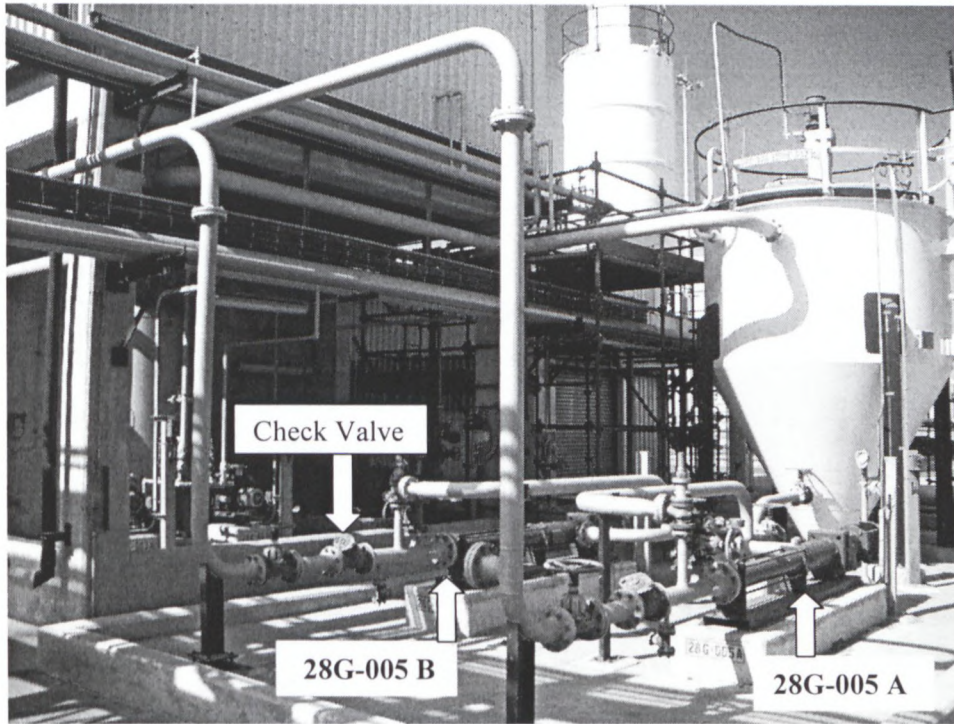


Fig. 3.14 Sludge feed pumps of the effluent treatment plant

The fluid that they pump is sludge water whose composition is 20% organic solids and 80% water. Each of these pumps is driven by a 500V 50Hz 22kW squirrel cage induction motor that operates at a full load speed of 1465RPM while drawing 32.8A. The suction, discharge and common delivery pipes of these pumps have a common size of 4" (101.60mm). This pipe size is based on considerations and calculations of the maximum expected flow rate and pressure drop. The required flow rate is up to 20m<sup>3</sup>/hr to achieve a maximum discharge pressure of 1500kPa. Each discharge pipe is fitted with a check valve which is a non-return or one-way valve to avoid backwards flow through the pumps.

The progressive cavity pump is inherently an unbalanced machine due to the eccentric rotation of the rotor (Nelik, 1999). The consequence of this is that a progressive cavity pump

produces vibration which depends on the size of the element, the offset, and the speed of rotation. Two measures to counter this involve the limitation of the speed and also the mounting system. For example, a typical limiting speed is about 1200 RPM for small pumps and 300 RPM for large pumps. As can be seen from Fig. 3.14 it is generally recommended that progressive cavity pumps be mounted on structural steel base-plates securely lagged down to concrete foundations. These base-plates are normally provided with means to grout them into place on the foundation for rigidity and dampening. However, a strict adherence to the manufacturer's instructions and recommendations on mounting ensures proper installation.

### **3.7 Conclusion**

A proper understanding of system and pump characteristics is crucial in parallel operation of pumps. It is more challenging to have two dissimilar pumps operated in parallel. Parallel pumping advantages include high system reliability and effective motor loading resulting to energy efficiency improvement. Unfortunately the benefits of parallel pumping are yet to be derived by most of the sites visited. Therefore the next chapter will examine current flow control methods of these sites.

## CHAPTER 4: PUMP FLOW CONTROLS

### 4.1 Introduction

This chapter aims at reviewing the different means of flow rate controls observed at the different sites highlighted in Chapter 3. Such a comparative analysis provides a great opportunity to understand the efficiency levels of these pumping systems.

Pump flow rate or pressure control could be through the control of the prime mover or the pump output. While controlling the prime mover is equivalent to changing the pump curve, controlling the pump output amounts to changing the system curve and aimed at getting a different operating point. On-off (Start-Stop) and use of VSDs are the common methods of controlling electric motors of pumping systems. On the other hand, the use of valves (throttling) on the pump output is a common flow control strategy. Parallel pumping is mostly considered as a method of flow rate control especially for situations with outstanding varying flow requirements. However, it should be noted that individual pumps of a parallel arrangement have to be controlled by either of the aforementioned means – prime mover or pump output control.

Affinity or Similarity Laws are usually utilised in the analysis of pump, especially centrifugal pumps, flow control. Affinity laws are the equations relating the kinetic, commonly called rotodynamic, pump performance parameters of flow rate, head and power absorbed, to speed. These laws enable the determination of the flow rate and head at different pump speeds or impeller diameters. Rishel (2002) has noted that positive displacement pumps have one affinity law in common with centrifugal pumps – flow varies directly with speed. Likewise, Europump and HI (2004) maintain that many positive displacement pump control systems are similar to rotodynamic (centrifugal) applications. According to them, the major difference is that positive displacement pumps have a direct relationship between speed and flow irrespective of pressure.

For a fixed impeller diameter, the affinity laws show that

- Flow rate is directly proportional to the rotational speed
- Head developed varies as the square of the rotational speed
- Power consumed by the pump is proportional to the cube of the rotational speed

Mathematically the affinity laws, for a given impeller diameter, are expressed as follows:

$$Q \propto N \quad (4.1)$$

$$H \propto N^2 \quad (4.2)$$

$$P \propto N^3 \quad (4.3)$$

where, Q = Flow rate; H = Head; P = Power absorbed; N = Rotational speed

Eqns 4.1 – 4.3 could be rewritten for two conditions namely initial and final conditions to reflect the proportionalities as follows,

$$\frac{Q_1}{Q_2} = \frac{N_1}{N_2} \quad (4.4)$$

$$\frac{H_1}{H_2} = \left[ \frac{N_1}{N_2} \right]^2 \quad (4.5)$$

$$\frac{P_1}{P_2} = \left[ \frac{N_1}{N_2} \right]^3 \quad (4.6)$$

Generally the basic relationship existing among these variables are graphically depicted as pump performance curves. Hydraulic efficiency ( $\eta$ ) is essentially independent of speed but varies when the diameter is changed within a particular casing (Europump & HI, 2004). A typical pump performance curve is shown in Fig. 4.1.

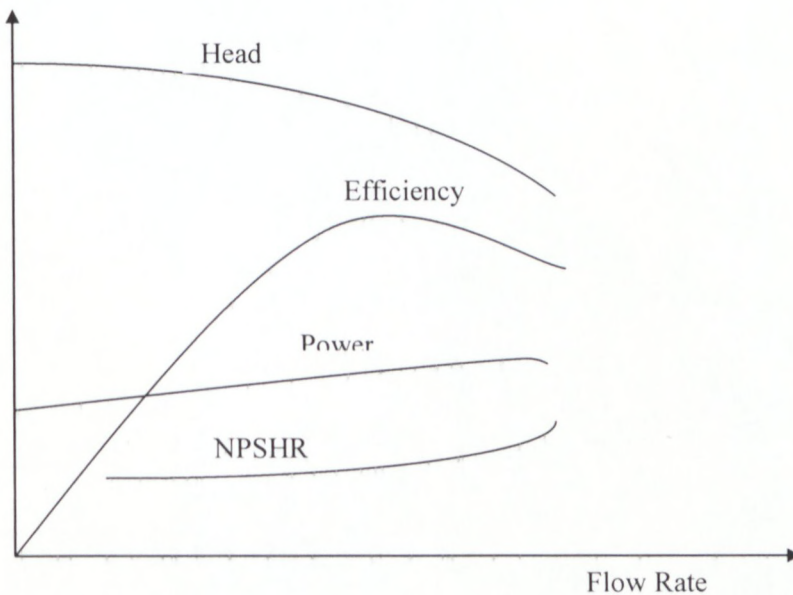


Fig. 4.1 Example of Pump performance curves

NPSHR is an important performance parameter of any centrifugal pump in order to avoid cavitation. Its equivalent for positive displacement pumps is NPSPR. NPSHR is a function of the pump design but NPSHA is a characteristic of the system design. NPSHA is the value by which the pressure in the pump suction exceeds the liquid vapour pressure expressed as a head of liquid. The need to carefully consider NPSH in variable speed pumping can be seen in Fig. 4.1. NPSHR increases as the flow through the pump increases. According to CT (2002), NPSHR also varies approximately with the square of speed in the same way as pump head and conversion of NPSHR from one speed to another can be made using the following equations:

$$Q \propto N \quad (4.7)$$

$$NPSHR \propto N^2 \quad (4.8)$$

It should be noted however that at very low speeds there is a minimum NPSHR plateau. This means that NPSHR does not tend to zero at zero speed.

In addition, as flow increases in the suction pipe-work, friction losses also increase, giving a lower NPSHA at the pump suction, both of which give a greater chance that cavitation will occur.

The phenomenon known as cavitation commences when a liquid entering the impeller eye turns and is split into separate streams by the leading edges of the impeller vanes. The resultant effect of this action is the local pressure drop below that in the inlet pipe to the pump. If the incoming liquid is at a pressure with insufficient margin above its vapour pressure, then vapour cavities or bubbles appear along the impeller vanes just behind the inlet edges. The three outstanding undesirable effects of cavitation are (CT, 2002; Europump & HI, 2004):

- The collapsing cavitation bubbles can erode the vane surface, especially when pumping water-based liquids.
- Noise and vibration are increased, with possible shortened seal and bearing life.
- The cavity areas will initially partially choke the impeller passages and reduce the pump performance. In extreme cases, total loss of pump developed head occurs.

These three undesirable effects of cavitation start at different values of NPSHA and often there will be cavitation erosion before there is a noticeable loss of pump head. However for a

consistent approach, manufacturers and industry standards, usually define the onset of cavitation as the value of NPSHR when there is a head drop of 3% compared with the head with cavitation free performance (CT, 2002). At this point cavitation is present and prolonged operation at this point will usually lead to damage. Therefore, it is a usual practice to apply a margin by which NPSHA should exceed NPSHR.

Another important parameter concerning pump flow control as shown in Fig. 4.1 is the efficiency. Efficiency initially increases with increase in flow rate but decreases when it attains a maximum point with flow rate increase. This is because centrifugal pumps are designed for a specific flow and differential head and at these conditions the pump is most efficient. This duty point which stipulates the pump's ideal conditions is commonly known as the Best Efficiency Point (BEP). Therefore, operation at flows less or greater than BEP results in increased energy consumption. A further implication is that NPSHR level tend to increase with the attendant implications as explained previously. Consequently, it is worthwhile to limit the operating range of centrifugal pumps. According to Nesbitt (2001), the reliable operating range is dependent upon pump size and detail design, but a good starting point would be  $0.7 \times \text{BEP flow}$  to  $1.2 \times \text{BEP flow}$ .

## **4.2 On-Off Control**

This pump control type also known as Start-Stop control is often deployed where stepless control is not necessary, such as keeping the pressure in a tank between preset limits. Therefore, the pump at any given time is either running or stopped. The average flow of such a system is the relationship between the "on" time and the "total" (on + off) time. The electric motor used for this control type must be rated as an intermittent duty motor depending on the frequency of the on and off states. The use of a continuously rated electric motor for on-off control of very short interval would pose danger to the motor windings because of the effect of inrush starting current. Generally the starting current of a squirrel cage induction motor is about six to seven times the rated current.

Europump and HI (2004) have noted that the stop/start operation causes additional loads on the power transmission components and increased heating in the motor. Therefore, they have suggested that the frequency of the stop/start cycle must be within the motor and pump capability and will be limited by the inertia of the load, the power and the speed of the pump, and the quality of the power supply.

The final effluent system of BWTP could be considered to be operating on this on-off control method. Worthy of note is that this system involves the emptying of a sump unlike a conventional pumping system that entails the filling up of a tank or reservoir. Two small pumps are run at constant speed to build up the pressure in order to realise a minimum pressure of 3 bars (300 kPa). If the pressure reaches or tends to exceed the preset point of typically 7 bars (700 kPa), a clayton valve that serves as the regulating valve operates thereby recycling the effluent. At this point the two small pumps are manually switched off and a VSD operated motor started to sustain the required established pressure. This system has provisions for automatic operation using mercury float switches and ultrasound sensors as switching inputs. While the former are used to operate the sump output pumps, the latter control the sump input pump.

Therefore, although a VSD is utilised as part of the final effluent system, the entire system is regarded as being on-off operated in the context of this research work. This is worthy of note because the two small pumps that run concurrently (paralleled) are not VSD operated. Equally important here is the location of the VSD. The author was surprised to find a panel left at the vagaries of nature inscribed VSD as shown in Fig. 4.2.

To satisfy his curiosity the author initiated the procedure of opening the panel. Fig. 4.3 shows Mr Deon Lategan (Mechanical Maintenance Personnel) explaining issues to the author after opening the panel.

The adverse effect of high temperature on the performance of semiconductors and in this case the VSD efficiency is well documented in many literatures as was highlighted in Section 2.5.2.7. Proper ventilation is a major means of ensuring that electronic equipments, VSDs inclusive, are not endangered by high temperatures. During winter ambient temperature rise of such an enclosed equipment could pose little or no challenge at all. On the contrary increase in temperature would definitely become a big issue during summer with a resultant decrease of the VSD efficiency.

However, it is necessary that the quality of ventilation air be given proper consideration to ascertain that they are devoid of harmful substances. According to Rishel (2002), these harmful substances include chemicals in the form of gases or particulate matter. Hydrogen sulphide is particularly dangerous to copper-bearing equipment such as electronics.

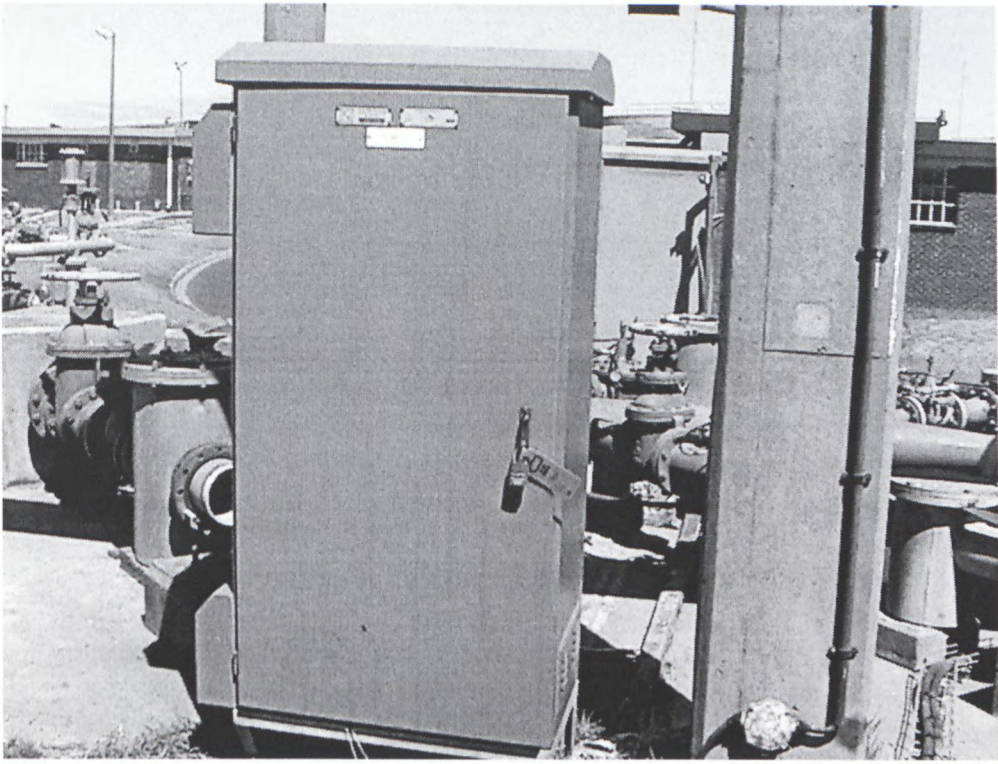


Fig. 4.2 Panel enclosing a VSD and left to the vagaries of nature

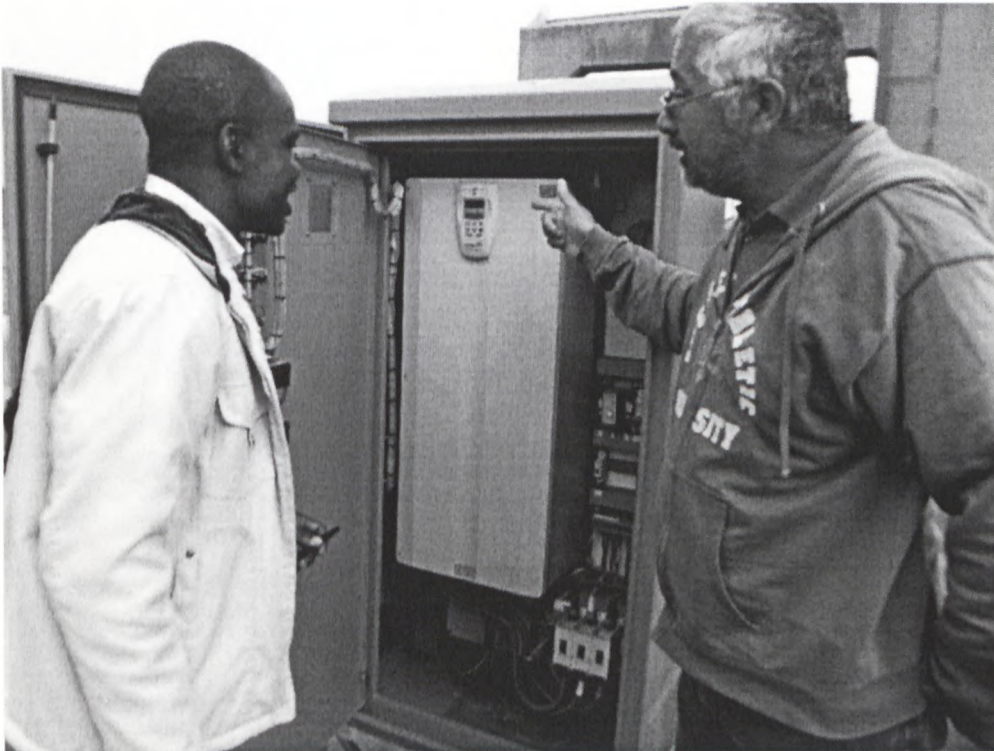


Fig. 4.3 Mr Deon Lategan and the author after the panel was opened

Rishel (2002) further asserts that sewage treatment operations generate this gas, so it is very important that any equipment installed in sewage treatment facilities be protected from ambient air that can include this chemical.

One means of protecting electronic equipments is by installing them in air-conditioned rooms as in the case of Caltex Refinery. But such installations should also be executed within the limits of maximum cable length in order to avoid the effect of voltage rise on the motor. In terms of the distance, the VSD installation in the final effluent pump system of BWTP is very good.

### 4.3 Throttling

Throttling, also known as valve control, is the most commonly used pump flow control method. With this control method, the pump is operated on a constant speed and a valve in the pump discharge line is opened or closed to adjust the flow to the required value. A diagrammatical representation of throttling is depicted in Fig. 4.4.

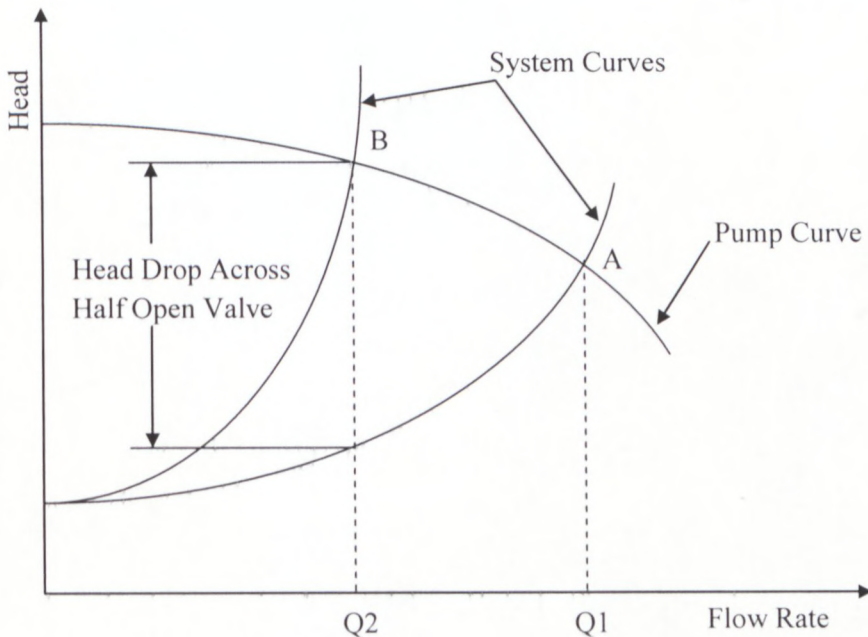


Fig. 4.4 Valve control of pump flow

Point A is the pump operating point with the valve fully open and the corresponding flow rate is  $Q_1$ . But when the valve is partially closed – for instance when it is half open – it introduces an additional friction loss in the system, which is proportional to flow squared. Therefore the operating point shifts to Point B with a flow rate of  $Q_2$ . The pressure drop across the valve is the difference between the head when the valve is partially closed and when it is fully open such that the same flow rate would be achieved. In other words the pressure drop across the valve is the head difference between the two curves. As can be seen from Fig. 4.4, throttling leads to high loss in the pump and the valve when the system is running at a reduced flow rate. But the motor loss remains relatively unchanged over the whole flow range because it is operated at a constant speed.

According to Europump and HI (2004), it is usual practice with valve control to have the valve 10% shut even at maximum flow. Energy is therefore wasted overcoming the resistance through the valve at all flow conditions. There is some reduction in pump power absorbed at the lower flow rate, but the flow multiplied by the head drop across the valve, is wasted energy. It should also be noted that, whilst the pump will accommodate changes in its operating point as far as it is able within its performance range, it can be forced to operate high on the curve where its efficiency is low, and where its reliability is impaired.

Maintenance cost of control valves can be high, particularly on corrosive and solids-containing liquids. So the lifetime cost could be unnecessarily high.

Both Pump Station 3 of Wynberg Pumping Station and Monterey Pumping Station are making complete use of valve control method. To guard against the inherent challenges of this flow control method such as cavitation and water hammer, these stations have written operating procedures. The initial start-up procedure for Wynberg Pump Station 3 is as follows:

- Open suction isolation valve
- Close delivery isolation valve
- Release pump-set emergency stop button at pump control console
- Check pump status pilot light on control console
- Push pump start button
- Open pump discharge isolation valve slowly in order to register a 900kPa pressure differential over the pump. **Do not** open the discharge isolation valve to register a pressure differential of less than 900kPa over the pump as cavitation will set in. **Do**

**not** run the pump against a closed valve for prolonged periods of time. The pump will trip on low flow if volume is restricted for more than 3 minutes

- Once the rising main is full, open the discharge isolation valve completely

However, the normal start-up procedure that is applicable during day-to-day operation is:

- Release pump-set emergency stop button at pump control console
- Check pump status pilot light at pump control console
- Push pump start button
- Open discharge valve

Monterey Pumping Station's start-up procedure has some necessary precautions or checks to be observed before starting the pump. These checks are:

- Check valves
  - Suction to be open
  - Delivery to be shut
- Check pump status
- Bleed pump where possible
- Check safety guards
- Check oil level where possible. Oil level to be on maximum mark on dipstick
- Check emergency stop button on control panel (to be released)
- Check pump status pilot light at pump control console. Pilot light to be on

Figs. 4.5-4.6 are typical valves in Wynberg Pump Station 3 and Monterey Pumping Station.

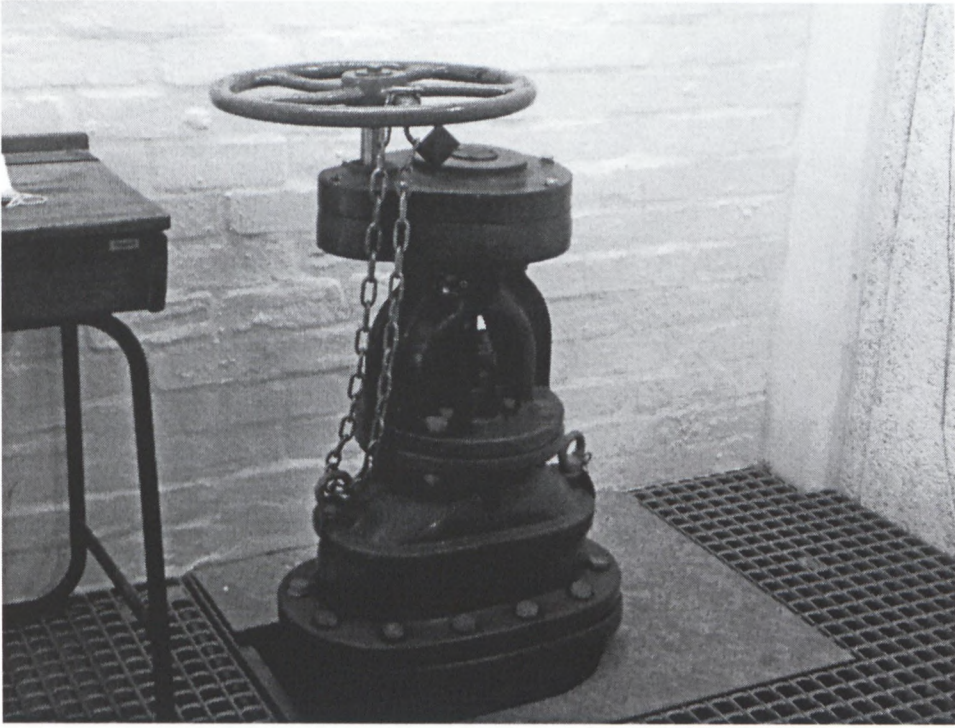


Fig. 4.5 Wynberg Pump Station 3 isolation valve

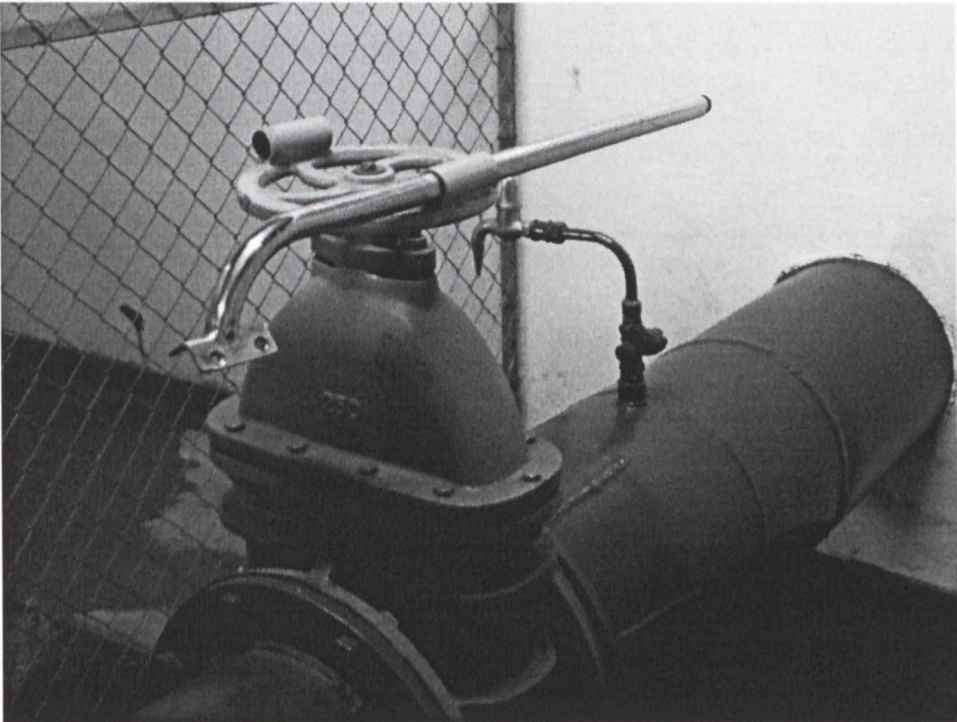


Fig. 4.6 Delivery valve in Monterey Pumping Station

After executing the checks enumerated earlier the starting-up sequence will simply be

- Push start button to start pump delivery
- Open delivery valve slowly
- Record all information on control console into logbook

Both stations have a common stopping sequence as follows:

- Close delivery valve
- Stop pump
- Record time in logbook

#### **4.4 Variable Speed Drive (VSD) Control**

The pressure drop across a valve, as was shown in Section 4.3, requires an additional power to overcome it. This amounts to a wasted energy which is unacceptable given the current global energy challenge. Therefore, it could be more economical to operate a pumping system with the valve fully open and control the pump speed to achieve the desired system performance. This is the underlying concept of VSD control of pumps. Driving a car on a high way and its probable speed control has been postulated as an analogy to explain the difference between VSD and valve pump flow control (Barnes, 2003; Volk 2005). According to them using a VSD to control pump flow is much like driving a car down a highway and controlling its speed by adjusting the position of the accelerator, without using the brake. By doing this, the output from the engine is directly controlled to meet the requirements of the system. In contrast, using a throttling valve to control pump flow resembles driving a car down a highway by keeping a fixed accelerator setting and using the brakes to control the car's speed.

While controlling the speed of the pump will provide the greatest energy savings, the pressure requirement of the system will dictate the maximum energy savings potential (Volk, 2005). He maintains that the most efficient method of continuously adjusting the flow from a pump is to directly control the speed of the electric motor that drives the pump.

A graphical representation of the basic operation principle of a VSD controlled pump flow is depicted in Fig. 4.7. Point A represents the pump operating point at a particular pump speed and  $Q_1$  is the corresponding flow rate. Also B is the operating point realised by operating the pump at another speed with  $Q_2$  as the flow rate.

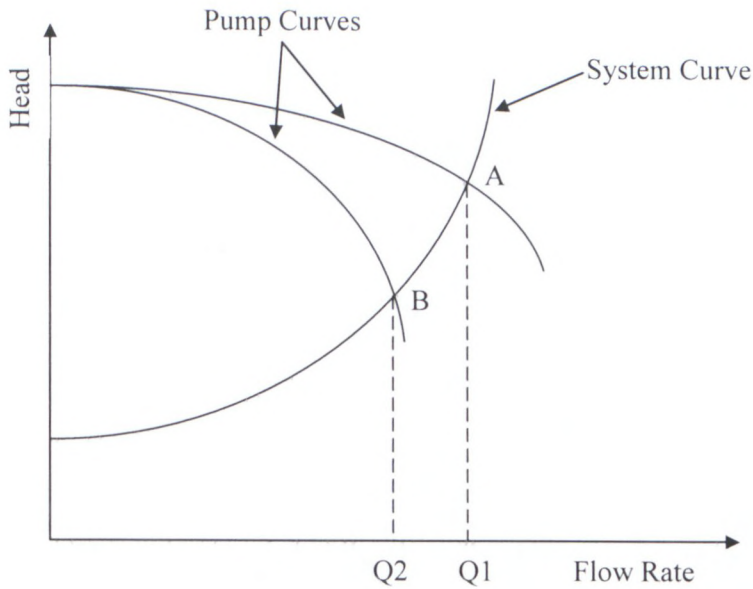


Fig. 4.7 Illustration of VSD pump flow control

According to CT (2002), and Europump and HI (2004), with low static head systems, the optimal efficiency of the pump follows the system curve. This principle is achieved with VSD control as shown in Fig. 4.7 where the duty point of the pump follows the unchanged system curve. In other words, in VSD control the operating point follows the system curve which is optimal for pump efficiency. Equally important is the fact that based on affinity laws the energy consumption drops dramatically when speed is reduced. Therefore, the energy savings with VSD control are significant thereby making it the most energy efficient control method for pumping applications.

As noted in Section 3.6.3 the prime movers of the Sludge Feed Pumps at the Effluent Treatment Plant of the Caltex Refinery are completely controlled by VSDs. Also these pumps are not centrifugal pumps but progressive cavity pumps, a sub-group of positive displacement pumps. Positive displacement pumps have only one affinity law in common with centrifugal pumps (Rishel, 2002; Europump & HI, 2004). This commonality is the proportionality of speed to the flow rate. But positive displacement pumps create flow with a resultant pressure given the restriction effect of the pipe. Therefore, the speed is proportional to the pressure developed assuming negligible losses.

The pumps are used to feed sludge to a Filter Press which is basically a big filter whose graphics is shown in Fig. 4.8.

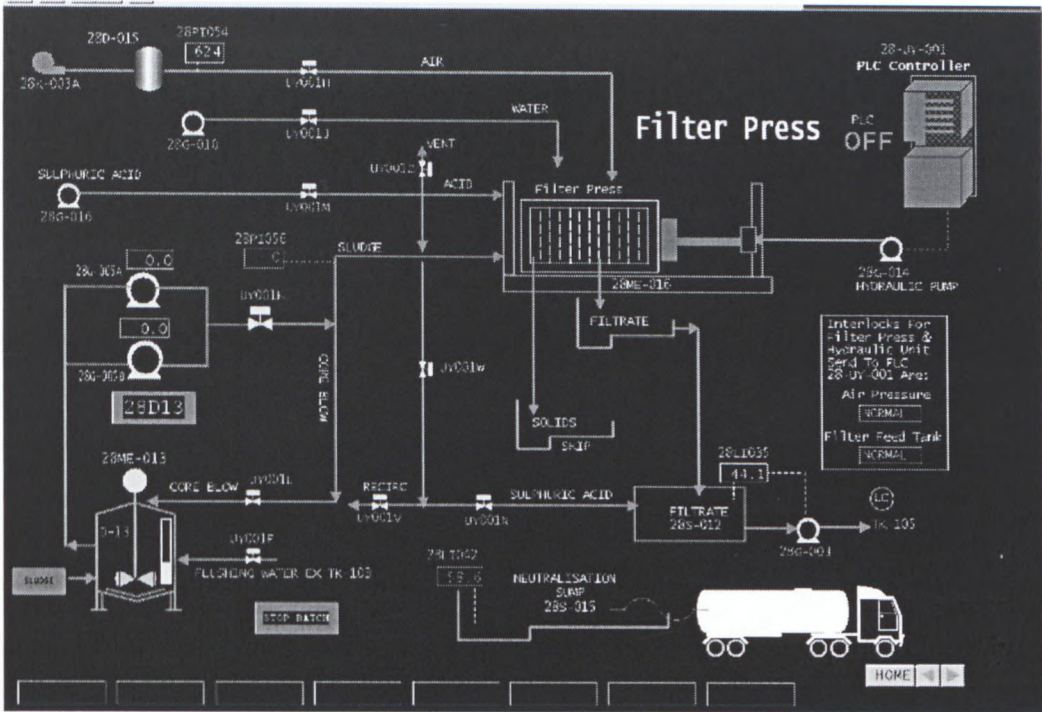


Fig. 4.8 Filter press graphics

The pressure drop over the filter elements increases as the sludge is pumped through the filter press. Both pumps are run at full speed, when the pressure drop over the filter is very low. As soon as the pressure reaches 100kPa (starting set point), a set point of 130kPa is given to the pumps. Once they reach the set point, a countdown timer holds the set point at 130kPa for 10 seconds, and then increases the set point again by 30kPa to 160kPa. The VSDs speed up the pumps through the motors to achieve the new set point. Immediately the set point is reached the countdown timer again holds for 10 seconds, and the process repeats. This continues until an end pressure of about 1500kPa is reached. The pressure levels are monitored by a pressure sensor which gives input to a PLC. The PLC in turn runs a program and the output feeds the VSD to control the pump discharge pressure according to a given set point.

All the time the VSD is used to control the motor speed and invariably the pump speed, which controls the pressure to the given set point. Depending on the sludge characteristic, the filter sometimes blocks up (forms cakes) quickly and the VSDs run at minimum speed to prevent over pressure. One pump will only cut out for the purpose of thermal overload protection when both pumps are running at minimum speed. The minimum speed of this installation is attained when the VSD modulation frequency is 20Hz. If both pumps are running at minimum

speed and the pressure remains higher than the set point value, then one pump will be disabled. This will result in a pressure loss but the remaining pump will increase its speed to maintain the set point value, and the process continues with only one pump.

A graphical analysis of the PI data of 24<sup>th</sup> March 2011 is shown in Fig. 4.9. The figure is a plot of developed pump pressure, motor speed and frequency against the process duration for each of the two pump sets in parallel. Evident from this figure is the initial drop in speed as the pump pressure builds up. This transient is normal because at the commencement of the process the motor appears to be running on no-load. This figure also clearly shows that the pressure increases gradually from zero to 1300kPa which is because of the step by step delayed increase in pressure set point according to the PLC logic. This peak pressure was attained as from about the 63<sup>rd</sup> minute of the process and it was sustained for the next ten minutes.

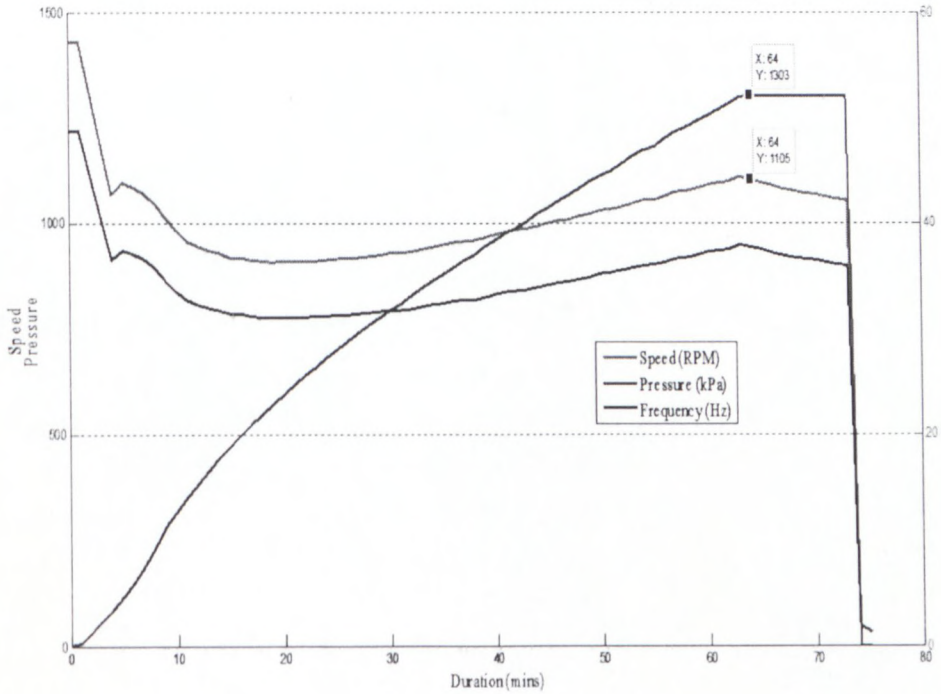


Fig. 4.9 Graph of speed, pressure and frequency versus process duration

As can be observed from Fig. 4.9 the motor’s apparent on-load highest speed coincides with the peak pressure. Thereafter the motor’s speed experiences a downward trend to avoid the development of excess pressure although the system has over-pressure protection. Worthy of note is that should there be only one set-point of 1300kPa, the motors would run at full speed

all the time and ramp up the pressure quickly until this set point is reached. Obviously this would negate the essence of the VSD.

A total of 74 readings required a total duration of 75 minutes to complete the process on the aforementioned date. Therefore, on the average readings were taken at a time interval of 1 minute.

The cable lengths between the VSDs and the electric motors are 102m and 107m respectively. These are 16mm<sup>2</sup> x 3 core PVC SWAPVC cables with a single core 16mm<sup>2</sup> GIEEC as earth return. These long cable lengths lead to voltage spikes on the motor windings and leakage currents that may be generated by the VSD which is common when long distance cables are used between a VSD and motor. There are many factors that influence the peak level ( $V_p$ ) and rise time ( $t_r$ ) of voltage spikes (WEG, 2011): Cable type, cable length, motor size, switching frequency and other variables all affect  $V_p$  and  $dv/dt$  (voltage rising rate).

According to WEG (2011), if the cables between a VSD and motor are longer than 100 m (300 ft), the cable capacitance to ground may cause nuisance over-current or ground fault trips. In this case it recommends the use of a load reactor because the use of a three-phase load reactor, with an approximate 2% voltage drop decreases the  $dv/dt$  of the PWM pulses commonly generated at the inverter output of any ac frequency converter. A load reactor connection is illustrated in Fig. 4.10.

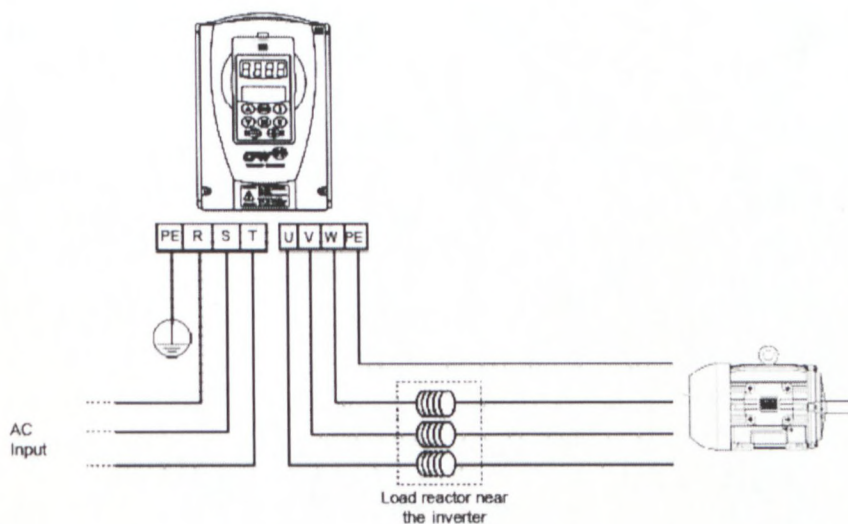


Fig. 4.10 Load reactor connection (WEG, 2011)

The value of either the line or load reactor needed to obtain the desired voltage drop is determined using Eq. 4.9 as follows

$$L = \frac{\text{Voltage Drop}[\%] \times \text{Line Voltage}[\text{V}]}{\sqrt{3} \times 2\pi \text{Line Frequency}[\text{Hz}] \times \text{Rated Current}[\text{A}]} \quad [\text{H}] \quad (4.9)$$

where Rated Current refers to the motor rated current.

The line reactor or the dc link inductor could be applied when required impedance is insufficient for limiting the input current peaks, thus preventing damage to the VSD. But the VSDs under consideration do not use line reactors because there are no input power problems. Therefore, given that the voltage drop is 2%, a line voltage of 525V, 50Hz frequency and 32A motor current rating, the load reactor is calculated as follows,

$$L = \frac{0.02 \times 525}{\sqrt{3} \times 2\pi 50 \times 32} = 0.603\text{mH}$$

The model of these VSDs is CFW0900445060ESZ where CFW09 means they belong to the WEG Series 09 Frequency Inverters; 0044 shows that the output rated current is 44A; 5060 is the power supply specification of 500-600V; and ESZ indicates that they are of the standard version with English manual. Alternating current supply voltages in the region of 525 to 575 and above are most widely used in North America and South Africa (GAMBICA & REMA, 2001). Therefore the operating voltage and frequency ranges for these VSDs are 525±15%V and 50±2Hz respectively with a phase unbalance of ≤ 3% of rated phase to phase input voltage.

This model has a rated switching frequency of 2.5kHz. WEG (2011) has noted that the switching frequency is a compromise between the motor acoustic noise level and the inverter IGBTs losses. Higher switching frequencies can use lower motor acoustic noise level, but increase the IGBTs losses, increasing inverter components temperature, thus reducing their useful life.

Fig. 4.11 shows Mr Inus Basson, Senior Electrical Project Engineer, attending to the author inside the sludge feed pump equipment room of Caltex Refinery.

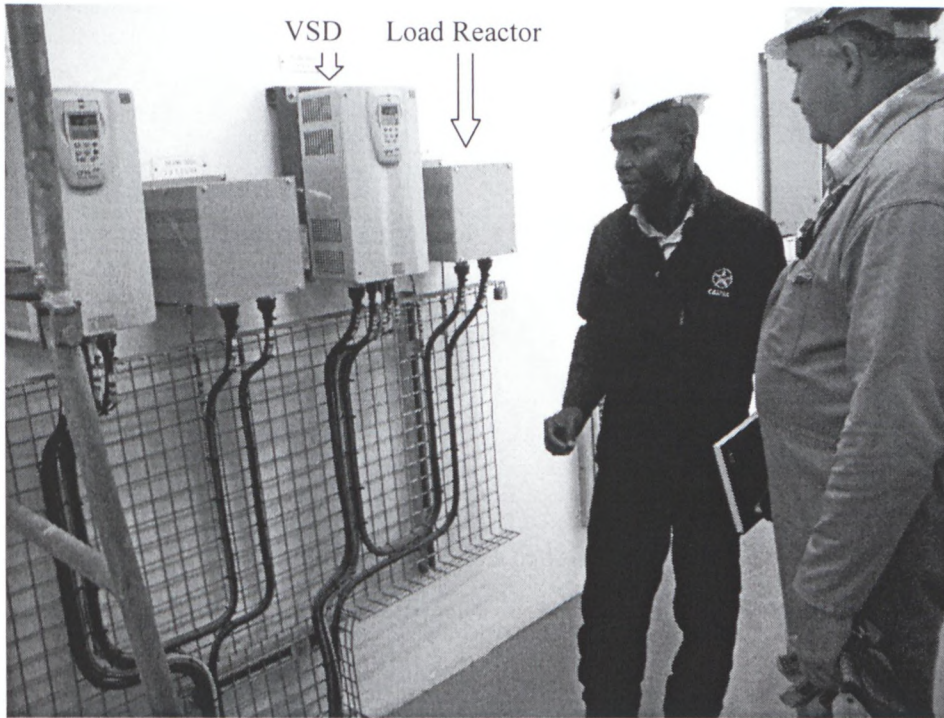


Fig. 4.11 Mr Inus Basson and author inside the Caltex Refinery sludge feed pump equipment room

#### 4.5 Conclusion

The advantages of VSD control of pumps make it the best choice for most pump control systems. However, the full realisation of such benefits would depend on a proper consideration being given to its environment. Such considerations include good ventilation and optimum cable distance. If the cable distance is beyond the manufacturer's specification an additional cost will be incurred in procuring the load inductors.

Start-stop and throttling are still common flow control methods in the sites visited. The implication of this is that there are great opportunities for energy efficiency improvements in these establishments.

## CHAPTER 5: COMPUTER SIMULATION

### 5.1 Introduction

According to Ljung and Glad (1994) the etymology of simulation shows that it has its origin from the Latin word *simulare* which means pretend. Therefore, in principle simulation is a fictitious representation of a real life system. But technically, simulation is a virtual or software representation of a physical circuit or system (Bose, 2006). Every simulation needs a model description by mathematical equations or circuit topology. Loosely put, a model of a system is a tool used in answering questions about the system without having to do an experiment (Ljung & Glad, 1994). Assume that for different reasons the experiment on the system cannot be carried out, but a model of the system is available. Then the model can be used to calculate or decide how the system would have behaved. An analytical approach to this would be by mathematically solving the equations that describe the system and studying the answer. This is a common means of using models, for example, in mechanics and electronics. Consequently, the value of the simulation results depends completely on the quality of the model of the system. In other words, simulation results are only as good as the model description.

With particular reference to simulation of power electronics and motor drives Giesselmann (2007) has noted that the accuracy of the simulation results depends on the accuracy of the component models and the proper identification and inclusion of parasitic circuit elements such as parasitic inductance, capacitance, and mutual coupling. According to him accuracy of component models in this context shall not mean that the model is actually faulty but rather that the limitations of the model are exceeded. For example, if the transformer inrush phenomenon were to be studied using a linear model for a transformer, the simulation would not yield useful results. In his view, the precise prediction of voltage and current traces during fast switching transitions in power electronics circuits has been proven to be difficult. As a result to obtain useful results, extensive experimental validation, advanced device models (and the values for their parameters), and detailed knowledge of parasitic elements, including the ones of the packaging of the circuit elements, are necessary. In addition, he has noted that numerical convergence is often a problem, if gate-drive signals, with rise and fall times as steep as in real circuits, are applied.

Effective computer capability and user-friendliness enable a numerical experiment to be performed on the model thereby making simulation an inexpensive, efficient, time saving and

safe way to experiment with the system. Simulation study is highly educational because there is no fear of damage due to fault or abnormal operation.

According to Bose (2006) a simulation study can provide the steady-state, transient, and fault performance of the system and also can help the design of system and its protection. For instance, the FFT analysis of waveforms can aid in line power quality studies and design. Therefore, the software emulation and virtual performance tests give the developer a lot of confidence in the product development. Using a newly developed converter or control system as an example, he suggests that such should be simulated on a computer prior to breadboard or prototype development, particularly if it is complex. Simulations therefore have a place in the analysis of existing equipment as well as the design of new systems (Giesselmann, 2007).

Simulation programs in this field of study are categorised into circuit and system level simulations. Ordinarily a system level simulation program such as the early MatLab based Simulink lack the capability to handle component level simulation. Circuit simulation programs such as PSpice provide the option of studying actual circuit level details in complex systems. A typical example of this capability is the simulation of the start-up of an induction motor, fed by a three-phase MOSFET inverter. However, in principle any program can be used for both circuit and system simulation (Bose, 2006). This is noteworthy given the current enhancements is some of these programs.

Among the readily available simulation programs for electrical and electronics research work in CPUT are Matlab-Simulink, PSIM and Labview. Powersim (2010) has asserted that PSIM is a simulation software specifically designed for power electronics and motor drives. Also with fast simulation and friendly user interface, PSIM provides a powerful simulation environment for power electronics, analog and digital control, magnetics, and motor drive system studies. The choice of PSIM for this research is mainly because it provides the advantage of circuit simulation hybridizing with system simulation.

Therefore the aim of this chapter is to undertake a virtual analysis of the sludge feed pump system of Caltex Refinery using the motor and pump parameters as provided by the manufacturers. The choice of this system is based on its being the only truly parallel operated pump system using VSDs among the sites visited.

## 5.2 Motor Data

The motor equivalent circuit as provided by the manufacturer (WEG) is shown in Fig. 5.1.

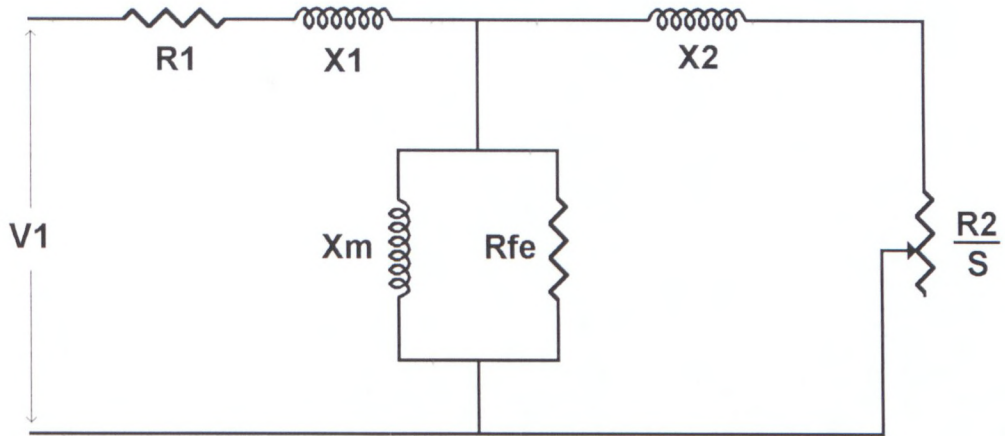


Fig. 5.1 Motor equivalent circuit

And the parameter values in ohms are as depicted in Table 5.1.

Table 5.1 Motor's parameter values in ohms at 20° C

R1	0.54493	X1	1.95339
R2	0.45864	X2	3.19370
Rfe	1349.728	Xm	61.24128

The respective inductance values for the stator, rotor and magnetising components of the motor's impedance were calculated from Table 5.1. This is because PSIM uses resistances and inductances. Given that for an inductive element,

$$X_L = 2\pi fL \quad (5.1)$$

where  $X_L$  = reactance,  $\Omega$ ;  $f$  = supply frequency, Hz;  $L$  = inductance, H

The inductance is given by

$$L = \frac{X_L}{2\pi f} \quad (5.2)$$

Therefore, the inductances are 0.0062H, 0.0102H and 0.1949H for stator, rotor and magnetisation respectively.

### 5.3 System Simulation

The simulation circuit diagram using the motor parameters, given by the manufacturer and as derived in Section 5.2, is shown in Fig. 5.2. Progressive cavity pumps are typical example of constant torque loads. Therefore each of them is represented by a constant torque load in the circuit. The paralleling is achieved by utilising a summation function whose inputs are the pump torque sensors. An electrical-mechanical interface block converts this summation output, a sensing signal, to mechanical signal that could drive a load. The presence of the gear-box with a gear ratio of 1 is to fulfil the master-slave requirement of PSIM. Finally the last constant torque load represents the system output whose speed and torque aid in predicting the combined flow rate and invariably the pressure. But the flow rate is directly proportional to the pump speed.

The complete motor parameters used in these simulations are as contained on Appendix 4. Also the VSD parameters are as highlighted in Section 4.4.

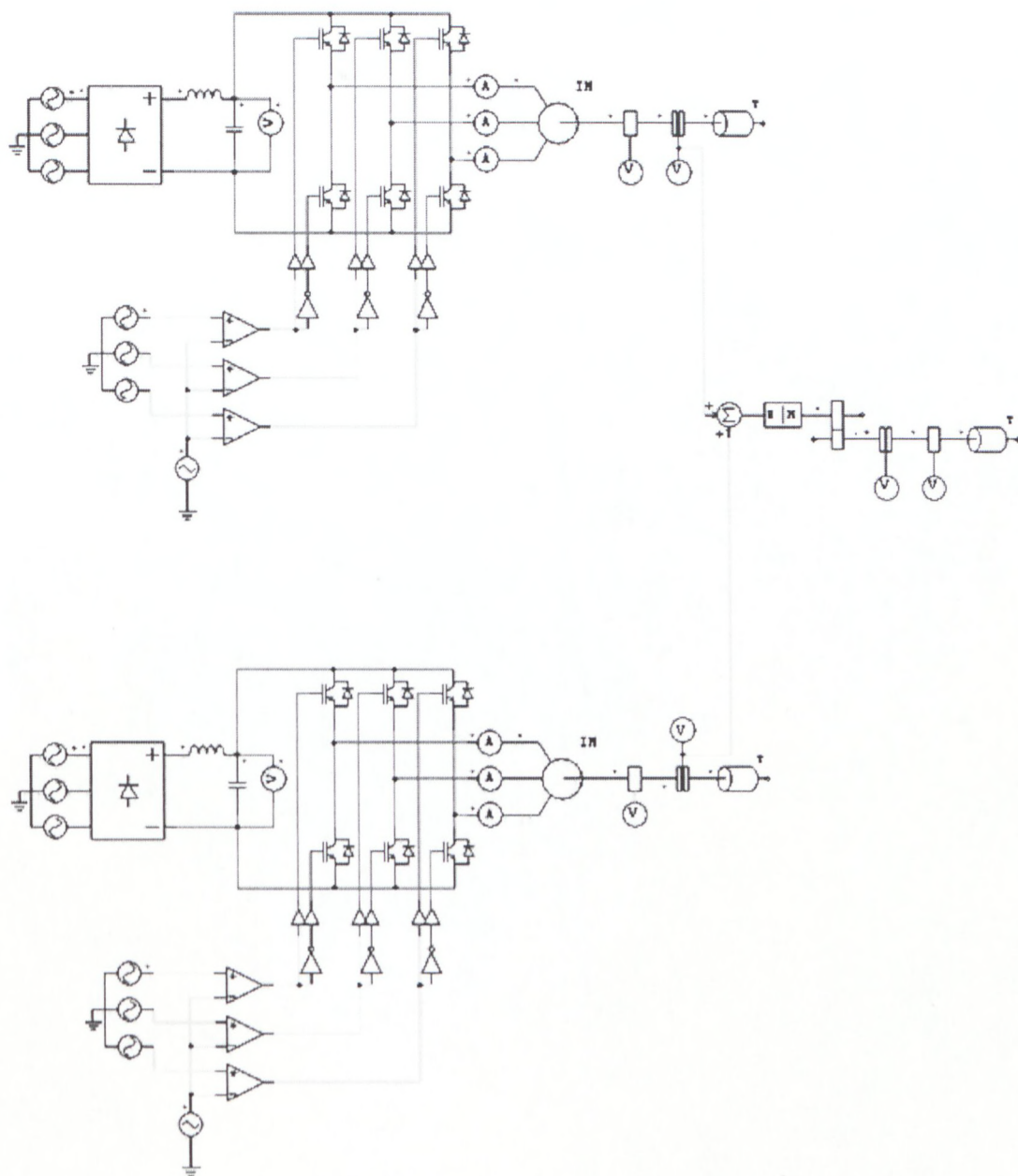


Fig. 5.2 Simulation circuit diagram

A comparison of the individual motor speed with the combined speed is illustrated in Fig. 5.3. The insert shows a reading after about 0.7s of the simulation.

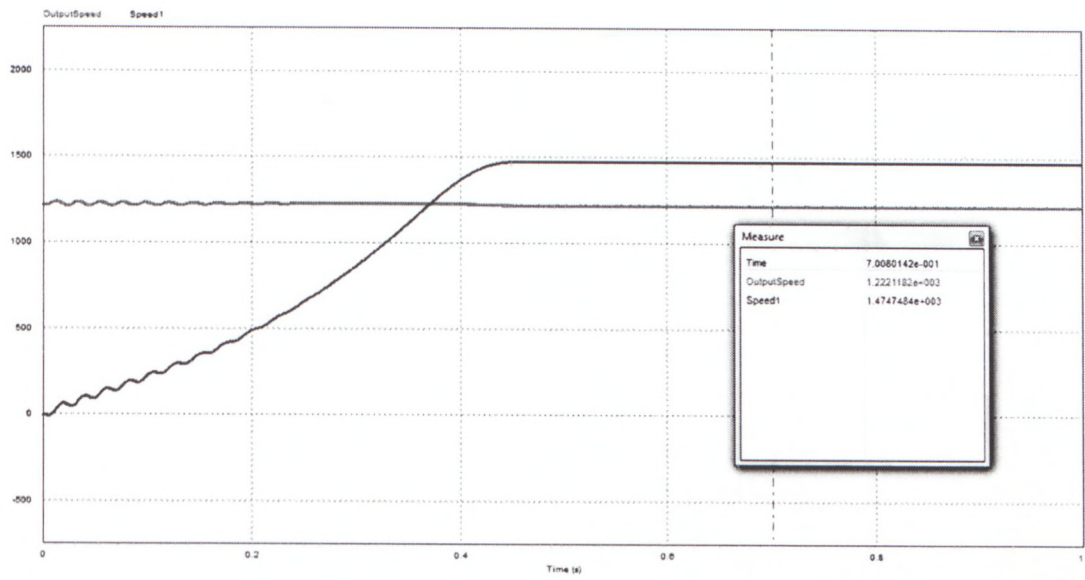


Fig. 5.3 Individual motor and combined motor speed

Fig. 5.4 shows the torque developed by the motor in relation to the load (pump) torque. Also inserted in this figure are the measured values.

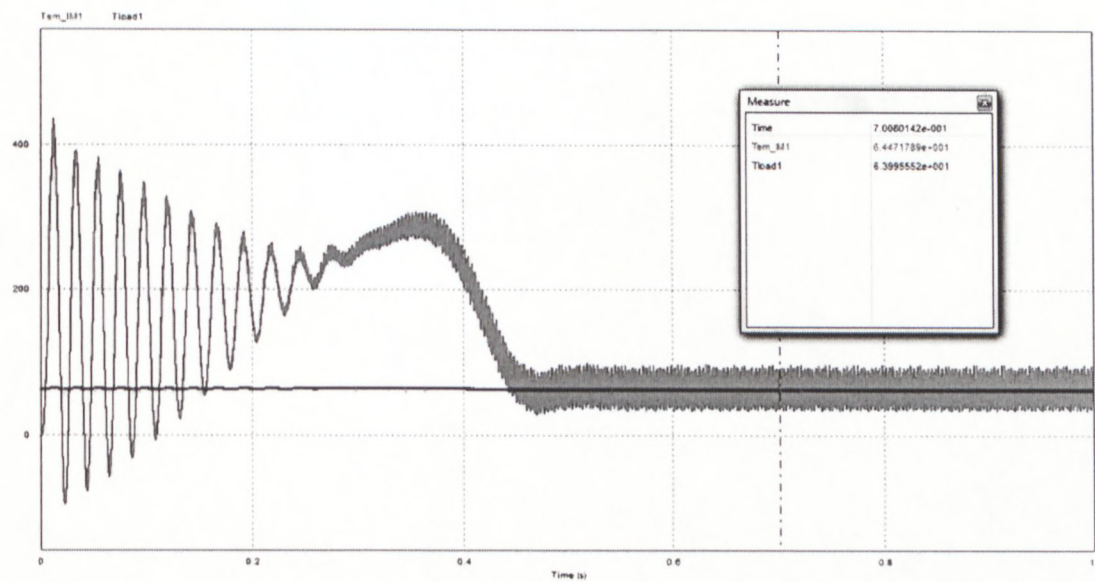


Fig. 5.4 Motor and pump torque curves

The relationship between the torque developed by each motor and the combined output torque is depicted in Fig. 5.5. The figure also contains some measured values of these parameters.

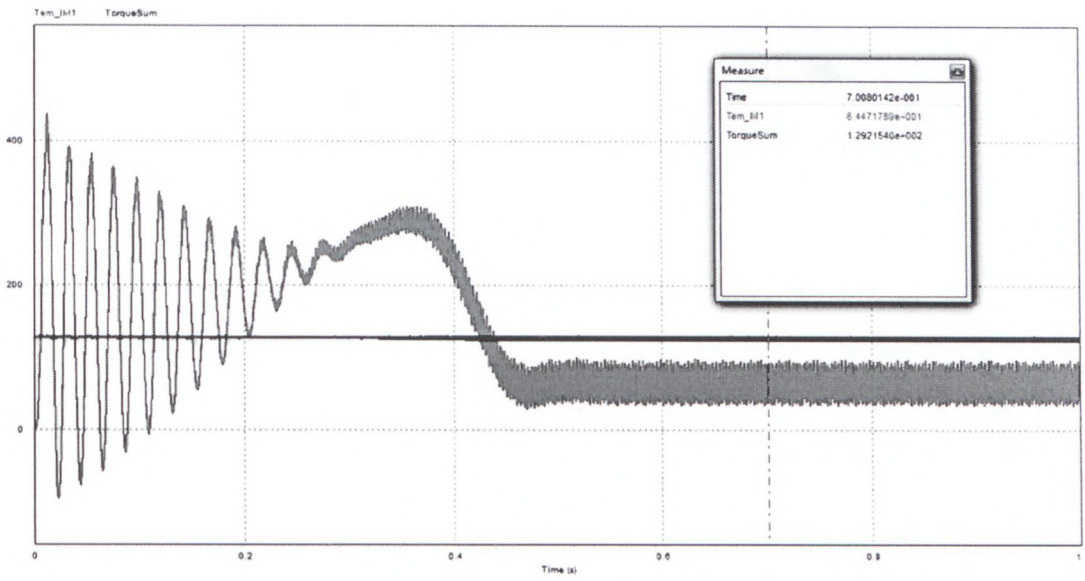


Fig. 5.5 Motor and pump cumulative torques

Finally shown in Fig. 5.6 is a comparison between the individual load torques and the total torque. Equally inserted in the figure are measurement values.

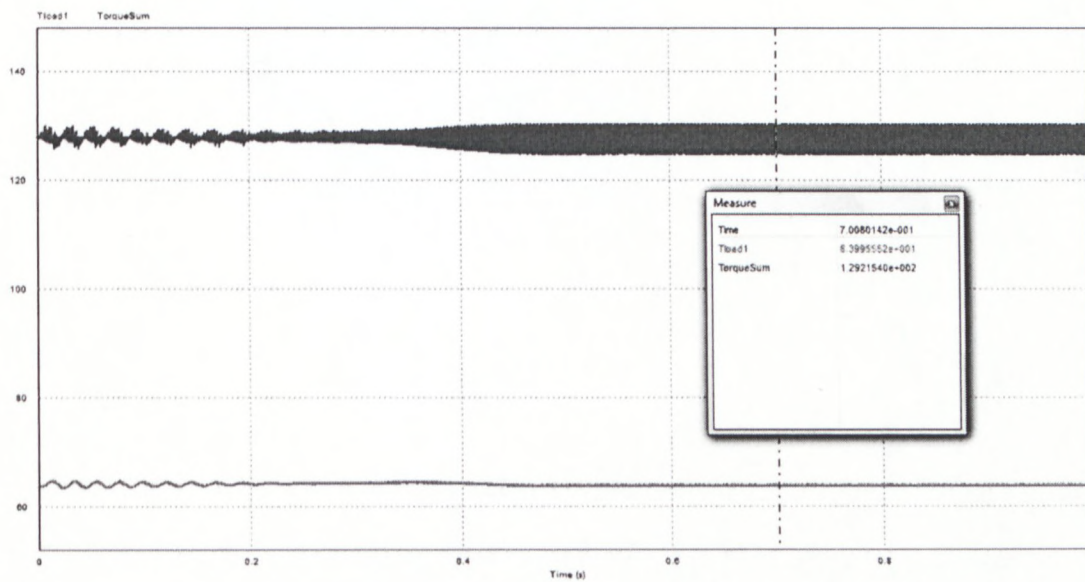


Fig. 5.6 Single pump and cumulative torques

## **5.4 Conclusion**

The PSIM simulation software has provided a good opportunity to experiment on the motor-drive system of the sludge feed pumps of Caltex Refinery. Analysis of the interesting results of these simulations is the focus of the next chapter.

## CHAPTER 6: RESULT ANALYSIS

### 6.1 Introduction

Having considered the process data of sludge feed pump of Caltex Refinery and also its equivalent computer simulation, this chapter therefore compares the results of Chapters 4 and 5. The aim is to discover any semblance between the computer simulation and actual system. However, worthy of note is that even the most modern simulation programs cannot perfectly represent all parameters and aspects of real equipment (Giesselmann, 2007). In Section 5.1 it was highlighted that with particular reference to simulation of power electronics and motor drives the accuracy of the simulation results depends on, among other things, the accuracy of the component models.

### 6.2 PSIM Motor Model

A snapshot of the motor's parameters used for the simulation is shown in Fig. 6.1. It shows the absence of the motor's core loss resistance. The core loss resistance enables the calculation of the iron loss, comprising of the hysteresis and eddy-current losses, in the magnetic circuit.

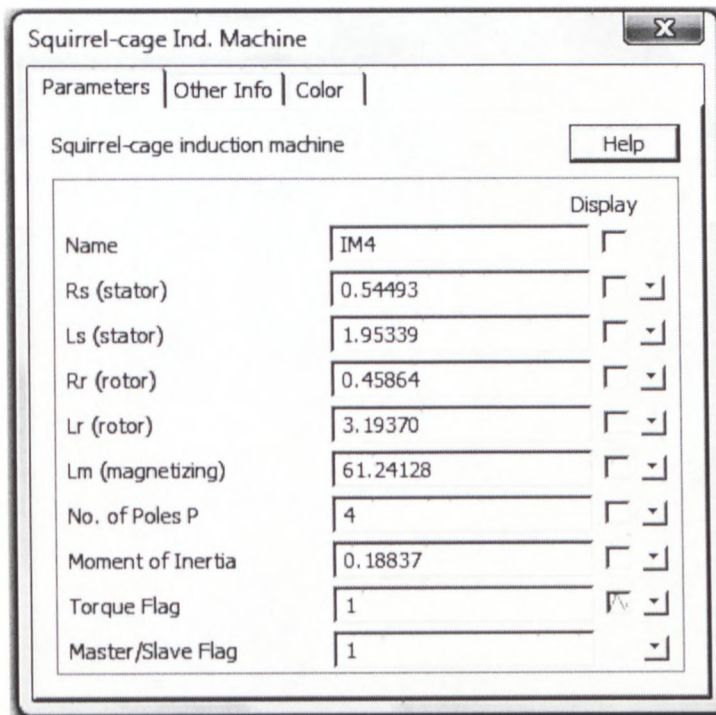


Fig. 6.1 Squirrel-cage induction machine snapshot

Although the windage, friction and iron losses of an electric motor are independent of the load their exclusion in any form from the simulation means that the simulation result will have a deviation, no matter the degree, from the actual system performance.

Also PSIM squirrel-cage induction machine models are symmetrical and are star connected in the stator (Powersim, 2010). This again presents an opportunity for a difference in the simulation result compared with the actual system because the motor is delta connected in the real system.

A comparison of the single pump speed with the cumulative speed as shown in Fig. 5.3 indicates that the later is slower than the former. However, Fig. 5.6 shows that the combined torque is higher than the individual pump torque. These results should be expected because the combined job requires a pump that could effectively handle the outputs of both pumps. A machine of higher torque is deemed to run at a lower speed based on the relationship between torque and speed as given by Eq. 6.1

$$P = \frac{TN}{9550} \text{ (kW)} \quad (6.1)$$

where P = power in kW, T = torque in N.m, N = speed in RPM

According to Nelik (1999) the power requirements for progressing cavity pumps are expressed differently by various manufacturers. Some manufacturers express the power requirements simply as power required at a certain speed, and others express them as torque. In his view, since the progressive cavity pump is considered a constant torque device when operating at a given differential pressure, using torque to determine power requirements is a simplified and accurate method of determining the power requirements. It will allow better selection of drive components, especially hydraulic and electrical variable speed type drives.

It is interesting to observe from Fig. 5.6 that the combined torque is not twice the individual torque. This also agrees with real life situation where frictional loss plays a major role especially at high speed.

It could be seen from Fig. 5.4 that each individual motor developed sufficient torque to drive each pump. As could be expected the cumulative torque is higher than the torque developed by each motor.

However, in all the results transients were observed and comparable to Fig. 4.9.

This result analysis has not duly considered the flow rate because the reference system's major interest is the pressure. But the relationship among speed, torque, flow rate and pressure could be established by equating two power equations of a progressive cavity pump namely Eqns. 2.17 and 6.1 as follows:

$$\left\{ \frac{105Q(pd - ps)}{102\eta} \right\} = \frac{TN}{9550} \quad (6.2)$$

Therefore the flow rate, in m<sup>3</sup>/s, will be given by

$$Q = \frac{102TN\eta}{9550 \times 105(pd - ps)} \quad (6.3)$$

where, pd is the pump outlet pressure, MPa; ps is the pump inlet pressure, MPa; η is the pump efficiency; N is pump speed in RPM; T is torque in Nm.

In the case of the system under review the inlet pressure is the atmospheric pressure which translates to 100kPa or 0.1MPa and if the manufacturer had provided the pump efficiency, then the flow rate could have been determined.

### 6.3 Conclusion

The simulation results compared favourably with the real life results despite the aforementioned PSIM motor model shortcomings.

## CHAPTER 7: CONCLUSION AND RECOMMENDATIONS

### 7.1 Introduction

This brief chapter aims at drawing conclusions from the work so far executed and thereafter make recommendations.

### 7.2 Conclusion

The diverse meanings of energy efficiency to different people have a commonality that energy efficiency is a veritable instrument in combating global energy challenges because it remains a low hanging fruit on the energy tree.

The Republic of South Africa is highly committed to energy efficiency improvements. This is evidenced in her Energy Efficiency Strategy of an overall target of a 12% energy saving by 2015 and an industry saving of 15% which is remarkable because to date only a handful of countries worldwide have set comprehensive targets for energy efficiency improvements. This commitment is yielding good results leading to her current reduction in energy intensity. Also she has a very clear understanding of the difference between energy efficiency and energy conservation although these are often interchangeably used. She believes that conservation by nature is only used in emergencies where there is not sufficient supply of energy and therefore will have a negative impact on production, as the only alternate for the extreme short term is to shut down activities. Whereas energy efficiency has a positive impact on production but takes place over a certain time period, more or less a 3 year cycle is followed to plan, implement and measure the implementation of energy efficiency project.

However, the 15% industrial energy saving will be elusive if the current trend of paying greater or only attention to electric motor efficiency improvement is not reversed. Industrial pumping systems energy consumption is outstanding in South Africa. Therefore, these pumping systems deserve a complete system approach to their energy efficiency improvement strategy in order to derive maxim energy efficiency benefits from them. This is because inefficiency in more than one component can add up quickly, resulting in a very inefficient pumping system. This underscores the importance of adopting efficient control methods for pumping systems with due consideration to the pump characteristics and the process requirements. Consequently, there is an urgent need to have efficiency standards and classifications for pumps and pumping system ancillary equipments such as the VSD.

Noteworthy is that any efficient equipment operated inefficiently results to energy wastage. A typical example is the operation of a VSD subjected to atmospheric conditions without proper ventilations at the Bellville Wastewater Treatment Plant.

Start-stop pump control method is simple and cheap but the high inrush starting current associated with electric motor and the constant speed of such a control makes it unsuitable for varying flow demand systems. Throttling or valve control requires some form of safety or caution to avoid water hammer which could burst pipe lines. This is in addition to the pressure drop across the valve which implies energy wastage. VSD control is the best pump control method especially for wide varying flow demand systems given its energy saving potentials because it ensures that the pump is operated at its optimum condition.

Although AFD, ASD, VFD, VSD and Inverter are frequently erroneously interchangeably used, they are not the same. But they are all terms encountered in electric motor speed control. Also an electric or electrical drive as a device is different from when it is considered as a system.

Proper matching of pumps and system consideration are needful for the actualisation of the gains of parallel pumping. The output of parallel pumping is less than the arithmetic sum of the individual pumps output. Therefore, the number of pumps to be paralleled is often limited to three because beyond that the output difference becomes infinitesimal and making the cost of additional pumps unjustifiable. However, parallel pumping remains an energy efficient approach to pump flow or pressure control for wide varying demand systems because it offers an opportunity for proper loading of the prime movers. The normal practice is to size the electric motor based on the maximum pump output whereas the pump often does not operate at that maximum output leading to a reduction in the motor efficiency and poor power factor with the associated cost. Parallel pumping also offers reliability and availability improvement of the entire system. This is because the reliability of a parallel system increases with the number of components within the system. High reliability does not mean failure proof but in this case when any component of the parallel system fails the system continues though at a lower capacity until such component is fixed. This implies that the entire system is virtually always operational or available.

Therefore given the respective benefits of VSD control and parallel pumping, their combination yields a remarkable energy gain through their energy efficiency enhancement potentials. This is particularly essential for wide varying flow demand processes.

Unfortunately these energy efficiency enhancement potentials are yet to be exploited fully in City of Cape Town and by extension South Africa with particular reference to government establishments. Throttling or valve control is still predominant despite its accompanying energy wastage.

Computer software simulation provides great opportunities to experiment with real life systems without fear of damage. However, it requires a good grasp of its model's capabilities and limitations. A lack of this understanding creates frustrations for the software user because the user could get results at variance with his expectations and different from the real system.

### **7.3 Recommendations**

Following the divergent definitions of energy efficiency among technical and economic professionals, there should be a synergy among them to effect a harmonised definition of energy efficiency and its relationship with energy conservation. This recommendation will enable a better quantification of the benefits of energy efficiency.

To eliminate or reduce to the barest minimum the frustration faced by anyone trying to study the literatures on ac drives, it is being recommended that authors of such literatures should clearly define from the beginning their perception of ac drive either as a device or a system. Also international professional bodies such as IEEE and IET should have clear meanings of AFD, ASD, VFD, VSD and Inverters while ensuring that their members comply with those definitions. This compliance is important because there is no uniformity of definitions of these terms among members of renowned professional bodies such as IEEE and IET.

There should be a balance between policy legislation and implementation to make the 15% industrial energy efficiency target a reality in South Africa beginning with City of Cape Town. This target will be a mirage should rewound electric motors and inefficient use of efficient equipments persist as was observed at Bellville Wastewater Treatment Plant.

To maximise the gains of pumping system energy efficiency enhancements there should be efficiency standards and classifications for pumps and the auxiliary equipments such as electric drives. This could be extrapolated to other EMDS such as fan and compressor systems.

Finally there is an opportunity for partnership between CPUT and City of Cape Town. If explored this could provide an avenue for consultancy services being rendered for the

automation of the existing manually operated parallel pumping at both Wynberg Pump Station 3 and Monterey Pump Station. This is a call for further research.

#### **7.4 Publications**

The following papers which are included in the appendices have emanated from this research work:

1. Onwunta, O.E.K & Kahn, M.T.E., 2011. Energy Efficiency and Reliability Improvement Strategies in Industrial Electric Motor-Driven Systems (EMDS). Proceedings of the 8<sup>th</sup> Conference on the Industrial and Commercial Use of Energy, Cape Town, South Africa, 16 – 17 August , pp103 -107
2. Onwunta, O.E.K & Kahn, M.T.E., 2011. Electric Drive and Energy Efficiency: Myriad Meanings. Proceedings of the 8<sup>th</sup> Conference on the Industrial and Commercial Use of Energy, Cape Town, South Africa, 16 – 17 August , pp109 -114
3. Onwunta, O.E.K & Kahn, M.T.E., Energy Efficiency and Conservation: South Africa's Perspective. To be presented at 'International Conference on Renewable Energies and Power Quality (ICREPQ'12)', that will be held in the Galicia's Conference and Exhibition Centre, Santiago de Compostela (Spain), from 28 to 30 of March 2012. REFERENCE OF THE PAPER: 226-onwunta

## REFERENCES

- ABB, 2002. Guide to variable speed drives. Available online [http://library.abb.com/global/scot/scot201.nsf/veritydisplay/596d0c6374a49608c1256de/00527253/\\$File/ABB\\_Technical\\_Guide4\\_8Feb02.pdf](http://library.abb.com/global/scot/scot201.nsf/veritydisplay/596d0c6374a49608c1256de/00527253/$File/ABB_Technical_Guide4_8Feb02.pdf) [10 Feb 2010]
- ABB, 2008. Variable-speed drive technology guide. Available online [http://www02.abb.com/db/db0003/db002698.nsf/ca7e93ab03030d22c12571380039e8fc/aa5853d43c2ad412c125720300632f74/\\$FILE/Tech+Guide\\_Drive.pdf](http://www02.abb.com/db/db0003/db002698.nsf/ca7e93ab03030d22c12571380039e8fc/aa5853d43c2ad412c125720300632f74/$FILE/Tech+Guide_Drive.pdf) [20 Sep 2010]
- ABB, 2011. South Africa: energy efficiency report. Available online [http://www05.abb.com/global/scot/scot316.nsf/veritydisplay/9344c8ededc6aa2fc12578640051aed8/\\$file/south%20africa.pdf](http://www05.abb.com/global/scot/scot316.nsf/veritydisplay/9344c8ededc6aa2fc12578640051aed8/$file/south%20africa.pdf) [18 June 2011]
- ABB, 2011b. Technical guide no. 3: EMC compliant installation and configuration for a power drive system. Available online [http://www05.abb.com/global/scot/scot201.nsf/veritydisplay/a8dc0a0e66d66118c12575d6002fd22d/\\$file/abb\\_technical%20guide%20no.3\\_rev.pdf](http://www05.abb.com/global/scot/scot201.nsf/veritydisplay/a8dc0a0e66d66118c12575d6002fd22d/$file/abb_technical%20guide%20no.3_rev.pdf) [7 August 2011]
- Abdelaziz, E.A, Saidur, R & Mekhilef, S., 2011. A review on energy saving strategies in industrial sector. *Renewable and Sustainable Energy Reviews* 15,150 – 168
- Arrillaga, J & Watson, N.R., 2003. Power system harmonics, 2<sup>nd</sup> ed. England:John Wiley
- Asdal, R., 2009. Optimizing pumping system. Chemical Engineering, April 2009 [http://www.che.com/technical\\_and\\_practical/4653.html](http://www.che.com/technical_and_practical/4653.html) [11 June 2010]
- Barnes, J. R., 2010. Harmonics standards for commercial electronic products. Available online <http://www.dbicorporation.com/harmonic.htm> [7 August 2011]
- Barnes, M., 2003. Practical variable speed drives and power electronics. Oxford:Elsevier
- Begg, C., 2002. Energy: management, supply and conservation. Oxford: Butterworth-Hienemann
- Benhaddadi, M & Olivier, G, 2010. Premium efficiency motors and market penetration policy. Available online <http://www.worldenergy.org/documents/congresspapers/436.pdf> [24 Feb 2011]
- Bhattacharyya, S. C., 2011. Energy economics: concepts, issues, markets and governance. London: Springer-Verlag
- Bocker, J., 2007. State of the art of induction motor control. IEEE International Electric Machines and Drives Conference, IEMDC 2007, Antalya, 3-5 May, 1459-1464.
- Boldea, I. & Nasar, S.A., 2002. The induction machine handbook. Boca Raton: CRC
- Boldea, I. & Nasar, S.A., 2010. The induction machines design handbook, 2<sup>nd</sup> ed. Boca Raton: Taylor and Francis
- Bolegoh, G.S., 2001. Pumps reference guide. 3<sup>rd</sup> ed. Ontario: Ontario Power Generation
- Bose, B.K ed., 1981. Adjustable speed ac drive systems. New York: IEEE Press
- Bose, B.K., 2000. Energy, environment, and advances in power electronics. *IEEE Transactions on Power Electronics*, Vol. 15, No. 4, July 2000
- Bose, B.K., 2006. Power electronics and motor drives. Boston: Elsevier

- Boteler, R., Brunner, C.U., de Almeida, A., Doppelbauer, M & Hoyt, W., 2009. Electric motor MEPS guide. Available online [http://www.motorsystems.org/files/otherfiles/0000/0038/MEPS\\_Guide\\_1st\\_Edition\\_February\\_2009.pdf](http://www.motorsystems.org/files/otherfiles/0000/0038/MEPS_Guide_1st_Edition_February_2009.pdf) [9 April 2010]
- Cameron, J.W., 2006, Centrifugal pumps. London: Merchant Book
- Cao, W., 2009. Comparison of IEEE 112 and new IEC standard 60034-2-1. *IEEE Transactions on Energy Conversion* 24:3, 802-808
- Cao, W., Huang, X., French, I & Xu, D., 2011. Assessment of IEC 60034-2-1 in determining induction machine efficiency. *European Transactions on Electrical Power* 21, 188-195
- Carlson, R., 2000. The correct method of calculating energy savings to justify adjustable-frequency drives on pumps. *IEEE Transactions on Industry Applications* 2000:36:6, 1725-1733
- Carpenter, R & Lipo, T.A., 1988. Electronic adjustable speed drive technology synopsis. Research Report 88-8. Available on-line <http://lipo.ece.wisc.edu/1980s%20pubs/88-08.pdf> [5 Nov 2010]
- CCT, 2011. Water services development plan (WSDP) for City of Cape Town 2011/12 – 2015/16, Executive summary. Available online [https://www.capetown.gov.za/en/Water/WaterservicesDevPlan/Documents/WSDP\\_2011\\_2012/WSDP\\_Exec\\_Sum\\_Sector\\_plan\\_18Feb11\\_printable.pdf](https://www.capetown.gov.za/en/Water/WaterservicesDevPlan/Documents/WSDP_2011_2012/WSDP_Exec_Sum_Sector_plan_18Feb11_printable.pdf) [10 June 2011]
- CCT, 2011b. Water services development plan for City of Cape Town 2011/12 – 2015/16 (Status: Final Report). Available online [http://www.capetown.gov.za/en/Water/WaterservicesDevPlan/Documents/WSDP\\_2011\\_2012/WSDP\\_%2018\\_%20April\\_%202011\\_12.pdf](http://www.capetown.gov.za/en/Water/WaterservicesDevPlan/Documents/WSDP_2011_2012/WSDP_%2018_%20April_%202011_12.pdf) [13 June 2011]
- CEMEP, 2011. Electrical motors and variable speed drives. Available online [http://www.cemep.org/fileadmin/downloads/CEMEP\\_Motors\\_and\\_VSD.pdf](http://www.cemep.org/fileadmin/downloads/CEMEP_Motors_and_VSD.pdf) [17 March 2011]
- Chapman, S. J., 2005. Electric machinery fundamentals, 4ed. New York: McGraw-Hill
- Chikuni, E., Khan, M.T & Okoro, O.I., 2008. Concise higher electrical engineering. Cape Town: Juta
- Cividino, L., 1992. Power factor, harmonic distortion; causes, effects and considerations. Proceedings of IEEE 14th International Telecommunications Energy Conference, INTELEC '92. 506 - 513
- CMSOGPE (2011a). Performance parameters of centrifugal pump. Available online [http://www.china-ogpe.com/buyingguide\\_content/Performance\\_parameters\\_of\\_centrifugal\\_pump\\_812.html](http://www.china-ogpe.com/buyingguide_content/Performance_parameters_of_centrifugal_pump_812.html) [11 July 2011]
- CMSOGPE (2011b). Performance parameters of positive displacement pump. Available online [http://www.china-](http://www.china-ogpe.com/buyingguide_content/Performance_parameters_of_positive_displacement_pump_812.html)

ogpe.com/buyingguide\_content/Performance\_parameters\_of\_positive\_displacement\_pump\_1253.html [11 July 2011]

Committee on America's Energy Future, National Academy of Sciences, National Academy of Engineering, and National Research Council of the National Academies, 2009. America's energy future: technology and transformation. Washington: National Academy of Sciences

Cookson, T.J., Lang, N.G & Thornton, E. J., 2008. Adjustable speed drives applied to large ac induction motor and pump systems. 24<sup>th</sup> International Pump Users Symposium, Houston, Texas, April 21 – 24, 75 – 80. Available online <http://turbolab.tamu.edu/uploads/files/papers/p24/P24Tut04.pdf> [20 August 2010]

CT, 2002. Variable speed driven pumps best practice guide (GPG344) <http://www.carbontrust.co.uk/Publications/pages/publicationdetail.aspx?id=GPG344&respos=0&q=Variable+Speed+driven+pumps&o=Rank&od=asc&pn=0&ps=10> [22 Feb 2010]

Cullen, J.M & Allwood, J.M., 2010. Theoretical efficiency limits for energy conversion devices. *Energy* 35, 2059-2069

da Costa Bortoni, E, 2009. Are my motors oversized? *Energy Conversion and Management* 50, 2282-2287

da Costa Bortoni, E, de Almeida, R.A & Viana, A.N.C., 2008. Optimization of parallel variable-speed-driven centrifugal pumps operation. *Energy Efficiency* 1, 167 – 173

de Almeida, A.T., Angers, P., Brunner, C.U & Doppelbauer, M., 2009. Motors with adjustable speed drives: testing protocol and efficiency standard. Proceedings EEMODS '09, 14 – 17 September, Nantes, France. Available online <http://www1.cetim.fr/eemods09/pages/programme/038-Brunner-final.pdf> [16 Feb 2010]

de Almeida, A.T., Bertoldi, P., Falkner, H & Fonseca, P., 2003. Market transformation of energy-efficient motor technologies in the EU. *Energy Policy* 31, 563-575

de Almeida, A.T., Bertoldi, P & Fonseca, P., 2003. Energy-efficient motor systems in the industrial and in the services sectors in the European Union: characterisation, potentials, barriers and policies. *Energy* 28, 673–90.

de Almeida, A.T., Fernando, J. T. E. F., Fong, J & Fonseca, P., 2008, EuP Lot 11 Motors. Available online [http://www.eup-network.de/fileadmin/user\\_upload/Produktgruppen/Lots/Final\\_Documents/Lot11\\_Motors\\_FinalReport.pdf](http://www.eup-network.de/fileadmin/user_upload/Produktgruppen/Lots/Final_Documents/Lot11_Motors_FinalReport.pdf) [27 June 2011]

---

de Capua, C & Landi, C., 2001. Quality assessment of electrical drives with strongly deformed supply waveform. *Measurement* 30, 269-278

de Keulenaer, H., Belmans, R., Blaustein, E., Chapman, D., de Almeida, A., de Wachter, B & Radgen, P., 2004. Energy efficient motor driven systems. Brussels: European Copper Institute

Deswal, S.S., Dahiya, R & Jain, D.K., 2008. Application of boost converter for ride-through capability of adjustable speed drives during sag and swell conditions. *World Academy of Science, Engineering and Technology* 47, 282-286

Djokic, S.Z., Stockman, K., Milanovic, J.C., Desmet, J.J.M & Belmans, R., 2005. Sensitivity of ac adjustable speed drive to voltage sags and short interruption. *IEEE Transactions on Power Delivery* 20:1, 494-505

Drury, W., 2005. Motors, motor control and drives. In: Warne, D.F., 2005 Newnes Electrical Power Engineer's Handbook, 2<sup>nd</sup> ed. Oxford:Elsevier

EC, 2000. VSD for electric motor systems. Available online <http://re.jrc.ec.europa.eu/energyefficiency/motorchallenge/pdf/VSDs-SAVE-Study-Final-Report.pdf> [3 Oct 2010]

EC, 2004. Energy efficient motor driven systems. Brussels:European Copper Institute. Available online [http://re.jrc.ec.europa.eu/energyefficiency/pdf/HEM\\_lo\\_all%20final.pdf](http://re.jrc.ec.europa.eu/energyefficiency/pdf/HEM_lo_all%20final.pdf) [2 Feb 2011]

EC, 2009. Reference document on Best Available Techniques for Energy Efficiency. Available online [ftp://ftp.jrc.es/pub/eippcb/doc/ENE\\_Adopted\\_02-2009.pdf](ftp://ftp.jrc.es/pub/eippcb/doc/ENE_Adopted_02-2009.pdf) [20 May 2011]

Emadi, A., 2005. Energy-efficient electric motors, 3<sup>rd</sup> rev. ed. New York:Marcel Dekker

Empson, T.M., 1998. Energy saving systems for induction motors. Available online <http://home.clear.net.nz/pages/lmphtonics/es090698.pdf> [6 June 2010]

Europump & HI, 2004. Variable speed pumping: a guide to successful applications. Oxford, UK:Elsevier.

Falkner, H & Holt, S., 2011. Walking the torque: proposed work plan for energy-efficiency policy opportunities for electric motor-driven systems. Paris: International Energy Agency. Available online [http://www.iea.org/papers/2011/Walking\\_the\\_Torque.pdf](http://www.iea.org/papers/2011/Walking_the_Torque.pdf) [3 May 2011]

Fanchi, J. R., 2004. Energy:technology and directions for the future. Burlington:Elsevier

Finch, J.W., 2008. Controlled ac electrical drives. *IEEE Transactions on Industrial Electronics*, 55:2, 481-491

Fitzgerald, A. E., Kingsley, C & Umans, S.D., 2003. Electric machinery, 6<sup>th</sup> ed. NY:McGraw-Hill

Fox, R.W., McDonald, A.T & Pritchard, P.J., 2011. Introduction to Fluid Mechanics, 8th ed. Hoboken, NJ: John Wiley

Gabus, R.O., 2006. Types of pumps. In: Jones, G.M., Bosserman, B.E., Sanks, R.L and Tchobanoglous, G eds., 2006. Pumping station design, 3<sup>rd</sup> ed. Burlington: Elsevier

Galceran, S., Teixido, M., Sumper, A., Casa, J & Sanchez, J., 2003. Adjustable speed drives and power quality, International Conference of Renewable Energies and Power Quality, Vigo, Spain, 9-12 April. Available online <http://www.icrepq.com/pdfs/SUDRIA364.pdf> [25 April 2010]

GAMBIA & REMA, 2001. Variable speed drives and motors: motor insulation voltage stresses under PWM inverter operation. Available online [http://www.rema.uk.com/pdfs/tech\\_rep\\_no\\_1\\_web.pdf](http://www.rema.uk.com/pdfs/tech_rep_no_1_web.pdf) [9 April 2010]

- Gibson, I.H., 1994. Variable-speed drives as flow control elements. *ISA Transactions* 33, 165-169
- Giesselmann, M., 2007. Computer simulation of power electronics and motor drives. In: Rashid, M.H ed., 2007. *Power electronics handbook*. Oxford:Elsevier
- Gnacinski, P., 2007. Energy saving work of frequency controlled induction cage machine. *Energy Conversion and Management* 48, 919-926
- Goldemberg, J & Lucon, O., 2010. *Energy, environment and development*, 2<sup>nd</sup> ed. London:Earthscan
- Goldemberg, J & Prado, L.T.S., 2011. The decline of the world's energy intensity. *Energy Policy* 39, 1802–1805
- Gottlieb, I.M., 1997. *Practical electric motor handbook*. Oxford:Butterworth-Heinemann
- Gupta, J.B., 2005. *Theory and performance of electrical machines*, 14<sup>th</sup> ed. Delhi:S.K Kataria
- Halpin, S. M., 2005. Comparison of IEEE and IEC harmonic standards. *IEEE Power Engineering Society General Meeting* 3: 2214 – 2216
- Hanitsch, R., 2002. Energy efficient electric motors. World Climate & Energy Event. Conference & Exhibition, Rio de Janeiro, January 6 - 11, 45-50. Available online [http://www.rio02.com/proceedings/pdf/045\\_Hanitsch.pdf](http://www.rio02.com/proceedings/pdf/045_Hanitsch.pdf) [10 August 2010]
- Harvey, L.D.D., 2010. *Energy and the new reality 1: energy efficiency and the demand for energy services*. London: Earthscan
- Herring,H & Sorrell,S. eds.,2009. *Energy efficiency and sustainable consumption: the rebound effect*. London:Palgrave Macmillan
- HI & US-DOE, 2006. *Improving pumping system performance: a sourcebook for industry*. 2<sup>nd</sup> ed. Parsippany, NJ:Hydraulic Institute. Available online <http://www.eere.energy.gov/industry/bestpractices/pdfs/pump.pdf> [1 April 2010]
- Hollander, J. M & Schneider, R.T., 1996. Energy-efficiency: issues for the decade. *Energy* 2:4, 273-281
- Hughes,E.,2008. *Electrical and electronic technology*, 10 ed. Revised by Hiley, J., Brown, K & Smith, M.I. Harlow, England:Pearson
- IEC, 2009. IEC 60034-31: Rotating electrical machines – Part 31: Guide for the selection and application of energy-efficient motors including variable-speed applications. Available online [http://www.motorsystems.org/file/otherfiles/0000/0039/21554\\_CD.pdf](http://www.motorsystems.org/file/otherfiles/0000/0039/21554_CD.pdf) [16 April 2011]
- IEEE, 2000. *IEEE 100: the authoritative dictionary of IEEE standard terms*, 7th ed. NY:IEEE
- IEEE, 2011. IEEE to develop standards limiting insertion of harmonics into power grid. Available online <http://standards.ieee.org/news/2011/harmonic.html> [7 August 2011]
- Inglesi,R & Pouris, A., 2010. Forecasting electricity demand in South Africa: a critique of Eskom's projections. *South African Journal of Science* 1/2: 106, 1-4. Available online <http://www.sajs.co.za/index.php/SAJS/article/download/16/158> \_\_[20 May 2010]

- Jasinski, M & Kazmierkowski, M. P., 2011. Fundamentals of AC–DC–AC converters control and applications. In: Wilamowski, B. M & Irwin, J. D eds., 2011. The industrial electronics handbook:power electronics and motor drives. Boca Raton:Taylor and Francis
- Johansson, J.,2009. Intelligent drives on the rise again. World Pumps, Octobers 2009
- Jordan, H.E., 1983. Energy efficient electric motors and their application. New York:Van Nostrand Reinhold
- Kaiser, T.F, Osman, R.H & Dickau, R.O., 2008. Analysis guide for variable frequency drive operated centrifugal pumps. 24<sup>th</sup> International Pump Users Symposium, Houston, Texas, April 21 – 24, 81 – 106. Available online <http://turbolab.tamu.edu/uploads/files/papers/p24/P24Tut06.pdf> [15 July 2010]
- Karassik, I.J, Messina, J.P, Cooper, P & Heald, C.C. eds., 2001. Pump handbook. 3<sup>rd</sup> ed. New York:McGraw-Hill
- Kazmierkowski, M. P., 2011. Control of converter-fed induction motor drives. In: Wilamowski, B. M & Irwin, J. D eds., 2011. The industrial electronics handbook:power electronics and motor drives. Boca Raton:Taylor and Francis
- Kazmierkowski, M. P., Malinowski, M & Bech, M., 2002. Pulse width modulation techniques for three-phase voltage source converters. In: Kazmierkowski, M.P., Krishnan, R & Blaabjerg, F eds., 2002. Control in power electronics:selected problems.New York:Elsevier
- Kirtley, J.L., 2010. Electric power principles: sources, conversion, distribution and use. Chichester: John Wiley
- Kosow,I.L., 1986. Electrical machines and transformers. Rio de Janeiro:Globo
- Kreith, F., 2008. Introduction to energy management and conservation.In: Kreith, F & Goswami, D. Y eds., 2008. Energy management and conservation handbook. Boca Raton,FL: Taylor & Francis
- Lander, C.W., 1993. Power electronics, 3<sup>rd</sup> ed. Berkshire:McGraw-Hill
- Laughy, R., Liang, X & Liu, J., 2007. Investigation of induction motors starting and operation with Variable Frequency Drives. IEEE Canadian Conference on Electrical and Computer Engineering, CCECE 2007, 556-561
- Lehman, M., 2004. Progressive cavity pumps in oil and gas production. World Pumps October 2004, 20-22. Available online [http://www.sciencedirect.com/science?\\_ob=MIimg&\\_imagekey=B6VJK-4DHNTCD-K-7&\\_cdi=6097&\\_user=3956543&\\_pii=S0262176204003566&\\_origin=&\\_coverDate=10%2F01%2F2004&\\_sk=979959542&view=c&wchp=dGLzVzb-zSkzk&md5=09b4ad21cd4e6883dfc7cb798691d483&ie=/sdarticle.pdf](http://www.sciencedirect.com/science?_ob=MIimg&_imagekey=B6VJK-4DHNTCD-K-7&_cdi=6097&_user=3956543&_pii=S0262176204003566&_origin=&_coverDate=10%2F01%2F2004&_sk=979959542&view=c&wchp=dGLzVzb-zSkzk&md5=09b4ad21cd4e6883dfc7cb798691d483&ie=/sdarticle.pdf) [25 Jan 2011]
- Leon, A.E. & Solsona, J.A., 2010. On state estimation in electric drives. *Energy Conversion and Management* 51, 600-605
- Leonhard, W., 1996. Controlled ac drives, a successful transition from ideas to industrial practice. *Control Engineering Practice* 4:7, 897-908
- Lipo,T.A., 1988. Recent progress in the development of solid state ac motor drives, *IEEE Transactions on Power Electronics* 3:2, 105-117

Lipo, T.A. & Novotny, D.W., 1988. Induction motor application considerations for adjustable speed drives. EPRI Workshop on Adjustable Speed Drive Motors, Albany, NY, 23-24, 10-24. Available online <http://lipo.ece.wisc.edu/1980s%20pub/88-34.pdf> [15 June 2010]

Ljung, L & Glad, T., 1994. Modeling of dynamic systems. New Jersey: Prentice-Hall

Malinowski, J., McCormick, J & Dunn, K., 2004. Advances in construction techniques of ac induction motors: preparation for super-premium efficiency levels. *IEEE Transactions on Industry Applications* 40:6, 1665-1670

Manoharan, S., Devarajan, N., Deivasahayam, S. M & Ranganathan, G., 2009. Review on efficiency improvement in squirrel cage induction motor by using DCR technology. *Journal of Electrical Engineering* 60:4, 227-236

Mardam-Bey, O., 2007. Life cycle cost optimization of pumping systems: brief methodology description. *Arab Research Institute in Science & Engineering* 3:2, 83-90

Matthews, C., 2002. Engineers guide to rotating equipment: the pocket reference. Suffolk: Professional Engineering

Matsumoto, J & Nakata, T., 2008. The energy system analysis and forecasts of the Republic of South Africa. Proceedings of the Industrial & Commercial Use of Energy (ICUE) Conference 2008. Cape Town. Available online: <http://active.cput.ac.za/energy/web/ICUE/DOCS/353/Paper%20-%20Matsumoto%20J.pdf> [1 June 2011]

Mecrow, B.C & Jack, A.G., 2008. Efficiency trends in electric machines and drives. *Energy Policy* 36, 4336-4341

Metwally, H.M.B, Abdel-Kader, F.E, El-Shewy, H.M & El-Kholy, M.M., 2002. Proposed torque optimized behaviour for digital speed control of induction motors. *Energy Conversion and Management* 43, 1675-1688

Mohan, N., Undeland, T.M & Robins, W.P., 2003. Power electronics: converters, applications, and design, 3<sup>rd</sup> ed. NJ: John Wiley

Mohanty, N.K, Muthu, R & Kumaran, M.S., 2009. A survey on controlled ac electrical drives. *International Journal of electrical and Power Engineering* 3:3, 175 - 183

Montanari, M., Peresada, S & Tilli, A., 2006. A speed-sensorless indirect field-oriented control for induction motors based on high gain speed estimation. *Automatica* 42, 1637-1650

Morvaj, Z.K & Gvozdenac, D.D., 2008. Applied industrial energy and environmental management. West Sussex, UK: John Wiley

Mthombeni, T.L & Sebitosi, A.B., 2008. Impact of introducing minimum energy performance standards for electric motors in South Africa. Proceedings of the International Conference on Industrial Use of Energy, Cape Town. Available online: <http://active.cput.ac.za/energy/web/ICUE/DOCS/324/Presentation%20-%20Mthombeni%20T.pdf> [25 June 2011]

Muravlev, O., Muravleva, O & Vekhter, E., 2005. Energetic parameters of induction motors as the basis of energy saving in a variable speed drive. *Electrical Power Quality and Utilisation* 11:2, 99-106. Available online <http://www.leonardo-energy.org/repository/Library/EPQU/JVoll1No2/muravlev.pdf> [1 October 2010]

- Nelik, L., 1999. Centrifugal and rotary pumps: fundamentals with applications. Boca Raton: CRC Press
- Nelik, L & Brennan, J., 2005. Progressive cavity pumps, downhole pumps, and mudmotors. Houston: Gulf
- NEMA, 2007. Application guide for ac adjustable speed drive systems. Rosslyn: NEMA.
- Nesbitt, 2001. Intelligent pump units and life cycle costs. *World Pumps* 2001:415, 20-25
- Okrasa, R., 1997. Adjustable speed drive: reference guide, 4<sup>th</sup> ed. Ontario: Ontario Hydro
- Ouadi, H., Giri, F., Elfadili, A & Dugard, L., 2010. Induction machine speed control with flux optimization. *Control Engineering Practice* 18, 55-66
- Pemberton, M., 2003. Strategies for optimizing pump efficiency and LCC Performance. Available online [http://www.ittrem.com/Strategies\\_Efficiency\\_Performance.html](http://www.ittrem.com/Strategies_Efficiency_Performance.html) [6 April 2010]
- Petruzella, F. D., 2010. Electric motors and control systems. New York: McGraw-Hill
- Polka, D., 2003. Motors and drives: a practical technology guide. NC: Instrumentation Systems and Automation Society
- Powersim, 2010. PSIM User's guide. Available online <http://www.powersimtech.com> [3 Oct 2010]
- PSRC, 2009. Adjustable speed drive motor protection applications and issues. Available online [http://www.pes-psrc.org/Reports/Final\\_J1\\_ASD\\_Motor\\_Protection\\_Applications\\_and\\_Issues\\_Working\\_Group\\_Report.pdf](http://www.pes-psrc.org/Reports/Final_J1_ASD_Motor_Protection_Applications_and_Issues_Working_Group_Report.pdf) [9 Nov 2010]
- Prachyl, S., 2010. Variable frequency drives and energy savings: it's more than just fan and pump applications. [http://www.sea.siemens.com/us/internet-dms/dt/DrivesComm/Drives/Docs/VariableFrequencyDrives\\_WhitePaper.pdf](http://www.sea.siemens.com/us/internet-dms/dt/DrivesComm/Drives/Docs/VariableFrequencyDrives_WhitePaper.pdf) [8 May 2010]
- PSM & HI, 2008. Optimizing pump systems: a guide for improved energy efficiency, reliability and profitability. Executive summary is available online [http://www.pumpsystemsmatter.org/content\\_detail.aspx?id=3792](http://www.pumpsystemsmatter.org/content_detail.aspx?id=3792) [6 April 2010]
- Qureshi, T.Q & Tassou, S.A., 1996. Variable-speed capacity control in refrigeration systems. *Applied Thermal Engineering* 16:2, 103-113
- Ramachandra, T.V., Yves, L & Shruthi, B.V., 2006. Intra and inter country energy intensity trends. *The Journal of Energy and Development* 31:1, 43-84. Available online [http://wgbis.ces.iisc.ernet.in/energy/paper/energy\\_development/Microsoft%20Word%20-%20energydev.pdf](http://wgbis.ces.iisc.ernet.in/energy/paper/energy_development/Microsoft%20Word%20-%20energydev.pdf) [1 June 2011]
- Rao, P.N.A.P., 2008. Proliferation of EMC standards – a case for harmonization. IEEE Proceeding of 10th International Conference on Electromagnetic Interference & Compatibility, INCEMIC 2008. 531 - 537

- Rice, D.E., 1988. A suggested energy-savings evaluation method for ac adjustable-speed drive applications. *IEEE Transactions on Industrial Applications* 24:6, 1107-1117
- Rishel, J.B., 2002. Water pumps and pumping systems. New York: McGraw-Hill
- Ritz-Atro, 2005. Archimedean screw pumps. Available online <http://www.ntkmy.com/products/ritz/pdf/Archimediandescrowpumpcatalogue.pdf> [20 March 2011]
- Rockwell Automation, 2000. Adjustable speed drives as applied to centrifugal pumps. <http://www.reliance.com/prodserv/standriv/appnotes/d7737.pdf> [10 May 2010]
- Rosen, H., 2009. Towards pump efficiency in South Africa, *Mechanical Technology* — August 2009  
[http://www.ipuc.co.za/press\\_release/MechTech%20Aug%202009%20IPUC%20article.pdf](http://www.ipuc.co.za/press_release/MechTech%20Aug%202009%20IPUC%20article.pdf) [12 Feb 2010]
- RSA, 2009. National energy efficiency strategy of the Republic of South Africa. Government Gazette 528:32342. Pretoria:RSA. Available online [http://www.energy.gov.za/files/media/explained/strategy\\_energyefficiency\\_2009.pdf](http://www.energy.gov.za/files/media/explained/strategy_energyefficiency_2009.pdf) [10 June 2011]
- Saidur, R., 2010. A review on electrical motors energy use and energy savings. *Renewable and Sustainable Energy Reviews* 14, 877–898
- Salon, S. J., 2004. Introduction to electric machines. In: Chen, S-K ed., 2004. The electrical engineering handbook. London: Elsevier
- SAPMA, 2005. Pumps: principles and practice. 5<sup>th</sup> ed. Johannesburg: South African Pump Manufacturers' Association.
- Sarhan, H & Issa, R., 2006. Improving mechanical characteristics of inverter-induction motor drive system. *American Journal of Applied Sciences* 3:8, 1961-1966
- Sebitosi, A B., 2008. Energy efficiency, security of supply and the environment in South Africa: moving beyond the strategy documents. *Energy* 33, 1591–1596
- Sen, P.C., 1997. Principles of electric machines and power electronics, 2<sup>nd</sup> ed. NY: John Wiley
- Shakweh, Y., 2007. Drives types and specifications. In: Rashid, M.H ed., 2007. Power electronics handbook. Oxford: Elsevier
- Singh, B.N., Singh, B & Singh, B.P., 1994. Performance analysis of a closed-loop field oriented cage induction motor drive. *Electric Power Systems Research* 29, 69-81
- Sola, A.V.H & de Paula Xavier, A.A., 2007. Organizational human factors as barriers to energy efficiency in electrical motors systems in industry. *Energy Policy* 35, 5784-5794
- Solmes, L. A., 2009. Energy efficiency: real time energy infrastructure investment and risk management. Dordrecht: Springer
- Square D, 1994. Power system harmonics: causes and effects of variable frequency drives relative to the IEEE 519-1992 Standard. Product Data Bulletin No. 8803PD9402. Available online <http://ecatalog.squared.com/pubs/Motor%20Control/AC%20Drives/8803PD9402.pdf> [20 June 2011]

- Subrahmanyam, V., 1994. *Electric drives: concepts and applications*. NY:McGraw-Hill
- Suehiro, S., 2007. Energy intensity of GDP as an index of energy conservation. *IEEJ Energy Journal*. Available online <http://eneken.ieej.or.jp/data/400.pdf> [13 June 2011]
- Sul, S-K., 2011. *Control of electric machine drive system*. NY:IEEE Press
- Swarupa, M.L., Das, G.T.R & Gopal, P.V.R., 2009. Simulation and analysis of SVPWM based 2-level and 3-level inverters for direct torque of induction motor. *International Journal of Electronic Engineering Research* 1:3, 169-184
- Tripathy, S.C., 1995. Energy conservation with efficient electric drives. *Energy Conversion and Management* 36:2, 125-134
- Trzynadlowski, A.M., 2001. *Control of induction motors*. CA:Academic Press
- Twining, E & Cochrane, I., 1999. Modelling variable speed ac drives and harmonic distortion. *Proceedings of Australasian Universities Power Engineering Conference, AUPEC '99*, Northern Territory University, Darwin, Sept 26-29
- US-DOE, 2002. *Energy Matters*. Available online [http://www1.eere.energy.gov/industry/bestpractices/energymatters/pdfs/em\\_volume19.pdf](http://www1.eere.energy.gov/industry/bestpractices/energymatters/pdfs/em_volume19.pdf) [5 March 2011]
- US-DOE, 2008. Improving motor and drive system performance: a source for industry. Available online <http://www1.eere.energy.gov/industry/bestpractices/pdfs/motor.pdf> [10 April 2011]
- US-EIA, 1995. Measuring energy efficiency in the United States' economy: a beginning <http://tonto.eia.doe.gov/ftproot/consumption/0555952.pdf> [4 March 2010]
- US-EIA, 2010. *International energy outlook 2010*. Available online [http://www.eia.gov/oiaf/ieo/pdf/0484\(2010\).pdf](http://www.eia.gov/oiaf/ieo/pdf/0484(2010).pdf) [9 April 2011]
- Vaez-Zadeh, S & Hendi, F., 2005. A continuous efficiency optimization controller for induction motor drives. *Energy Conversion and Management* 46, 701-713
- Vas, P & Drury, W., 1996. *Electrical machines and drives: present and future*. IEEE Proceedings of Electrotechnical Conference, MELECON '96, Bari, Italy, 13-16 May, 1, 67-74
- Viholainen, J., Kortelainen, J., Ahonen, T., Aranto, N & Vakkilainen, E., 2009. Energy efficiency in variable speed drive (VSD) controlled parallel pumping. *Proceedings of 6<sup>th</sup> International Conference on Energy Efficiency on Motor Driven Systems*, Nantes (France), 14-17 September 2009
- Volk, M., 2005. *Pump characteristics and applications*. 2<sup>nd</sup> ed. Boca Raton: Taylor & Francis
- Vukosavic, S.N., 1998. Controlled electrical drives – status of technology. *ETRAN XLII Conference*, Vrnjacka Banja, Yugoslavia, 2-5 June, 1, 3-16. Available online <http://energetika.etfbl.net/~mpuemp/TE5MUE/Trendovi.pdf> [15 July 2010]
- Waide, P & Brunner, C. U., 2011. *Energy-efficiency policy opportunities for electric motor-driven systems*. Paris:International Energy Agency. Available online [http://www.iea.org/papers/2011/EE\\_for\\_ElectricSystems.pdf](http://www.iea.org/papers/2011/EE_for_ElectricSystems.pdf) [20 May 2011]

WAG, 2002. Motors and variable speed drives. Available online <http://igs.nigc.ir/IGS/ARTIC/MT-08.PDF> [1 April 2011]

Wang, Lijun ,2008.Energy efficiency and management in food processing facilities. Boca Raton:CRC Press

Warwick, J, Van Zyl, E & De Lange, Y., 2008. Energy efficiency made simple. Vol. II. Bedfordview[Johannesburg]:Crown Publications

WEC, 2008. Energy efficiency policies around the world:review and evaluation. London:World Energy Council. Available online [http://www.worldenergy.org/documents/energy\\_efficiency\\_es\\_final\\_online.pdf](http://www.worldenergy.org/documents/energy_efficiency_es_final_online.pdf) [3 April 2010]

WEC, 2010. Energy efficiency: a recipe for success. London: World Energy Council. Available online [http://www.worldenergy.org/documents/fdeneff\\_v2.pdf](http://www.worldenergy.org/documents/fdeneff_v2.pdf) [24 April 2011]

WEG, 2010. Induction motors fed by PWM frequency inverters. Available online <http://www.weg.net/files/products/WEG-induction-motors-fed-by-pwm-frequency-converters-technical-guide-028-technical-article-english.pdf> [10 Nov 2010]

WEG, 2011. Frequency inverter (CFW-09) user's manual. Available online <http://catalogo.weg.com.br/files/wegnet/WEG-cfw-09-users-guide-0899.5306-4.4x-manual-english.pdf> [10 June 2011]

Wikipedia, Adjustable-speed drive [http://en.wikipedia.org/wiki/Adjustable-speed\\_drive](http://en.wikipedia.org/wiki/Adjustable-speed_drive) [12 Feb 2010]

Wikipedia, Conservation of energy [http://en.wikipedia.org/wiki/Conservation\\_of\\_energy](http://en.wikipedia.org/wiki/Conservation_of_energy) [4 June 2011]

Wikipedia, Efficient energy use [http://en.wikipedia.org/wiki/Efficient\\_energy\\_use](http://en.wikipedia.org/wiki/Efficient_energy_use) [5 March 2010]

Wikipedia, Pulse-width modulation [http://en.wikipedia.org/wiki/Pulse-width\\_modulation](http://en.wikipedia.org/wiki/Pulse-width_modulation) [27 July 2011]

World Pumps, 2009. A brief history of pumps. Available online <http://www.worldpumps.com/view/813/a-brief-history-of-pumps/> [7 July 2011]

Wu, B., 2006. H-power converters and ac drives. New York: IEEE Press

Yanagisawa,A., 2011. Trade-off in energy efficiencies and efficient frontier. IEEJ Energy Journal. Available online <http://eneken.ieej.or.jp/data/3618.pdf> [16 June 2011]

Yang, G., 2007. Life cycle reliability engineering. Hoboken, NJ: John Wiley

## APPENDICES

### Appendix 1: Wynberg Pumping Trend

Pumping Trend Of Pumps in Pump house no3 - May 2011			
Date	Consumption Pump No 1	Consumption Pump No 2	Hours
1	15,681		15
2	23,625		24
3	17,661		17.5
4	23,995		24
5	10,875		10
6			
7			
8			
9			
10		21,153	21
11		20,777	20
12		21,703	21.5
13		19,382	19
14		22,049	22
15		23,303	23.5
16		17,877	17
17			
18			
19			
20			
21			
22			
23			
24	17,684		17.5
25	19,700		19.5
26	21,272		22
27	20,120		22
28	22,757		24
29	17,073		17
30	21,214		21
31		18,182	18

## Appendix 2: Monterey Pumping Trend

Pumping Trend Of Monterey Pumps - May 2011			
Date	Consumption Pump No 1	Consumption Pump No 2	Hours
1		9,046	15
2		10,264	17
3		10,700	17
4	10,477		12.5
5	11,073		17
6	11,904		19.5
7	10,275		17
8	11,177		17.5
9	8,548		14.5
10		13,363	17.5
11		9,571	15.5
12	10,872		17.5
13	10,484		16.5
14		11,490	16.5
15		11,735	18.5
16		9,640	16.5
17	11,422		17
18	11,692		18.5
19	10,661		16
20	12,430		19.5
21	11,660		18.5
22	11,248		18.5
23	9,572		16.3
24	10,497		15
25		10,076	15
26		10,949	19
27		9,231	15
28		12,185	20.5
29		8,826	17.5
30		10,890	18.5
31	9,413		15.5

### Appendix 3: Caltex Refinery Sludge feed pump PI data

28PI056.PV		28SI056A.PV		28SI056B.PV	
Date/Time	Pressure(kPa)	Date/Time	Hz	Date/Time	Hz
24-Mar-11		24-Mar-11		24-Mar-11	
10:48:24	1.971862793	10:48:24	48.83	10:48:24	48.83
24-Mar-11		24-Mar-11		24-Mar-11	
10:49:24	8.184118271	10:49:24	48.83	10:49:24	48.83
24-Mar-11		24-Mar-11		24-Mar-11	
10:52:24	85.99331665	10:52:24	36.49	10:52:24	36.49
24-Mar-11		24-Mar-11		24-Mar-11	
10:53:24	118.0725327	10:53:24	37.37	10:53:24	37.37
24-Mar-11		24-Mar-11		24-Mar-11	
10:54:24	150.8729095	10:54:24	37.07	10:54:24	37.07
24-Mar-11		24-Mar-11		24-Mar-11	
10:55:24	191.2017975	10:55:24	36.58	10:55:24	36.58
24-Mar-11		24-Mar-11		24-Mar-11	
10:56:24	238.0912476	10:56:24	35.71	10:56:24	35.71
24-Mar-11		24-Mar-11		24-Mar-11	
10:57:24	282.1463623	10:57:24	34.58	10:57:24	34.58
24-Mar-11		24-Mar-11		24-Mar-11	
10:58:24	317.8993225	10:58:24	33.45	10:58:24	33.45
24-Mar-11		24-Mar-11		24-Mar-11	
10:59:24	350.6919861	10:59:24	32.68	10:59:24	32.68
24-Mar-11		24-Mar-11		24-Mar-11	
11:00:24	383.0259705	11:00:24	32.29	11:00:24	32.29
24-Mar-11		24-Mar-11		24-Mar-11	
11:01:25	414.3485718	11:01:25	31.89	11:01:25	31.89
24-Mar-11		24-Mar-11		24-Mar-11	
11:02:25	444.5175476	11:02:25	31.72	11:02:25	31.72
24-Mar-11		24-Mar-11		24-Mar-11	
11:03:25	472.7531738	11:03:25	31.38	11:03:25	31.38
24-Mar-11		24-Mar-11		24-Mar-11	
11:04:25	499.8994751	11:04:25	31.34	11:04:25	31.34
24-Mar-11		24-Mar-11		24-Mar-11	
11:05:25	524.6124878	11:05:25	31.19	11:05:25	31.19
24-Mar-11		24-Mar-11		24-Mar-11	
11:06:25	548.0740356	11:06:25	31.03	11:06:25	31.03
24-Mar-11		24-Mar-11		24-Mar-11	
11:07:25	571.0078735	11:07:25	31.01	11:07:25	31.01
24-Mar-11		24-Mar-11		24-Mar-11	
11:08:25	595.1099243	11:08:25	31.03	11:08:25	31.03
24-Mar-11		24-Mar-11		24-Mar-11	
11:09:25	616.9055786	11:09:25	31.04	11:09:25	31.04
24-Mar-11		24-Mar-11		24-Mar-11	
11:10:25	639.1902466	11:10:25	31.07	11:10:25	31.07
24-Mar-11		24-Mar-11		24-Mar-11	
11:11:25	659.2887573	11:11:25	31.11	11:11:25	31.11
24-Mar-11		24-Mar-11		24-Mar-11	
11:12:25	679.7758789	11:12:25	31.15	11:12:25	31.15
24-Mar-11		24-Mar-11		24-Mar-11	
11:13:25	699.8109131	11:13:25	31.22	11:13:25	31.22

24-Mar-11			24-Mar-11		24-Mar-11
11:14:25	719.0501099		11:14:25	31.30	11:14:25 31.30
24-Mar-11			24-Mar-11		24-Mar-11
11:15:25	737.828125		11:15:25	31.37	11:15:25 31.37
24-Mar-11			24-Mar-11		24-Mar-11
11:16:25	756.2000732		11:16:25	31.47	11:16:25 31.47
24-Mar-11			24-Mar-11		24-Mar-11
11:17:25	773.913208		11:17:25	31.55	11:17:25 31.55
24-Mar-11			24-Mar-11		24-Mar-11
11:18:25	792.0272827		11:18:25	31.67	11:18:25 31.67
24-Mar-11			24-Mar-11		24-Mar-11
11:19:25	807.446106		11:19:25	31.75	11:19:25 31.75
24-Mar-11			24-Mar-11		24-Mar-11
11:20:25	824.3788452		11:20:25	31.79	11:20:25 31.79
24-Mar-11			24-Mar-11		24-Mar-11
11:21:25	843.864502		11:21:25	31.99	11:21:25 31.99
24-Mar-11			24-Mar-11		24-Mar-11
11:22:25	860.6664429		11:22:25	32.20	11:22:25 32.20
24-Mar-11			24-Mar-11		24-Mar-11
11:23:26	877.9326782		11:23:26	32.40	11:23:26 32.40
24-Mar-11			24-Mar-11		24-Mar-11
11:24:26	894.8526611		11:24:26	32.55	11:24:26 32.55
24-Mar-11			24-Mar-11		24-Mar-11
11:25:26	910.1013184		11:25:26	32.66	11:25:26 32.66
24-Mar-11			24-Mar-11		24-Mar-11
11:26:26	923.5762329		11:26:26	32.70	11:26:26 32.70
24-Mar-11			24-Mar-11		24-Mar-11
11:27:26	941.9370117		11:27:26	32.93	11:27:26 32.93
24-Mar-11			24-Mar-11		24-Mar-11
11:28:26	959.354126		11:28:26	33.18	11:28:26 33.18
24-Mar-11			24-Mar-11		24-Mar-11
11:29:26	974.581604		11:29:26	33.43	11:29:26 33.43
24-Mar-11			24-Mar-11		24-Mar-11
11:30:26	987.4268799		11:30:26	33.55	11:30:26 33.55
24-Mar-11			24-Mar-11		24-Mar-11
11:31:26	1001.918762		11:31:26	33.66	11:31:26 33.66
24-Mar-11			24-Mar-11		24-Mar-11
11:32:26	1021.116333		11:32:26	33.91	11:32:26 33.91
24-Mar-11			24-Mar-11		24-Mar-11
11:33:26	1037.102539		11:33:26	34.15	11:33:26 34.15
24-Mar-11			24-Mar-11		24-Mar-11
11:34:26	1052.891113		11:34:26	34.34	11:34:26 34.34
24-Mar-11			24-Mar-11		24-Mar-11
11:35:26	1065.330444		11:35:26	34.44	11:35:26 34.44
24-Mar-11			24-Mar-11		24-Mar-11
11:36:26	1081.579102		11:36:26	34.66	11:36:26 34.66
24-Mar-11			24-Mar-11		24-Mar-11
11:37:26	1097.908325		11:37:26	34.92	11:37:26 34.92
24-Mar-11			24-Mar-11		24-Mar-11
11:38:26	1112.721191		11:38:26	35.16	11:38:26 35.16
24-Mar-11			24-Mar-11		24-Mar-11
11:39:26	1124.493286		11:39:26	35.27	11:39:26 35.27
24-Mar-11			24-Mar-11		24-Mar-11
11:41:09	1191.091919		11:41:09	35.49	11:41:09 35.49

11:40:26		11:40:26		11:40:26	
24-Mar-11		24-Mar-11		24-Mar-11	
11:41:26	1158.235107	11:41:26	35.75	11:41:26	35.75
24-Mar-11		24-Mar-11		24-Mar-11	
11:42:26	1171.754272	11:42:26	35.98	11:42:26	35.98
24-Mar-11		24-Mar-11		24-Mar-11	
11:43:26	1182.115234	11:43:26	36.05	11:43:26	36.05
24-Mar-11		24-Mar-11		24-Mar-11	
11:44:27	1200.345947	11:44:27	36.31	11:44:27	36.31
24-Mar-11		24-Mar-11		24-Mar-11	
11:45:27	1215.658691	11:45:27	36.64	11:45:27	36.64
24-Mar-11		24-Mar-11		24-Mar-11	
11:46:27	1227.686768	11:46:27	36.77	11:46:27	36.77
24-Mar-11		24-Mar-11		24-Mar-11	
11:47:27	1241.012207	11:47:27	36.97	11:47:27	36.97
24-Mar-11		24-Mar-11		24-Mar-11	
11:48:27	1256.140869	11:48:27	37.26	11:48:27	37.26
24-Mar-11		24-Mar-11		24-Mar-11	
11:49:27	1269.022217	11:49:27	37.43	11:49:27	37.43
24-Mar-11		24-Mar-11		24-Mar-11	
11:50:27	1281.508545	11:50:27	37.54	11:50:27	37.54
24-Mar-11		24-Mar-11		24-Mar-11	
11:51:27	1298.192749	11:51:27	37.89	11:51:27	37.89
24-Mar-11		24-Mar-11		24-Mar-11	
11:52:27	1303.260132	11:52:27	37.70	11:52:27	37.70
24-Mar-11		24-Mar-11		24-Mar-11	
11:53:27	1301.657837	11:53:27	37.45	11:53:27	37.45
24-Mar-11		24-Mar-11		24-Mar-11	
11:54:27	1302.540405	11:54:27	37.21	11:54:27	37.21
24-Mar-11		24-Mar-11		24-Mar-11	
11:55:27	1302.10376	11:55:27	36.98	11:55:27	36.98
24-Mar-11		24-Mar-11		24-Mar-11	
11:56:27	1302.009888	11:56:27	36.78	11:56:27	36.78
24-Mar-11		24-Mar-11		24-Mar-11	
11:57:27	1301.606689	11:57:27	36.59	11:57:27	36.59
24-Mar-11		24-Mar-11		24-Mar-11	
11:58:27	1301.873413	11:58:27	36.46	11:58:27	36.46
24-Mar-11		24-Mar-11		24-Mar-11	
11:59:27	1302.023193	11:59:27	36.27	11:59:27	36.27
24-Mar-11		24-Mar-11		24-Mar-11	
12:00:27	1300.878784	12:00:27	36.12	12:00:27	36.12
24-Mar-11		24-Mar-11		24-Mar-11	
12:01:27	1301.254761	12:01:27	36.00	12:01:27	36.00
24-Mar-11		24-Mar-11		24-Mar-11	
12:02:27	44.11249542	12:02:27	0.00	12:02:27	0.00
24-Mar-11		24-Mar-11		24-Mar-11	
12:03:27	32.71473312	12:03:27	0.00	12:03:27	0.00

## Appendix 4: Electric motor data



**WEG EQUIPAMENTOS ELETRICOS S.A**  
 Rua Prof. Waldemar Grubba, 3000 - Caixa Postal 420  
 89256-900 - Jaraguá do Sul, SC - Brasil

Phone (047)372-4000  
 Fax (047)372-4070 e 372-4040

Date: **25.04.2012**

Re. N.º: **411335581**

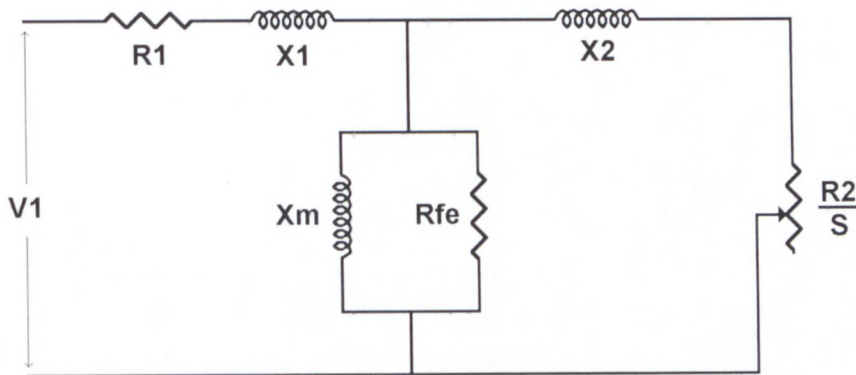
From:

To: **Onwunta**

Page: **1/1**

Attn:

N.º Fax:



R1	0.54493	X1	1.95339
R2	0.45864	X2	3.19370
Rfe	1349.728	Xm	61.24128

Values indicated in  $\Omega$ , at 20°C.

### Motor data

Serial Number	BZ85120	Item	070543161		
Power	22kW	4 Poles	500 V	50 Hz	
Frame size	180L	F c/ $\Delta$ t	80	K - 1.0	RP M 1465
Product line	Standard				

Regards,

Daniele Michels Hornburg

**(A) Energy Efficiency and Reliability Improvement Strategies in Industrial Electric Motor-Driven Systems (EMDS)**

**OEK Onwunta and MTE Kahn**

**Electrical Department, Cape Peninsula University of Technology, South Africa**

**ABSTRACT**

Electric motor has remained a major prime mover of most industrial driven systems. Global estimates are that 40% of industrial electricity is consumed by electric motor systems, and South African estimates are around 60%. Therefore improving energy efficiency of EMDS (Electric Motor-Driven Systems) will ensure the supply of more consumers using the same electricity production capacity; and slow down the electricity demand growth, and reduce the investment needed for the expansion of the electricity sector. There have been growing concerns and innovations on the reduction of losses incurred by a typical electric motor. Harmonisation of electric motor efficiency standards by International Electrotechnical Commission (IEC) and the replacement of die-cast aluminium rotors with die-cast copper rotors are such innovations. EMDS have ancillary components whose collective poor efficiency performance impedes the system efficiency. Therefore there is a need for a system approach to the efficiency improvement.

Most components, if not all, of EMDS are global commodities. They could be manufactured by a company in one part of the globe for another company in another part of the world and to be finally used in yet another part of the world. The preference of a component manufactured in a particular region or country is common in the industry based on the reliability of such a component.

Therefore there exists an interplay between component reliability and efficiency in the overall performance of EMDS. This paper aims at harnessing this interplay.

**1. INTRODUCTION**

Electric Motor-Driven Systems (EMDS) refer to a system whose prime mover is an electric motor. Globally, EMDS consume at least 7000 TWh/yr, roughly equivalent to 45% of all end-use electricity consumption [1] making it the largest end-user of electricity. Also global estimates are that 40% of industrial electricity is consumed by electric motor systems, and South African estimates are around 60% [2]. Such systems could be described by their load characteristics basically as variable torque, constant torque or constant power loads. The most common type of load has variable torque characteristics, in which power and torque are proportional to speed. For example, in centrifugal pumps and fans, torque varies according to the square of speed. This means that the torque varies at a rate proportional to the square of the speed and the power varies as the cube of the speed, reaching 100 percent load torque and power at a defined speed.

In a constant torque load, the torque is independent of speed. So the load torque remains constant throughout the speed range and the power changes linearly with speed for constant torque loads. Common applications include conveyor systems, positive displacement pumps, hoists, and cranes. For example, conveying a 230kg load along an assembly line requires the same amount of torque whether it is moving at a

constant speed of 1.5 metre per minute or 3.0 metre per minute. Although power varies according to speed, torque is constant.

In a constant power load, the torque increases with decreasing speed and vice versa. A good example of this type of load is a winding machine in which the torque increases as the roll thickness builds up but the rotational speed slows down. Machine tools such as lathes and cutting machines display these operating characteristics.

Three phase squirrel cage induction electric motor has become a better and popular choice over direct current motor in the industry. This is because of its inherent characteristics such as being simple in construction, economical, rugged, reliable, and available in wide power ranges [3-5]. Following its wide patronage in industrial processes, ac induction motor has been dubbed the *workhorse* of industrial processes. Mainly due to power electronics and digital control, the induction motor may add to its old nickname of “the workhorse of industry” the label of “the racehorse of high-tech” [6]. Induction motors are very much their own “worst enemy” in that they are reliable, quiet, will survive with little or no maintenance, and so are very much “out of sight, out of mind” [7]. Despite their reliability and being considered as a matured product, induction motors have received continuous attention aimed at improving their efficiency and reliability.

Pumping system is an outstanding EMDS. Pumping systems account for nearly 20% of the world’s energy used by electric motors and 25% to 50% of the total electrical energy usage in certain industrial facilities [8] such as water and waste water treatment plants.

It is estimated that in the United Kingdom, pumps use a total of 20TWh/annum, responsible for the emission of 2.7MtC/annum (2.7 million tons of carbon). Pumps therefore represent the largest single user of motive power in industry and commerce as shown in the breakdown of energy usage by motor driven equipment [9]:

Table 1 Energy Usage by Motor Driven Equipment in EU [9].

S/No	Equipment	Energy Usage (%)
1	Pumps	31
2	Fans	23
3	Compressors	14
4	Air Compressors	8
5	Others	16

Expectedly South Africa with its strong developing economy has a fair share of this high pump energy consumption. In South Africa, an estimated 15% of generated electrical power is consumed by pumping systems [10]. A graphical representation of the industrial energy consumption of South Africa is shown in Fig. 1 [11]. The high energy consumption of pumps is outstanding from this chart and estimated at 13%. The caption of Fig. 1 appears confusing because of its inclusion of Homes & Hotels among others. However, the authors’ interest is the outstanding high percentage of the pumping system energy consumption.

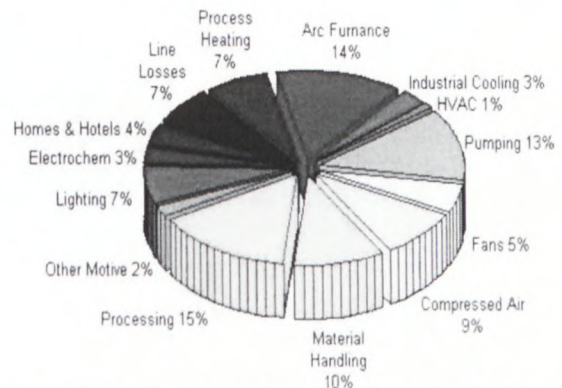


Fig. 1 Maximum energy demand in the industrial sector of South Africa [11]

Therefore this paper considers pumping system and the findings could be adapted to other EMDS.

## 2. ELECTRIC MOTOR EFFICIENCY

Efficiency is one of the performance parameters of an electric motor. It is a measure of the effectiveness with which electrical energy is converted to mechanical energy, and is expressed as the ratio of power output to power input:

$$\begin{aligned} \text{Efficiency} &= \frac{\text{Output Power}}{\text{Input Power}} \\ &= \frac{\text{Output Power}}{\text{Output Power} + \text{Losses}} \end{aligned}$$

Motor efficiencies are usually given for rated load, although 75% load and 50% load may also be provided. The efficiency of a motor is primarily a function of load, rated power, and speed, as indicated below [12]:

- A change in efficiency as a function of load is an inherent characteristic of motors.  
Operation of the motor at loads substantially different from rated load may result in a change in motor efficiency.
- Generally, the full-load efficiency of motors increases with physical size and rated output of motors.
- For the same power rating, motors with higher speeds generally, but not always, have a higher efficiency at rated load than motors with lower rated speeds. This does not imply, however, that all apparatus should be driven by high-speed motors. Where speed-changing mechanisms, such as pulleys or gears, are required to obtain the necessary lower speed, the additional power losses could reduce the efficiency of the system to a value lower than that provided by a direct-drive lower-speed motor.

## 2.1 MOTOR LOSSES

The efficiency of an electric motor as an energy converter is adversely affected by the losses it incurs while in operation. These losses which have been documented in so many literatures are

- Electrical (stator and rotor) losses (vary with load) – Current flowing through the motor windings produces losses which are proportional to the current squared times the winding resistance ( $I^2R$ ). Rotor losses also increase with slip.
- Iron (core) losses (essentially independent of load) – These losses are confined mainly to the laminated

core of the stator and to a lesser degree the rotor. The magnetic field, essential to the production of torque in the motor, causes hysteresis and eddy current losses.

- Mechanical (friction and windage) losses (essentially independent of load) – Mechanical losses occur in the bearings, fans, and seals of the motor. These losses are generally small in slow speed motors, but may be appreciable in large, high-speed or totally-enclosed motors.
- Additional load losses (stray load losses) –The additional fundamental and high-frequency losses in the iron; strand and circulating-current losses in the stator winding; and harmonic losses in the rotor conductors under load. These losses are assumed to be proportional to the torque squared.

The proportions of these losses in a typical motor of 90% efficiency is illustrated in Fig. 2

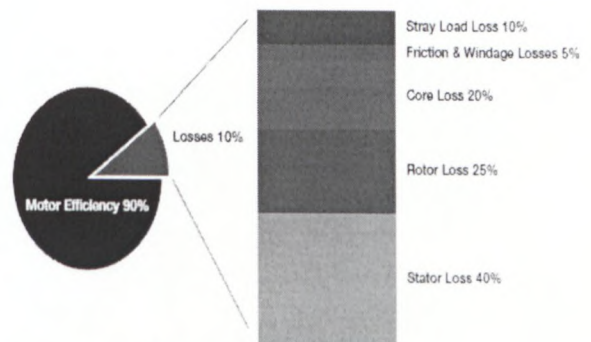


Fig. 2 Typical motor losses [13]

Concerted efforts have been made in the improvement of electric motor efficiency although induction motors are regarded as being a mature technology. Such efficiency improvements have been attributed to adding more copper to the windings, upgrading the laminations to premium-grade low-loss steel, enhanced lamination designs, precision airgap between rotor and stator, and reducing fan and other losses in the motor. The use of die-cast copper rotors (DCR) in place of die-cast aluminium rotors is one method enabling motor efficiency to be increased by as much as 1%–2% [14]. Use and technical issues of

DCR have been addressed [14-15]. The result of using high quality materials is the design and manufacture of high efficient motors.

## 2.2 MOTOR EFFICIENCY CLASSIFICATIONS

Electric motor efficiency classifications have mostly anchored on the manufacturing design and efficiency measurement methods giving rise to various regions having different efficiency standards. Equally efficiency standards could be voluntary or mandatory in different regions of the globe. Two common efficiency measurement standards existed prior to late 2007, namely IEEE 112B and IEC 60034-2:1996, which most nations and regions adapted. These standards differed in their treatment of stray load losses. The vital need to conduct motor efficiency comparisons using a uniform product testing methodology resulted to the harmonisation of these standards as IEC 60034-2-1:2007 and the international efficiency classes as IEC 60034-30:2008. The efficiency class system specified under IEC 60034-30 is valid for low voltage three-phase cage-induction motors with the following specifications [16]:

- Rated voltage up to 1,000 V
- Rated output between 0.75 kW and 375 kW
- Either 2, 4 or 6 poles
- Rated on the basis of continuous duty (S1) or intermittent periodic duty (S3) with cyclic duration factor of 80% or higher;
- Capable of operating direct on-line
- Rated for operating conditions in accordance with IEC 60034-1 (temperature, installation altitude, etc.)

According to [16] IEC 60034-30:2008 defines the efficiency classes as

- IE1 = Standard efficiency
- IE2 = High efficiency
- IE3 = Premium efficiency

## 3. EFFICIENCY OF LOAD AND ANCILLARY COMPONENT

Unfortunately other components (control system and load) of EMDS apparently receive little or no attention in terms of their efficiency measurements and classes. An efficiency-labelling scheme for pumps has been objected to [17] because there would be confusion on pump sets if both the motor and pump have labels with different efficiency ratings. However, [18] suggests that efficiency values for pumps be normally given as a range. Hence, a standard pump would have an efficiency range between 30 and 80%, and a high efficiency pump would have an efficiency range of 60 to 80%.

Variable speed drives (VSDs) continue to be veritable technology deployed for efficient and reliable control of EMDS especially pump systems. Their merits far outweigh their demerits over such traditional control methods as throttling, by-pass or recycling and on-off options. Equally their technical and environmental challenges which include harmonics and EMC (electromagnetic compatibility) effects have continuously received adequate attention. Unfortunately their efficiency testing methodology and efficiency classifications yearn for proper attention. One manufacturer has provided efficiency values for pulse-width modulated variable frequency drives (VFDs) as a function of operating speed for both variable torque loads (centrifugal fans and pumps) and constant torque loads (cranes, hoists) [19]. According to [19], there is no widely accepted test protocol that allows for efficiency comparisons between different drive models or brands. However a solution is in the offing as the VSD test standard (IEC 60034-2-3) will be adopted later in 2011 [1].

## 4. EMDS EFFICIENCY

Table 2 summarizes a typical pump system efficiency values and shows that inefficiency in more than one component can add up quickly, resulting in a very inefficient pumping system. This clearly underscores the essence of a holistic or system approach to the efficiency and reliability improvements of EMDS.

Table 2 Typical pump system efficiency [20]

Pump System Component	Efficiency			
	Range	Low	Average	High
Pump	30 - 85%	30%	60%	85%
Flow Control	20 - 98%	20%	60%	98%
Motor	85 - 95%	85%	90%	95%
Efficiency of System		5%	32%	80%

## 5. FINDINGS

Despite these technological advancements and standardisations aimed at the efficiency improvements of electric motors, over sizing of electric motors remains a source of EMDS efficiency degradation. In an EMDS it is important that the motor power rating be able to support the power requirement of the load without being oversized. Oversized motors tend to incur higher purchase, maintenance, and operating costs which includes costs for power factor correction. A well known solution has been the substitution of multiple smaller motors instead of a single large one to utilize the motors close to their power ratings, thus increasing the system efficiency at partial load in addition to full load. Parallel pumping using VSD technology is an important example of this approach. The advantage of this is the elimination of common pump challenges such as cavitation and hammer associated with some of the traditional pump flow controls. However the percentage of standard or even rewind motors and throttling control systems is still high in Cape Town area of South Africa.

## 6. CONCLUSION

This paper has highlighted the huge energy consumption of EMDS with particular emphasis on pump systems. It is hoped that very soon all EMDS components will have harmonised efficiency classifications being global commodities to ensure general acceptability without regards to place of

manufacture. The resultant effect of this will be energy efficiency and reliability improvements of EMDS.

## 7. REFERENCES

- [1] Falkner, H and Holt, S., 2011. Working the torque: proposed work plan for energy-efficiency policy opportunities for electric motor-driven systems. Paris:IEA. Available online [http://www.iea.org/papers/2011/Walking\\_the\\_Torque.pdf](http://www.iea.org/papers/2011/Walking_the_Torque.pdf) [30 April 2011]
- [2] Mthombeni, T.L and Sebitosi, A.B., 2008. Impact of introducing minimum energy performance standards for electric motors in South Africa. *Proceedings of the International Conference on Industrial Use of Energy, Cape Town*. Available online: <http://active.cput.ac.za/energy/web/ICUE/DOCS/324/Presentation%20-%20Mthombeni%20T.pdf> [1 April 2011]
- [3] Bose, B.K., 2006. Power electronics and motor drives. Boston:Elsevier
- [4] Chikuni, E., Khan, M.T and Okoro, O.I., 2008. Concise higher electrical engineering. Cape Town:Juta
- [5] Ouadi, H., Giri, F., Elfadili, A and Dugard, L., 2010. Induction machine speed control with flux optimization. *Control Engineering Practice* 18, 55-66
- [6] Boldea, I. and Nasar, S.A., 2002. The induction machine handbook. Boca Raton: CRC
- [7] European Commission, 2000. Improving the penetration of energy-efficient motors and drives. Available online <http://re.jrc.ec.europa.eu/energyefficiency/motorchallenge/pdf/SAVEII-Motors-Final-Report-Mar-2000.pdf> [3 April 2011]
- [8] Hydraulic Institute, Europump and US-DOE, 2004. Variable speed pumping: a guide to successful applications. NY:Hydraulic Institute. Executive summary available online

[www.eere.energy.gov/industry/bestpractices/pdf/variable\\_speed\\_pumping.pdf](http://www.eere.energy.gov/industry/bestpractices/pdf/variable_speed_pumping.pdf) [1 April 2010]

[9] Carbon Trust, 2002. Variable speed driven pumps best practice guide (GPG344). Available online <http://www.carbontrust.co.uk/Publications/pages/publicationdetail.aspx?id=GPG344&response=0&q=Variable+Speed+driven+pumps&order=asc&pn=0&ps=10> [22 Feb 2010]

[10] Rosen, H., 2009. Towards pump efficiency in South Africa, *Mechanical Technology* — August 2009. Available online [www.ipuc.co.za/press\\_release/MechTech%20Aug%202009%20IPUC%20article.pdf](http://www.ipuc.co.za/press_release/MechTech%20Aug%202009%20IPUC%20article.pdf) [12 Feb 2010]

[11] Warwick, J, van Zyl, E and de Lange, Y., 2008. Energy efficiency made simple. Vol. II. Bedfordview[Johannesburg]:Crown

[12] IEC(International Electrotechnical Commission), 2009. IEC 60034-31: Rotating electrical machines – Part 31: Guide for the selection and application of energy-efficient motors including variable-speed applications. Available online [www.motorsystems.org/file/otherfiles/0000/0039/21554\\_CD.pdf](http://www.motorsystems.org/file/otherfiles/0000/0039/21554_CD.pdf) [16 Feb 2011]

[13] WAG (Western Australian Government), 2002. Motors and variable speed drives. Available online <http://igs.nige.ir/IGS/ARTIC/MT-08.PDF> [1 Feb 2011]

[14] Malinowski, J.,McCormick, J and Dunn, K., 2004. Advances in construction techniques of ac induction motors: preparation for super-premium efficiency levels. *IEEE Transactions on Industry Applications* 40:6, 1665-1670

[15] Manoharan, S., Devarajan, N., Deivasahayam, S. M and Ranganathan, G., 2009. Review on efficiency improvement in squirrel cage induction motor by using DCR

technology. *Journal of Electrical Engineering* 60:4, 227-236

[16] CEMEP(European Committee of Manufactureres of Electrical Machines and Power Electronics), 2011. Electric motors and variable speed drives. Available online [http://www.cemep.org/fileadmin/downloads/CEMEP\\_Motors\\_and\\_VSD.pdf](http://www.cemep.org/fileadmin/downloads/CEMEP_Motors_and_VSD.pdf) [17 March 2011]

[17] de Almeida, A.T., Fonseca, P., Falkner, H and Bertoldi, P., 2003. Market transformation of energy-efficient motor technologies in the EU. *Energy Policy* 31, 563-575

[18] European Commission, 2004. Energy efficient motor driven systems. Brussels:European Copper Institute. Available online [http://re.jrc.ec.europa.eu/energyefficiency/pdf/HEM\\_lo\\_all%20final.pdf](http://re.jrc.ec.europa.eu/energyefficiency/pdf/HEM_lo_all%20final.pdf) [2 Feb 2011]

[19] US Department of Energy, 2002. Energy Matters. Available online [http://www1.eere.energy.gov/industry/bestpractices/energymatters/pdfs/em\\_volume19.pdf](http://www1.eere.energy.gov/industry/bestpractices/energymatters/pdfs/em_volume19.pdf) [5 March 2011]

[20] US Environmental Protection Agency, 2010. Evaluation of energy conservation measures for wastewater treatment facilities. Available online <http://water.epa.gov/scitech/wastetech/upload/Evaluation-of-Energy-Conservation-Measures-for-Wastewater-Treatment-Facilities.pdf> [3 March 2011]

## 8. AUTHORS

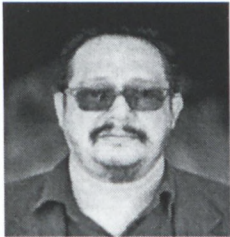
**Principal Author:** Onwunta E.K Onwunta is



currently a Masters student of Cape Peninsula University of Technology, South Africa in the Department of Electrical Engineering. He is a graduate of Federal University of Technology, Owerri,

Nigeria. A corporate member of Nigerian Society of Engineers (NSE) and registered with Council for Regulation of Engineering in Nigeria (COREN) has worked in the Oil & Gas and Manufacturing Sectors in Nigeria. His current research is on energy efficient pumping using VSD.

**Co-author:** MTE Kahn is a Full Professor in the Department of Electrical Engineering of Cape Peninsula University of Technology, South Africa. He is also Head of Centre for Distributed Power and Electronic Systems.



**Presenter:** This paper is presented by Onwunta E.K Onwunta

## (B) ELECTRIC DRIVE AND ENERGY EFFICIENCY:

### MYRIAD MEANINGS

OEK Onwunta and MTE Kahn

Cape Peninsula University of Technology, South Africa

#### ABSTRACT

**The recent advancements in electric motor speed control and application in the industrial and commercial sectors have warranted several authors describing or defining electric drive from their perspectives. This has resulted to the immense growth of the literature on ac (alternating current) drives which has proliferated in different directions, so that a motivated reader attempting to study the literature gathers only frustration.**

**Likewise energy efficiency means different things to different people. To some energy efficiency is the same as energy conservation, and to others energy efficiency should be preferred to energy efficiency.**

#### 1. INTRODUCTION

The operations of most industrial loads require wide ranges of speed. These loads could be driven by hydraulic, pneumatic or electric motors [1]. Three major means of achieving variable speed control in the industries are mainly mechanical, hydraulic, and electrical/electronic [2-3]. Each of these control options has its strengths and weaknesses. Electric motor especially squirrel cage induction motor has remained an excellent prime mover even in the mechanical and hydraulic speed controls. In both mechanical and hydraulic speed controls the electric motor is operated in constant speed mode and the actual variable speed achieved through belts, chains, pulleys, hydraulic pumps, valves and hydraulic motors. However in electrical/electronic speed control variable

speed is realised directly on the electric motor.

Direct current (dc) and alternating current (ac) electric motors are the classes of electric motor based on electric power supply type. Dc motor enjoyed wide patronage in variable speed control because of its historical and controllability advantages over ac motor especially squirrel cage induction motor. But currently squirrel cage induction motor drives have become the industry workhorse for variable speed applications in a wide power range. This feat has been achieved in preference to dc machines because of the inherent characteristics of squirrel cage induction motor of being rugged and has low cost purchase and minimal maintenance requirement.

According to [4] it is often said that solid-state electronics brought in the first electronics revolution, whereas solid-state power electronics brought in the second electronics revolution. Interestingly the perceived disadvantages of using induction machine are continuously being successfully challenged by power electronics advancements through relevant and effective control systems. These good control methods are based on physical insight into the machine characteristics [5]. However these control methods or drive technologies and their widespread applications especially in the industrial community have resulted to different meanings to the word "electric drive" or "electrical drive". A great awakening had been observed by [6] in the industrial community with an intense urge to understand the basics of ac drives technology. Unfortunately, according to [6], the literature on ac drives has grown

immensely and has proliferated in different directions, so that a motivated reader trying to study the literature gathers only frustration.

Part of this frustration is whether an electrical drive is a system or device. Equally confusing is its reference as a Variable Speed Drive (VSD), Adjustable Speed Drive (ASD), Variable Frequency Drive (VFD) and Inverter. A lot of authors accept that these can be used interchangeably.

There are many and diverse reasons for using variable speed drives, and the needs for speed and torque control are usually fairly obvious. In general, variable speed drives are used to [3]:

- Match the speed of a drive to the process requirements
- Match the torque of a drive to the process requirements
- Save energy and improve efficiency

It could be proper to assume that energy saving is currently synonymous with energy efficiency. Unfortunately energy efficiency means different things to different people resulting to another confusion and frustration to a motivated reader who intends to study the literature. These diverse meanings could equally jeopardise the effective quantification of energy efficiency benefits in the industrial and commercial sectors.

## 2. ELECTRIC DRIVE

An invaluable job in chronicling the developments in the power electronics and invariably electrical drives has been executed [7-8]. A comparison of the two appears to confirm the view of [9] on the difficulty of assigning specific dates to scientific and or technological inventions. For instance [7] records 1891 as when Ward Leonard dc motor speed control was introduced contrary to 1886 which [8] documents as the birth of the electric variable speed drive system represented by Ward Leonard system. But there is no controversy on the astronomical

and constant growth in the field of power electronics and electrical drives.

### 2.1 Drive as a Device or System

In the most generic sense, a drive is a device that controls speed, torque, direction, and the resulting power of a system [2]. As a device drives interface between the utility input and control the motor speed by changing the magnitude of voltage, current or frequency, and are composed of three main components [10-13] namely a rectifier, a dc link and an inverter. According to [14] a variable-speed drive is a piece of equipment that regulates the speed and rotational force, or torque output, of an electric motor. It observes that one of the main reasons why drives save energy is because they can change the speed of an electric motor by controlling the power that is fed into the machine. The consideration of an electric drive as a device has led to the classification of drives as shown in Fig. 1.

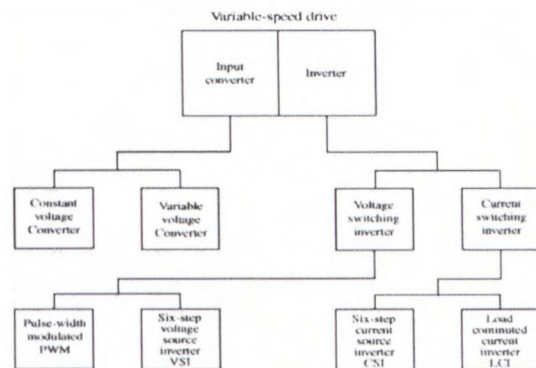


Fig. 1 Classification of electronic drives [10, 13]

As shown in Fig. 2 drives as a system are generally composed of the following [15-17]:

- A static energy conversion group (ac/dc converter and inverter);
- An electrical motor; and
- A microprocessor-based measurement and control system.

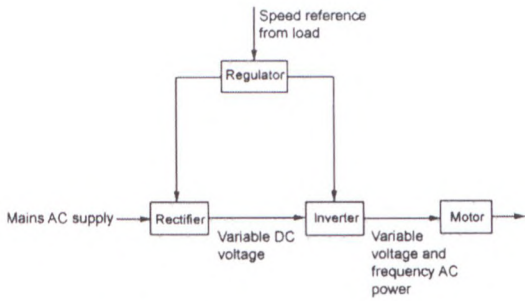


Fig. 2 Electrical drive system [13]

However, [18] defines an electric drive as “a system consisting of one or several electric motors and of the entire electric control equipment designed to govern the performance of these motors. The control equipment may or may not include various rotating electric machines”.

### 2.2 Adjustable Speed Drive (ASD) or Variable Speed Drive (VSD)

According to [19] an adjustable speed drive (ASD) is a device used to provide continuous range process speed control (as compared to discrete speed control as in gearboxes or multi-speed motors) as shown in Fig 3.

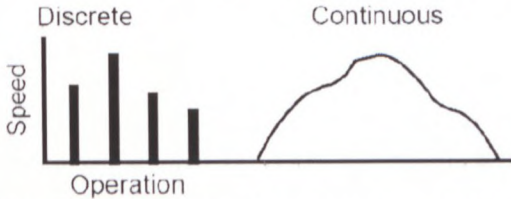


Fig. 3 Comparison of range process speed control [19]

But [20] notes that where speeds may be selected from several different pre-set ranges, usually the drive is said to be “adjustable” speed. If the output speed can be changed without steps over a range, the drive is usually referred to as “variable speed”. A reference to [18] shows a distinction between adjustable-speed drive and variable-speed drive. Adjustable-speed drive is described as an electric drive designed to provide easily operable means for speed adjustment of the motor, within a specified speed range. But a variable-speed drive refers to an electric drive so designed

that the speed varies through a considerable range as a function of load.

### 2.3 Variable Frequency Drive (VFD) or Variable Speed Drive (VSD)

The application of balanced three-phase voltage to the three-phase winding of an ac motor stator sets up a magnetic flux in the air gap. This magnetic flux pattern remains constant in form throughout the alternating cycle, rotating one pole pair in one cycle. The speed of rotation of the flux is known as the synchronous speed given by Eqn. 1

$$N_{syn} = \frac{f}{p} \text{ rev/s} \quad (1)$$

where,  $f$  is the frequency in Hz, and  $p$  the number of pole pairs.

However, the rotor of our industrial workhorse (cage induction motor) must always rotate at a different speed from the synchronous speed for a voltage, and hence current and torque to be induced in the rotor. The relative speed of the rotor to the synchronous speed of the rotor flux is known as the slip  $s$  (Eqn. 2):

$$s = \frac{\text{synchronous speed} - \text{rotor speed}}{\text{synchronous speed}} = \frac{N_{syn} - N_{rotor}}{N_{syn}} \quad (2)$$

For an induction motor, rotor speed, frequency of the voltage source, number of poles and slip are interrelated according to the following equation [21]:

$$n = \frac{120f_1}{p} (1 - s) \quad (3)$$

where:  $n$  : mechanical speed (rpm);  $f_1$  : fundamental frequency of the input voltage (Hz);  $p$  : number of poles, and  $s$  : slip

Eqn. (3) shows that the mechanical speed of an induction motor is a function of three parameters. Thus the change of any of those parameters will cause the motor speed to vary as shown in Table 1.

Table 1 Induction machines speed variation [21]

Speed Variation	
Parameter	Application characteristics
Number of poles	Discrete variation
	Oversizing
Slip	Continuous variation
	Rotor losses
	Limited frequency range
Voltage frequency	Continuous variation
	Utilization of STATIC FREQUENCY Inverters!

Most authors only consider Eqn.1 in their consideration of cage induction motor speed control resulting to the conclusion that frequency is the only variable for continuous variable speed control of cage induction motor. It should be noted that the speed being referred to here is the synchronous speed which could also be seen as the electrical speed and it is different from the rotor speed or the mechanical speed given by Eqn. 2. And this is dangerous because it ignores the crucial role of slip in the production of useful torque in an induction motor. Talking about speed control of pumps, [22] maintains that speed can be controlled in a number of ways, with the most popular type of variable speed drive (VSD) being the variable frequency drive (VFD). Similarly the view of [23] is that the most common variable speed drives (VSDs) used in heat pump and similar applications are variable frequency drives (VFDs) controlling conventional alternating-current induction motors. Therefore it could be proper to conclude that VFDs are parts of VSDs and are not the same irrespective of their erroneous interchangeability. Perhaps the view of [24] on the terms vector control and field orientation control (FOC) could buttress this. According to [24] in both the

U.S. and Japan the term vector control is frequently used in lieu of F.O.C. Field orientation control is mechanically descriptive of the accomplished control, whereas vector control describes the technique by which it is accomplished. The technique involves a vector analysis of current which separates the magnetizing component of current from the work component of current.

#### 2.4 Inverter

In Section 2.1 inverter was identified as part of the power converter unit of an electric drive. Its function is the changing of dc power to ac power. As shown in Fig. 1, inverters could be classified as voltage or current switching inverters and their respective sub-groups. Literature is replete with information on inverters but the concern is its common erroneous usage as being synonymous with an electric drive. Reference to [22] shows that the most common form of VFD is the voltage-source, pulse-width modulated (PWM) frequency converter (often incorrectly referred to as an inverter). This misnomer becomes very worrisome when it is rampant in reputable publications such as [21]. The crucial role of an inverter in an electric drive does not justify its being synonymous with the power converter or the entire drive system. A vehicle or an automobile makes a good analogy. It would be improper to address the engine as the vehicle though the vehicle is rendered useless without an engine. Likewise the engine is worthless without the other key parts of the motor such as the body, tyres and even battery in some cases.

### 3. ENERGY EFFICIENCY

Energy efficiency is a “low hanging fruit” on the “energy tree” which can help address a number of objectives at the same time and at a low or negative cost: security of supply, environmental impacts, competitiveness, balance of trade, investment requirements, social implications and others [25].Reference

[26] has observed that initially or ordinarily ‘energy efficiency’ appears to be simple to understand. However, it is not usually defined where it is used, so ‘energy efficiency can mean different things at different times and in different places or circumstances’. This lack of clarity has been described as ‘elusive and variable’, leading to ‘inconsistency and muddle’ and where energy savings need to be presented in quantitative terms, the lack of adequate definitions is ‘embarrassing especially when comparisons are made between major industries or between industry sectors’.

### 3.1 Energy and Exergy Efficiency

While commenting on the use of energy efficiency indicators, [26] has noted that to be informative and useful, energy efficiency must be comparable, e.g. to another unit or installation, or over time and for comparison there must be rules or convention. In other words, it is possible to affirm that a product or process is energy efficient only when compared with a standard or another similar.

Conventional energy efficiency ( $\eta$ ) is based on the first-law of thermodynamics and takes no account of the type of an energy source in terms of its thermodynamic quality and in contrast exergy efficiency ( $\epsilon$ ) is based on both the first and second laws of thermodynamics which facilitates the assessment of the maximum amount of work achievable in a given system with different energy sources.

Energy efficiency and exergy efficiency are typically defined for a conversion device as Eqn. 4 and 5 respectively:

$$\eta = \frac{\text{energy output (useful)}}{\text{energy input}} \quad (4)$$

$$\epsilon = \frac{\text{exergy output}}{\text{exergy input}} = \frac{\text{work output}}{\text{max. possible work output}} \quad (5)$$

The efficiency of an energy conversion process is the ratio of the useful output energy to the input energy. Exergy is similar

in concept to effectiveness or availability and thereby providing a more equitable measure of conversion efficiency. This is because exergy utilises mechanical work rather than energy as the basis for comparing devices with each other and their thermodynamic ideal.

### 3.2 Energy Efficiency and Conservation

Energy efficiency and energy conservation are frequently interchangeably used. This could be attributed to the duality of energy. According to [27] energy has duality as intermediate input to produce goods and services (or a factor of production in a wide sense) and as final goods used for space heating, water heating, travelling etc. Fig. 3 clearly shows this duality of energy.

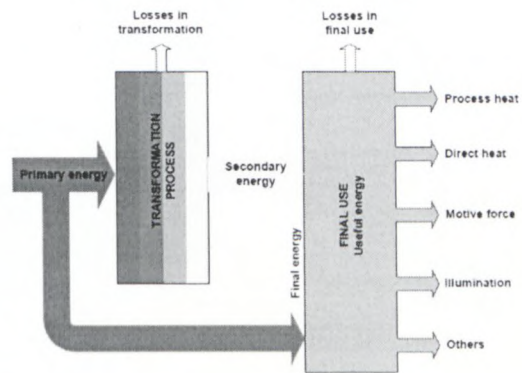


Fig. 3 Definition of primary, secondary and final energies [26]

Energy conservation carries the connotation of deprivation, of doing without, of reducing amenities to save energy, for example, turning down the heat and being less comfortable or wearing a sweater indoors in cool weather: or, driving one’s car fewer miles each year in order to save fuel. In contrast, a system that becomes more energy-efficient may retain, or even enhance, the level of amenities while using less energy.

Conservation by nature is only used in emergencies where there is not sufficient supply of energy and therefore will have a

negative impact on production, as the only alternate for the extreme short term is to shut down activities [28]. Whereas energy efficiency has a positive impact on production but takes place over a certain time period, more or less a 3 year cycle is followed to plan, implement and measure the implementation of energy efficiency project.

Reference [25] has adduced a reason for this deprived energy strategy. According to it, in some cases because of financial constraints imposed by high energy prices, consumers may decrease their energy consumption through a reduction in their energy services such as reduction of comfort temperature; in car mileage. It further notes that such reductions do not necessarily result in increased overall energy efficiency of the economy, and are easily reversible. Consequently, concludes that they should not be associated with energy efficiency.

The foregoing shows that efficient tertiary energy usage will ensure lower demand for energy production from the primary energy sources. This implies the conservation of the primary energy sources – reduction of the rate at which primary energy sources are depleted or converted. However, arbitrary reduction of the rate of depletion of the primary energy sources does not result to efficient usage of tertiary energy. A resultant conclusion from this is that energy efficiency leads to energy conservation but not vice versa.

### 3.3 Energy Efficiency and Intensity

The measure of energy efficiency will always depend upon how ‘useful’ is defined and how inputs and outputs are measured [29]. The options include:

- Thermodynamic measures: where the outputs are defined in terms of either heat content or the capacity to perform useful work;
- Physical measures: where the outputs are defined in physical terms, such as

vehicle kilometres or tonnes of steel; or

- Economic measures: where the outputs (and sometimes also the inputs) are defined in economic terms, such as value-added or GDP.

When outputs are measured in thermodynamic or physical terms, the term ‘energy efficiency’ tends to be used, but when outputs are measured in economic terms it is more common to use the term ‘energy productivity’. This is because economists are primarily interested in energy-efficiency improvements that are consistent with the best use of all economic resources. The inverse of both measures is termed ‘energy intensity’.

According to [27] energy efficiencies of countries are focused frequently on issues relating to energy conservation, climate change and energy security. There, however, are number of macro indicators for energy efficiency. Among them are energy consumption per gross domestic product or GDP – GDP intensity – and energy consumption per capita. Furthermore, although both of them are calculated without considering factors determining energy consumption such as economic structure, climate, geographical features, etc, they have advantages including clearness, possibility of broad application and data availability.

Therefore energy intensity which shows how much energy is used to produce one unit of GDP in a country [30] is mathematically expressed as

$$\text{Energy intensity} = \frac{\text{Total primary energy consumption (Mtoe)}}{\text{GDP (billionUSD2000)}} \quad (6)$$

where Mtoe = million tonnes of oil equivalent, and the GDP is based on US dollar exchange rate of 2000.

Compared with developed countries, South African economy uses a lot of energy for every Rand of value added [28]. For instance, in 2006 South Africa had the 42<sup>nd</sup> biggest GDP in the world but was the

world's 21<sup>st</sup> largest consumer of energy. Indeed, by international standards the South African economy uses a relatively high amount of energy per unit of national economic output, or GDP (4.96 MJ per million Rand in 2004).

Fig. 4 gives an indication of the energy consumption in Petajoules ( $10^{15}$ J) per capita of some selected developed and developing countries. It is clear that South Africa is closer to the developed countries in terms of energy intensity than to the developing countries when the Market Exchange Rate (MER) is used rather than the Purchase Power Parity (PPP).

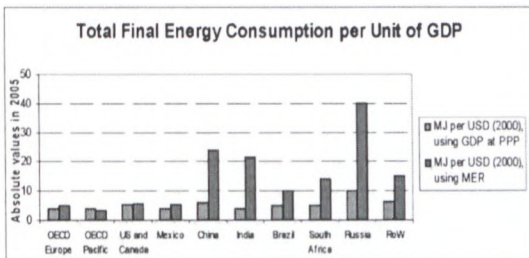


Fig. 4 Final energy demand per capita (2005) [28]

Energy intensity (energy per unit wealth) is decreased when energy is used more efficiently.

#### 4. CONCLUSION

This paper has highlighted the crucial role of power electronics in the speed control of electric motor especially squirrel cage induction motor. Equally emphasised is the appropriateness of electric drive as a device or system, ASD, VFD, VSD and Inverter which are terms encountered in electric motor speed control. To avoid the apparent confusion and frustration created by the proliferation of ac drive's literature, it would be proper that authors desist from using these terms interchangeably.

The authors of this paper are proposing a synergy between engineers and economists for a better understanding and interpretation

of energy efficiency. This will enable a proper quantification of the benefits of energy efficiency. Given the starvation connotation of energy conservation, efforts should be intensified to use energy (especially tertiary energy) more efficiently to achieve effective primary energy conservation.

#### 5. REFERENCES

- [1] Subrahmanyam, V., 1994. Electric drives: concepts and applications. NY:McGraw-Hill
- [2] Polka, D., 2003. Motors and drives: a practical technology guide. NC:Instrumentation Systems and Automation Society
- [3] Barnes, M., 2003. Practical variable speed drives and power electronics. Oxford:Elsevier
- [4] Bose, B.K., 2000. Energy, environment, and advances in power electronics. *IEEE Transactions on Power Electronics*, Vol. 15, No. 4, July 2000
- [5] Finch, J.W., 2008. Controlled ac electrical drives. *IEEE Transactions on Industrial Electronics*, 55:2, 481-491
- [6] Bose, B.K ed., 1981. Adjustable speed ac drive systems. New York:IEEE Press
- [7] Bose, B.K., 2006. Power electronics and motor drives. Boston:Elsevier
- [8] Shakweh, Y., 2007 Drives types and specifications. In: Rashid, M.H ed., 2007. Power electronics handbook. Oxford:Elsevier
- [9] Gottlieb, I.M., 1997. Practical electric motor handbook. Oxford:Butterworth-Heinemann
- [10] Qureshi, T.Q and Tassou, S.A., 1996. Variable-speed capacity control in refrigeration systems. *Applied Thermal Engineering* 16:2, 103-113

- [11] Twining, E and Cochrane, I., 1999. Modelling variable speed ac drives and harmonic distortion. Proceedings of Australasian Universities Power Engineering Conference, AUPEC '99, Northern Territory University, Darwin, Sept 26-29
- [12] Deswal, S.S., Dahiya, R and Jain, D.K., 2008. Application of boost converter for ride-through capability of adjustable speed drives during sag and swell conditions. World Academy of Science, Engineering and Technology 47, 282-286
- [13] Saidur, R, 2010. A review on electrical motors energy use and energy savings. *Renewable and Sustainable Energy Reviews* 14, 877-898
- [14] ABB, 2008. Variable-speed drive technology guide. Available online [http://www02.abb.com/db/db0003/db002698.nsf/ca7e93ab03030d22c12571380039e8fc/a5853d43c2ad412c125720300632f74/\\$FILE/Tech+Guide\\_Drive.pdf](http://www02.abb.com/db/db0003/db002698.nsf/ca7e93ab03030d22c12571380039e8fc/a5853d43c2ad412c125720300632f74/$FILE/Tech+Guide_Drive.pdf) [20 Sep 2010]
- [15] Leonhard, W., 1996. Controlled ac drives, a successful transition from ideas to industrial practice. *Control Engineering Practice* 4:7, 897-908
- [16] de Capua, C and Landi, C., 2001. Quality assessment of electrical drives with strongly deformed supply waveform. *Measurement* 30, 269-278
- [17] Mecrow, B.C and Jack, A.G., 2008. Efficiency trends in electric machines and drives. *Energy Policy* 36, 4336-4341
- [18] IEEE (Institute of Electrical and Electronic Engineers), 2000. IEEE 100: the authoritative dictionary of IEEE standard terms, 7th ed. NY:IEEE
- [19] Okrasa, R., 1997. Adjustable speed drive:reference guide, 4<sup>th</sup> ed. Ontario:Ontario Hydro
- [20] Wikipedia, Adjustable-speed drive [http://en.wikipedia.org/wiki/Adjustable-speed\\_drive](http://en.wikipedia.org/wiki/Adjustable-speed_drive) [12 Feb 2010]
- [21] WEG, 2010. Induction motors fed by PWM frequency inverters. Available online <http://www.weg.net/files/products/WEG-induction-motors-fed-by-pwm-frequency-converters-technical-guide-028-technical-article-english.pdf> [10 Nov 2010]
- [22] Hydraulic Institute, Europump & US-DOE, 2004. Variable speed pumping: a guide to successful applications. NY:Hydraulic Institute. Executive summary available online [www.eere.energy.gov/industry/bestpractices/pdf/variable\\_speed\\_pumping.pdf](http://www.eere.energy.gov/industry/bestpractices/pdf/variable_speed_pumping.pdf) [1 April 2010]
- [23] Vaez-Zadeh, S and Hendi, F., 2005. A continuous efficiency optimization controller for induction motor drives. *Energy Conversion and Management* 46, 701-713
- [24] Carpenter, R and Lipo, T.A., 1988. Electronic adjustable speed drive technology synopsis. Research Report 88-8. Available on-line <http://lipo.ece.wisc.edu/1980s%20pubs/88-08.pdf> [5 Nov 2010]
- [25] World Energy Council, 2010. Energy efficiency: a recipe for success. London: World Energy Council. Available online [www.worldenergy.org/documents/fdeneff\\_v2.pdf](http://www.worldenergy.org/documents/fdeneff_v2.pdf) [24 April 2011]
- [26] EC (European Commission), 2009. Reference document on Best Available Techniques for Energy Efficiency. Available online [ftp://ftp.jrc.es/pub/eippcb/doc/ENE\\_Adopted\\_02-2009.pdf](ftp://ftp.jrc.es/pub/eippcb/doc/ENE_Adopted_02-2009.pdf) [20 May 2011]
- [27] Yanagisawa, A., 2011. Trade-off in energy efficiencies and efficient frontier. IEEJ Energy Journal. Available online <http://eneken.ieej.or.jp/data/3618.pdf> [16 May 2011]
- [28] Republic of South Africa, 2009. National energy efficiency strategy of the Republic of South Africa. Government Gazette 528:32342. Pretoria:RSA. Available online

[http://www.energy.gov.za/files/media/explained/strategy\\_energyefficiency\\_2009.pdf](http://www.energy.gov.za/files/media/explained/strategy_energyefficiency_2009.pdf)  
[10 May 2011]

[29] Herring,H and Sorrell,S. eds.,2009.Energy efficiency and sustainable consumption: the rebound effect. London:Palgrave Macmillan

[30] Matsumoto,J and Nakata,T.,2008. The energy system analysis and forecasts of the Republic of South Africa. *Proceedings of the Industrial & Commercial Use of Energy (ICUE) Conference 2008. Cape Town.* Available online:  
<http://active.cput.ac.za/energy/web/ICUE/D/OCS/353/Paper%20-%20Matsumoto%20J.pdf>  
[10 April 2011]

## 6. AUTHORS

**Principal Author:** Onwunta E.K Onwunta is currently a Masters student of Cape Peninsula University of Technology, South Africa in the Department of Electrical Engineering. He is a graduate of Federal University of Technology, Owerri, Nigeria.



A corporate member of Nigerian Society of Engineers (NSE) and registered with Council for Regulation of Engineering in Nigeria (COREN) has worked in the Oil & Gas and Manufacturing Sectors in Nigeria. His current research is on energy efficient pumping using VSD.

**Co-author:** MTE Kahn is a Full Professor in the Department of Electrical Engineering of Cape Peninsula University of Technology, South Africa. He is also Head of Centre for Distributed Power and Electronic Systems.



**Presenter:** This paper is presented by Mr Onwunta E.K Onwunt

**(C) Energy Efficiency and Conservation:  
South Africa's Perspective  
OEK Onwunta and MTE Kahn**

Electrical Department, Cape Peninsula University of Technology, South Africa

Phone: +27 21 953 8630, 6208; Fax: +27 21 959 6117

Email: [onwuntao@cput.ac.za](mailto:onwuntao@cput.ac.za); [khant@cput.ac.za](mailto:khant@cput.ac.za)

**ABSTRACT:** A nation's wealth and its use of energy are closely related. Energy exists in diverse forms and of great importance are end-use energy services – such as warmth, motion, mechanical power or process heat for industrial manufacturing. The energy received by a user could be both primary and secondary energies. Duality of energy implies that energy can be a factor of production and a final good, which has created the apparent confusion between energy efficiency and energy conservation leading to both being often used interchangeably. Although energy efficiency could mean different things to diverse people in different places at different times, it has remained a hanging fruit on the energy tree. Energy conservation has a starvation connotation which by nature is only used in emergencies where there is insufficient supply of energy. Efficient use of tertiary energy leads to conservation of primary energy, but not vice versa. South Africa (SA) being a strong developing economy of the world is a partaker of the global energy challenges. Therefore this paper highlights how SA has effectively confronted her energy crisis through a combination of energy efficiency and energy conservation strategies.

**KEY WORDS:** Energy, Efficiency, Conservation, Energy Efficiency and

Demand Side Management (EEDSM), Energy Conservation Scheme (ECS)

## 1. INTRODUCTION

Energy remains the life-blood for continual progress of human civilisation resulting to huge amount of energy being required for countries with faster economic growth which makes energy a crucial factor for economic competitiveness and employment. Therefore energy as the backbone of a city or nation is an entirely cross-cutting sector whose social, economic and environmental impacts are immense.

Energy could be classified based on its source as primary, secondary or tertiary energy respectively. An energy source that is extracted from a stock of natural resources or captured from a flow of resources and that has not undergone any transformation or conversion other than separation and cleaning is termed primary energy. Examples of primary energy include coal, crude oil, natural gas, solar power and nuclear power. Secondary energy on the other hand refers to any energy that is obtained from a primary energy source employing a transformation or conversion process. Thus oil products or electricity are secondary energies as these require refining or electric generators to produce them. Both electricity and heat can be obtained as primary and secondary energies [1]. However, even these energy forms are not really of interest to end users.

Of great importance are end-use energy services – such as warmth, motion, mechanical power or process heat for industrial manufacturing. These are referred to as tertiary energy [2]. According to [3] final energy is the energy that is received by the user, and may be both primary and secondary energies (e.g natural gas as the primary energy and electricity as the secondary energy used in an installation). The relationship is shown in Fig.1.

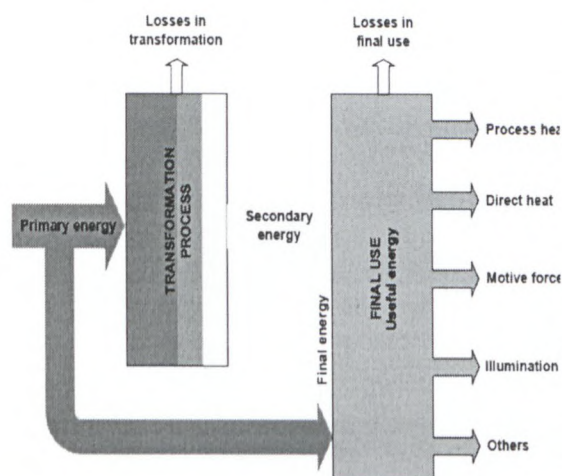


Fig.1 Definition of primary, secondary and final energies [3]

Fig. 1 highlights the duality of energy as an intermediate input to produce goods and services (or a factor of production in a wide sense) and as final goods used amongst other things for space and water heating, and travelling. This duality of energy could be considered as being responsible for the frequent erroneous interchangeability usage of energy efficiency and energy conservation. Equally worthy of note is the synonymy of energy with electricity.

## 2. ENERGY EFFICIENCY

It is rather difficult to define or even to conceptualise the words "energy efficient" and "energy efficiency" which are often used qualitatively. For instance an engineer may

define energy efficiency in a very restrictive equipment sense, whereas an environmentalist may have a broader view of energy efficiency. Equally an economist, politician, sociologist and others may each have a different concept of energy efficiency. But basically energy efficiency means ways of reducing the energy used by specific end-use devices and systems, typically without affecting the service provided. Therefore energy efficiency is a "low hanging fruit" on the "energy tree" which can help address a number of objectives at the same time and at a low or negative cost: security of supply, environmental impacts, competitiveness, balance of trade, investment requirements, social implications and others [4].

In recent years especially since 2005 and the release of the first Energy Efficiency Strategy, energy efficiency has significantly gained in stature in SA and has become recognised as one of the most cost-effective ways of meeting the demands of sustainable development [5]. The benefits of energy efficiency upon the environment are self-evident. These benefits are of particular relevance, as SA remains the largest emitter of GHGs (greenhouse gases) in Africa and one of the most carbon emission-intensive countries in the world, annually emitting some 7 tonnes of CO<sub>2</sub> per capita as shown in Fig. 2.

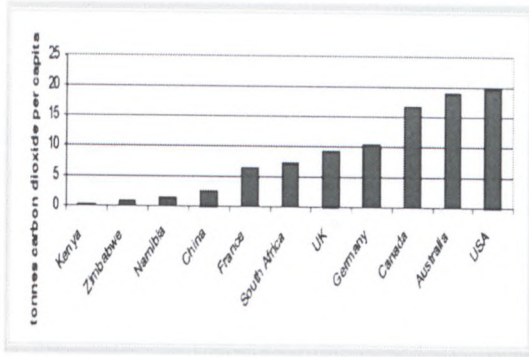


Fig. 2 Carbon Dioxide Emission per capita [5]

At a local level the problems of SO<sub>2</sub> and smoke emissions have been the focus of concern for many communities living adjacent to heavily industrialised areas. This is because such substances are known to have an adverse effect on health and are frequently a primary cause of common respiratory ailments. Energy efficiency can address both the macroscopic and microscopic aspects of atmospheric pollution.

South African estimates of the energy efficiency potential are conservatively between 20-30% across many segments, and she has not harnessed the full potential to date.

The Energy Efficiency Strategy sets an overall target of a 12% energy saving by 2015 and an industry saving of 15%. This efficiency target shows SA's commitment towards energy efficiency because to date only a handful of countries worldwide have set comprehensive targets for energy efficiency improvements [5]. These countries include Slovenia, Japan, The Netherlands and New Zealand.

### 3. ENERGY CONSERVATION

According to [6] energy conservation carries the connotation of deprivation, of doing without, of reducing amenities to save

energy, for example, turning down the heat and being less comfortable or wearing a sweater indoors in cool weather: or, driving one's car fewer miles each year in order to save fuel. In some cases because of financial constraints imposed by high energy prices, consumers may decrease their energy consumption through a reduction in their energy services such as reduction of comfort temperature; in car mileage. Such reductions do not necessarily result in increased overall energy efficiency of the economy, and are easily reversible. Consequently, they should not be associated with energy efficiency [4]. For instance the National Energy Regulator of South Africa (NERSA) on 24<sup>th</sup> February 2010 approved electricity tariff for the period 2010/11 – 2012/13 as follows:

- 24.8% increase in 2010/11;
- 25.8% increase in 2011/12; and
- 25.9% increase in 2012/13

Such price increases could result to arbitrary reduction in electricity consumption and the rate at which coal is being depleted. This means conservation of coal which constitutes 73.4% of the primary energy mix of SA.

Reference [5] believes that energy conservation by nature is only used in emergencies where there is not sufficient supply of energy and therefore will have a negative impact on production, as the only alternative for the extreme short term is to shut down activities. However, energy efficiency has a positive impact on production but takes place over a certain time period, more or less a 3 year cycle is followed to plan, implement and measure the implementation of energy efficiency project.

The foregoing shows that efficient tertiary energy usage will ensure lower demand for energy production from the primary energy sources. This implies the conservation of the

primary energy sources – reduction of the rate at which primary energy sources are depleted or converted. However, arbitrary reduction of the rate of depletion of the primary energy sources does not result to efficient usage of tertiary energy. A possible conclusion from this is that energy efficiency leads to energy conservation but not vice versa.

#### 4. ENERGY CHALLENGES

Global economic recession or meltdown appears to be a new phenomenon in this 21<sup>st</sup> century because worldwide poor financial situation seemed forgotten after the Great Depression of the 1930s. However, energy crisis has been a common and persistent global challenge with its attendant discourse since the October 1973 war in the Middle East which sparked off the first of two waves of energy-price increases in the 1970s[4]. That event catapulted the debate about energy and conservation from its obscure beginnings in academic and policy circles to sudden public prominence. Therefore, globally nations are beginning to face up to the challenge of sustainable energy – in other words to alter the way that energy is utilised so that social, environmental and economic aims of sustainable development are supported.

The Republic of South Africa (RSA) being a major developing economy of the world is not immune to this global energy challenge. The coincidence of her energy crisis with the economic meltdown in 2008 was a double tragedy, to say the least. Consequently, the economic growth of the first quarter of 2008 fell to 1.57% from 5.4% in the last quarter of 2007. The President in his State of the Nation speech on the 8th of February 2008 re-emphasised the nature of the emergency and indicated that a focused effort on energy efficiency programmes was required. He also

indicated that Government would lead such an effort. Eskom was tasked to develop this programme on behalf of Government. Eskom is a South African government authority mandated to generate, transmit and in some cases, distribute electric power.

SA's current energy situation stems from higher than anticipated growth in electricity demand, and limited investment in new generation infrastructure over the last 15 years. The latter resulted to limited additional supply coming online. Consequently at the peak of the crisis, the generation net reserve margin fell below 10% - well below conventional industry benchmark of at least 15%.

Compared with developed countries, South African economy uses a lot of energy for every Rand of value added. For instance, in 2006 SA had the 42<sup>nd</sup> biggest GDP in the world but was the world's 21<sup>st</sup> largest consumer of energy. Indeed, by international standards the South African economy uses a relatively high amount of energy per unit of national economic output, or GDP (4.96 MJ per million Rand in 2004) [5]. Two reasons have been adduced for this and the first being the nature of the activities which dominate the economy. Mining, minerals processing, metal smelting and synfuel (synthetic fuel) production are inherently intensive users of energy. South African gold mines are very deep with low ore concentrations, so it necessarily requires much energy per ounce (28.349 g) of gold. The process used to convert coal into liquid fuels is such that only about a third of the energy in the coal ends up in the liquid fuel. Although SA's aluminium smelters are among the most efficient in the world, they still require large amounts of electricity to produce one ton of aluminium. The second reason for the high energy intensity is that SA is sometimes wasteful in the use of energy. Low energy

costs have not encouraged industry, commerce, transport and households to adopt energy efficiency measures.

Fig. 3 gives an indication of the energy consumption in Petajoules ( $10^{15}$ J) per capita of some selected developed and developing countries. It is clear that SA is closer to the developed countries in terms of energy intensity than to the developing countries when the Market Exchange Rate (MER) is used rather than the Purchase Power Parity (PPP).

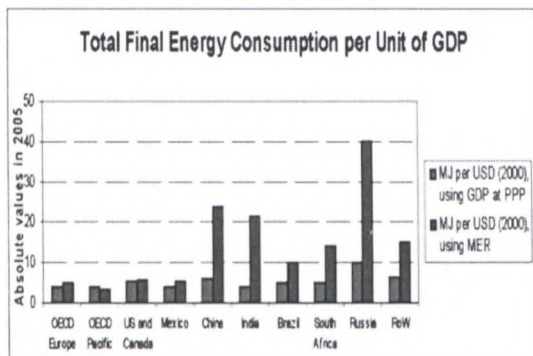


Fig.3 Final energy demand per capita (2005)[5]

However, the energy intensity in SA is falling as the mining industry becomes less dominant in the economy while the service sector grows.

## 5. STRATEGIES AGAINST ENERGY CHALLENGES

The traditional approach or solution to meet SA's electricity demand rise had been by merely increasing the supply. In response to the energy crisis the Department of Minerals and Energy (DME) – now Department of Energy (DoE) – established the Power Conservation Programme (PCP). PCP is the key government initiative designed to provide a demand-side solution to the energy challenges facing SA. As the only quick solution available, it is aimed at closing the

supply-demand gap in the short-term, until new base-load stations come online. PCP has two central elements namely:

- Energy Conservation Scheme (ECS) to reduce energy consumption by approximately 10%. ECS caps the electricity energy available per large power user – Key Industrial Customer (KIC).
- Electricity Growth Management (EGM) to manage new electrical connections in line with available supply capacity. The EGM strategy prioritises new connections requiring 20MVA or more of power.

ECS as the name implies is critical as part of a contingency plan for the industrial sector, to conserve energy in the event that an electricity load-shedding risk materialised. A potential customer of 20MVA load or more is at the mercy of Eskom and stands to be starved or denied of power in view of the EGM.

Having recognised that energy efficiency represents an economically attractive option, SA has embarked on the implementation of different initiatives including the implementation of energy efficiency programmes under the guidance of the Energy Efficiency and Demand Side Management (EEDSM). This is to ensure that the “first fuel” option relating to energy efficiency is exploited ahead of more expensive supply side options. DSM aims to save 4 255MW over a period of 20 years which equates to the generating capacity of one six-pack power stations.

Energy efficiency improvements are being achieved largely via enabling instruments and interventions. These include among other things economic and legislative means, efficiency labels and performance standards,

energy management activities and energy audits, as well as the promotion of efficient practices.

The estimate of SA's industry electric motor consumption is 60% of the total electricity produced. This translates to roughly 10,000MW of the total demand. Recognising that a small percentage increase in efficiency of these motors would have a significant impact on the total electric demand of SA, the National Energy Efficient Motor Retrofit Programme was initiated. The programme has been widely embraced in the industrial sector not without technical challenges. Retrofitting of energy efficient motors on centrifugal loads (centrifugal pumps and fans) has left some users wondering about the energy saving power of energy efficient motors.

Eskom has been effective in the promotion of efficient practices and also leading by example. For instance its Billion kWh saving programme focuses on its Internal Energy Efficiency (IEE) drive to implement energy efficiency internally in its facilities. It has reduced its energy consumption by an estimated 10-18% at its largest facility (headquarters), Magawatt Park, in the process reducing operational cost by over R3 million per month. Eskom achieved this feat by adopting the two common energy efficiency strategies:

- Replacement of inefficient electrical products and appliances, and
- Modification of human behaviour

With a nationwide focus on improving and optimising energy consumption, driven by the need to be more responsible with a limited resource, Eskom has succeeded in raising the conscientiousness of the populace on the benefits of energy efficiency.

## 6. CONCLUSION

This paper has highlighted energy classifications and the crucial role of energy especially tertiary energy in national economic growth. It has also shown a clear distinction between energy efficiency and energy conservation which could be a solution to the apparent confusion between them and their erroneous interchangeability usage. Therefore a possible inference from this is that while efficient usage of tertiary energy leads to conservation of primary energy, arbitrary starvation of especially primary energy does not necessarily result to efficient usage of tertiary energy.

South African government being mindful of SA's important role in the global economy and the challenges of energy has embraced energy efficiency improvements through enabling instruments and interventions. Her energy efficiency strategies or programmes and implementations have yielded positive and encouraging results leading to a decrease in her energy intensity.

SA's Power Conservation Programme (PCP) summarily denies heavy energy consumers the opportunity of using energy at will. This power deprivation should be seen by KIC as a sacrifice towards nation building. Whereas Eskom's EEDMS is a voluntary incentive approach to mitigate electricity usage, the ECS under the PCP is a command and control (CAC) attempt to fast track energy efficiency.

Therefore suffice it to say that SA has effectively been combining energy efficiency and energy conservation in addressing her energy challenges.

## 7. REFERENCES

- [1] Bhattacharyya, S. C., 2011. Energy economics: concepts, issues, markets and governance. London: Springer-Verlag

- [2] Harvey, L.D.D., 2010. Energy and the new reality 1: energy efficiency and the demand for energy services. London: Earthscan
- [3] EC (European Commission), 2009. Reference document on Best Available Techniques for Energy Efficiency. Available online [ftp://ftp.jrc.es/pub/eippcb/doc/ENE\\_Adopted\\_02-2009.pdf](ftp://ftp.jrc.es/pub/eippcb/doc/ENE_Adopted_02-2009.pdf) [20 May 2011]
- [4] World Energy Council, 2010. Energy efficiency: a recipe for success. London: World Energy Council. Available online [http://www.worldenergy.org/documents/fden\\_eff\\_v2.pdf](http://www.worldenergy.org/documents/fden_eff_v2.pdf) [24 April 2011]
- [5] Republic of South Africa, 2009. National energy efficiency strategy of the Republic of South Africa. Government Gazette 528:32342. Pretoria:RSA. Available online [http://www.energy.gov.za/files/media/explained/strategy\\_energyefficiency\\_2009.pdf](http://www.energy.gov.za/files/media/explained/strategy_energyefficiency_2009.pdf) [10 June 2011]
- [6] Hollander, J. M & Schneider, R.T., 1996. Energy-efficiency: issues for the decade. *Energy* 2:4, 273-281

CAPE PENINSULA  
**UNIVERSITY OF TECHNOLOGY**

