ANALYSIS OF THE EFFECT OF RENEWABLE GENERATION ON THE POWER QUALITY OF THE GRID, MODELLING AND ANALYIS OF HARMONIC AND VOLTAGE DISTORTION

by

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DECLARATION

I, **Emmanuel Nkusi Musoni** hereby declare that I am the sole author of this thesis, that the contents of this thesis represent my own unaided work, and that the thesis has not previously been submitted for academic examination towards any qualification. I the author authorize CPUT to lend this thesis to other institution or individual for the purpose of scholarly research.

NE.MUSONI

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ABSTRACT

As the electric energy demand grows, there is a significant increase in the penetration of renewable generation (RG) in the existing electrical grid network. Interconnecting of renewable generation technologies to an existing distribution system has proven to provide various benefits such as meeting the growing load demand and its contribution to energy system decarbonisation, long-term energy security and expansion of energy access to new energy consumers in the developing urban and rural areas. However, the aim of this thesis is to conduct a study on the impacts of renewable generation on the power quality of electrical grid. Therefore, this work aims at assessing the potential effects of Distributed Generation (DG) on the operation of electric power system by modelling of harmonics and voltage distortion. With different types of renewable generation available at present, it is believed that some designs contribute significantly to electrical network's Power Quality (PQ). After the analysis of harmonic currents (chapter 6 and 7 of this thesis) introduced by renewable generation technologies, their negative impact on the power quality of the grid is seen to be apparent at point of connection (POC) but only within controlled limits. Analytical method for modeling of harmonic interactions between the grid and aggregated distributed generation technologies are investigated using DIgSILENT Power Factory software and the results obtained are discussed.

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DEDICATION

I dedicate this thesis to my beloved late Grandfather **Simon Bagiriye**, to my late close friend **Ivan Rugima,** and to late **Uncle Augustine Kamari**. Cancer robed us but your memories remain in our hearts.

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Thesis Title

“Analysis of the effect of renewable generation on the power quality of the grid; Modelling and Analysis of Harmonic Stability and Voltage distortion”

List of abbreviations

Table 1: Clarification of basic terms and concepts

AC	Alternating Current.
AEPR	African Energy Policy Research Network
AFD	African Development Bank
AMI	Advanced Metering Infrastructure
AMR	Automated Meter Reading
APF	Activate Passive Filter
Arms	True RMS current
AVR	Automatic Voltage Regulator
BEE	Black Economic Empowerment
CDM	Clean Development Mechanism
CHD	Current Harmonic Distortion
CHP	Combined Heat and Power
CIGRE	Grands Réseaux Électriques abbreviated
CMOS	Complementary metal–oxide–semiconductor
CPV	Concentrated Photovoltaic
CREEE	Centre for Renewable Energy and Energy Efficiency
CSP	Concentrated Solar Power
DC	Direct Current
DG	Distributed Generation

DMS	Distribution Management System
DoE	Department of Energy
DPF	Displacement Factor
DRC	Democratic Republic of Congo
DS	Distribution System
DSM	Demand Side Management
D-STATCOM	Distribution Static Synchronous Compensator
DVR	Dynamic Voltage Restorer
EAC	East African Community
EARS	East African rift valley
ECOWAS	Economic Community of West African States
ELA	Earth Life Africa
EMI	Electromagnetic interference
EVMS	Earned Value Management System
FACTS	Flexible Alternating Current Transmission System
FAO	Food and Agricultural organisation
FHL	Harmonic loss Factor
FK	K-factor
FT	Fully Tuned
GHG	Green House Gas
GHI	Global Horizontal Irradiation
GTO	Gate turn off thyristor
GWEC	Global wind energy Council
HC	Hybrids filter
HPS	Hybrid Power Systems
HPS	Hybrid Power Systems
IEA	International energy agency
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronic Engineers
IGBT	Insulated gate bipolar transistor
IPMS	Integrated Power Quality Management System

IPP's	Independent Power Producers
IREE	International Review of Electrical Engineering
LV	Low Voltage
LVRT	Low Voltage Ride Through
MG	Mini Grid
MV	Medium Voltage
NSP	Network Service Provider
PCC	Point of Common Coupling
PCS	power conditioning system
PF	Power Factor
PJ	Pico joule
PLT	Long term flicker
POC	Point Of Connection
POI	Point of Interface
PQ	Power Quality
PQMS	Power Quality Management System
PST	Short term flicker
PV	Photovoltaic
PWM	Pulse width Modulation
PWM	Pulse Width Modulation
REIPPPP	Renewable Energy Independent Power Producer Procurement Programmes
RFI	Radio Frequency interference
RMS	Root-mean-square
RTD	Real time digital simulator
SADC	Southern African Development Community
SAEA	Southern Africa Economics Association
SANEDI	South African National Energy Development Institute
SAPF	Shunt Active Passive Filter
SAREGC	South Africa Renewable Grid Code
SASGI	South African Smart Grid Initiative
SAWEA	South African Wind Energy Association

SCADA	Supervisory Control and Data Acquisition
SECCP	Sustainable energy and climate change Project
SED	Social Economic Development
SPF	Shunt Passive Filter
SRECs	Solar Renewable Energy Credits
SSA	Sub Saharan Africa
SSEG	Small Scale Embedded Generation
SVR'S	Static Var Compensator
TDD%	Total demand distortion
THD%	Total Harmonic Distortion
THD%f	Total harmonic distortion of current in % f ((%f)Fundamental value as reference)
THD%r	Total harmonic distortion of current in %r ((%r)Total value as reference)
TPED	Total Primary Energy Demand
TS	Transmission System
UNIDO	United Nations Industrial Development Organization
Urms	True RMS phase
VA	Voltage Ampere
VHD	Voltage Harmonic Distortion
VSD	Variable Speed Drive
VSI	Voltage Source Inverter

Glossary of terms

Table 2: Glossary of terms

Band pass Filter	A band-pass filter is a device that passes frequencies within a certain range and rejects frequencies outside that range
Bus	Electrical wiring in general refers to insulated conductors used to carry electricity, and associated devices.
Capacitance	Capacitance is the ability of electrical circuit to store an electric charge

Capacitor	A device used to store an electric charge, consisting of one or more pairs of conductors separated by an insulator.
Charger Controller	Is the circuit which limits the rate at which electric current is added to or drawn from electric batteries
Complex	Term that is indicating the difficulty of fully understanding of a process characterized by nonlinearities and several interacting variables.
Conductor	C**onductor** is an electrical material or type of material that allows the flow of an electrical current in one or more directions.
Distributed generation	Refers to decentralized energy is electrical generation and storage performed by a variety of small, grid-connected devices
Distribution System	Is the final stage in delivery of electrical power from transmission substation to consumers
Dynamic Stability	The ability of a power system to maintain stability under continuous small disturbances
Electrical Load	An **electrical load** is an electrical component or portion of a circuit that consumes active electric power.
Electrical Utility	An **electric utility** is a company in the electric power industry (often a public utility) that engages in electricity generation and distribution of electricity for sale generally in a regulated market
Filter	an electronic circuit which processes signals, for example to remove unwanted frequency components
Frequency	**Frequency** is the number of occurrences of a repeating event per unit of time
Generation System	Is the bulk movement of electricity energy from generating site to electrical distribution substations
Generator	A machine that converts mechanical energy into electrical energy.
Grid	A system of high tension cables by which electrical power is distributed throughout a region power grid, or power system.
Grid Code	A **grid code** is a technical specification which defines the parameters a facility connected to a public **electric** network has to meet to ensure safe, secure and economic proper functioning of the **electric** system
Harmonics	**Harmonic** is multiple of the fundamental frequency and it can be voltage and current in an electric power system are a result of non-linear electric loads.

High pass Filter	A **high-pass filter** is an electronic filter that passes signals with a frequency higher than a certain cutoff frequency and attenuates signals with frequencies lower than the cutoff frequency
Hybrid System	Hybrid power systems are combination of multiple power source or generator to deliver non-intermittent electrical power.
Impedance	**Electrical impedance** is the measure of the opposition that a circuit presents to a current when a voltage is applied
Inductance	**Inductance** is a property of an electrical conductor which opposes a change in current
Inverter	is an electronic device or circuitry that changes direct current (DC) to alternating current (AC)
Islanding grid	Islanding is the condition in which a distributed generator (DG) continues to power a location even though electrical grid power is no longer present
Magnetising Current	A varying current in one coil of the transformer produces a varying magnetic field, which in turn induces a varying electromotive force (EMF) in a second coil
Method	The procedures and techniques characteristics, orderly arrangement of parts or steps to accomplish an end.
Micro grid	Microgrid are a localized grouping of electricity generation, energy storage, and loads that normally operates connected to a traditional centralized grid
Mini grid	Mini-grids are electricity generation designed for isolated communities which integrates several sources such as solar and wind.
Model	A usable knowledge based on representation of the essential aspects of an existing system.
Modelling	Refers to electrical power system simulation of the designed network in order to analyze electrical power systems data offline or real-time
Network	The apparatus, equipment, plant and buildings used to convey, and control the conveyance of, electricity to customers (whether wholesale or retail) excluding any connection assets.
Power Quality	PQ is defined as a steady supply voltage that stays within the prescribed range, steady a.c. frequency close to the rated value, and smooth voltage curve waveform
Power System	A network when includes the point where the power is generated to transmission networks up to distribution. A system of high tension

	cable by which electrical power is distributed throughout a region.
Protection System	A system, which includes equipment, used to protect facilities from damage due to an electrical or mechanical fault or due to certain conditions of The power system.
Reliability	The possibility of a system, performing its function sufficiently for The period of time intended, under the encountered operating conditions.
Renewable	Renewable is refers to those energy resources whose common characteristic is that they are non-depletable or naturally replenishable
Renewable generation	The process of generating electricity using renewable energy resources – these resources generating the electricity are usually distributed over an area, like a photovoltaic farm.
Simulator	A machine for simulating certain environmental and other conditions for purposes of training or experimentation.
Stability	The quality or attribute of being firm and steadfast, reliable and balanced power system.
System Stability	We define the system stability as the ability of the power system to return to steady state without losing synchronism
Transient	A sudden, brief increase in current or voltage in a circuit that can damage sensitive components and instruments.
Transient Stability	The ability of a power system to maintain stability under continuous major disturbances
Voltage Stability	Voltage stability refer to the ability of power system to maintain steady voltages at all buses in the system after being subjected to a disturbance from a given initial operating point.
Waveform	The general definition, waveform can be an alternating function or direct function
Electrical network	A system of cables and equipment designed to deliver power to consumers at usage voltage levels
DIgSILENT	Simulation power factory software used for network design and modeling of Power system network and network studies

CHAPTER 1: INTRODUCTION

1.0. Introduction

As electrical energy customers in residential and commercial areas become more energy conscious and environmentally aware, the installation of grid-connected renewable generation technologies for small-scale electricity generation is growing at an exponential rate. The world is currently experiencing severe energy shortages as the fossil-fuel deposits are decreasing at an alarming rate (Reed et al., 1999; Nguyen & Saha., 2004). Moreover, the energy security concerns have urged nations to look for sustainable sources of energy to replace depleting fossil fuels. The increased awareness about declining fossil-fuel deposits and environmental hazards, caused by the burning of fuels, is also forcing the governments towards exploiting renewable-energy resources as an alternative (Bollen & Gu, 2006:, pp 41 & 392). As a result, the interconnection of Renewable Energy Sources (RES) and power system stability has become more complex and challenging for power system engineers as the grid gradually increase over the years due - to modern interconnected grid and complex dynamic structures. These are subject to various constantly acting (possibly overlapping) physical phenomena that range from very fast ones such as transients due to lightning strikes, to quite slow ones, such as, for instance, the dynamics of boilers, harmonics, and voltage distortion etc. (Singh & Adhya., 2006). Lastly, concerns faced by Independent Power Producers (IPP's) and consumers are the quality and reliability of power supplies at various load locations. The vast use of power electronics in a distributed technology network such as grid-tied inverters, variable speed drives, computerized processing lines PCs, Uninterruptable Power Supply (UPS) and non-linear electronic gadgets in power system, provides an increased deformation in current and voltage waveform called harmonics (Justus Rabi & Arumugam., 2005). Harmonic current injecting devices add huge burden into power system grid which causes harmonic voltage distortion. These conditions in turn can cause motor and transformer overheating as well as the problematic operation of susceptible electronic equipment non-linear load results in voltage harmonics which creates a serious

PQ problem in the power system network (Taylor, 1995, Justus Rabi & Arumugam., 2005; Reddi et al., 2013:17).

1.2. Awareness of the Problem

Renewable Energy Sources (RES) like solar and wind provide sustainable and environmentally friendly alternatives for power generation. However, some technical and economic challenges have to be resolved before these sources can substitute the current power generation resources (Ackermann et al, 2001:204). First, these RES are intermittent, unpredictable, and uncontrollable, which means that they cannot solely be used to supply the load demand in a reliable manner. Also, renewable power generation technologies are generally more expensive than conventional generators of comparable size, especially if used in conjunction with energy storage devices to enhance their reliability (Enslin & Heskes, 2004:1520-1593). As a result, they cannot supply energy at a competitive price. Furthermore, their distributed nature and locational dependency cause difficulties with respect to their integration into the centralized architecture of the contemporary power generation and delivery systems (Masid & Moriun, 2004).

Lastly, the extensive use of power electronics based equipment and non-linear loads at the Point of Common Coupling (PCC) generate harmonic currents, which may deteriorate the quality of power, non-linear loads which typically have a low power factor, force many industrial facilities to use capacitor banks to improve power the factor in order to avoid utility penalty charges. High harmonic distortions result in the reduction of productivity, reduce components life and can even damage equipment (Fitzer et al., 2004).

As a result, the utility is concerned due to the high penetration level of intermittent RES in distribution systems as it may pose a threat to the network in terms of stability, voltage regulation, and power quality issues. Therefore, the DG systems are required to comply with strict technical and regulatory frameworks to ensure safe, reliable and efficient operation of the overall network (McGranaghan et al., 1993).

1.3. Research Motivation

There has been on-going research focused on renewable generation technologies and a lot of investigation conducted by many research groups to determine the impact of renewable energy (RE) on the power quality of the grid, economic challenges, integration feasibility studies, as well the benefits attached to RE. According to the latest published article on Germany’s energy production, in 2011 Germany proposed the decommissioning of their nuclear power plants with supplement of renewable energy. In 2014 Germany added 30% renewable generation power, astonishing statistics from 6.3% in 2000 to 30% in 2014 (Kerekes et al, 2013). Research has proven that Africa’s abundance of sun and wind can create boundless potential for the energy economy in Africa and South Africa due to the wealth of these natural resources.

The research motivation was inspired by a desire to understand why, while Germany has managed to phase out some of its nuclear power plants and proposes complete phase-out of nuclear power plants by 2030, meanwhile South Africa is planning to build more nuclear power plants (Lund & Mathiesen, 2009:524-529). While the research primarily focuses more on the integration effect on power quality of the grid by renewable generation, the research review will also incorporate the economic challenges facing very slow implementation of renewable generation in both the South African and African energy markets (Ackerman & Knyazkin, 2002:1300).

1.4. Statement of research problem

The simulations of large RES interconnected in power systems network are feasible, but they remain time-consuming and complex. The focus of this study is to define and investigate the effect of RES integrated on grid, modeling and analysis of harmonic distortion, modeling and analysis of voltage distortion and intervention to improve stability and power quality.

1.5. Research Objectives

The objective of this research is to therefore understand the impact of renewable generation on the power quality of the grid by designing a model in DIgSILENT power factory software to mimic renewable generation technologies on the grid and to observe their effect on voltage stability, thereafter, proposing interventions to improve stability and power quality.

The actualisations of the objective are as follows:

1. To carry-out an intensive literature review on renewable integration and integration limitations
2. To design a non-linear inverter model in DIgSILENT that will act as a harmonic current source at the point of integration. The model represents renewable generation technologies interconnected on the grid.
3. To analyse the effect of the model on the power system grid
4. To design harmonic filter that will limit a harmonics currents at PCC to stabilize voltage at PCC.
5. To evaluate Load Profiles to ensure that simulation results obtained meet the IEEE Voltage Distortion Limits and currents injection limit standards.

1.6. Hypothesis

Currently, renewable generation is an “add-on” to existing electrical power generated. Renewable energy is considered to be clean for the environment but dirty for the power system grid. However, a greater understanding of the relationship between RE and power quality of the grid will provide an answer to hypothesis questions. The investigation to address renewable generation effect on power quality of grid integration is needed to evaluate and validate the performance network design.

The key questions in this study are: What are renewable generation technologies? What are the impacts of renewable generation on the power quality of the grid? What are the interventions to mitigate the effects of power quality? DIgSILINT is electrical engineering software that can simulate the operation and design of power distribution network.

In this study, DIgSILENT purpose is to address the raising concerns of RES on the power quality of electric grid, discussion of power quality reliability, Intervention to mitigate the challenges of RES upon grid integration.

1.7. Research design and Methodology

Case study 1- This case study will look at the impact of renewable generation on the power quality of the grid without a passive filter design model. The aim is to observe the impact of integration of the non-linear model which represents the renewable technologies on the power quality of the grid.

Case study 2- This case study will introduce the passive filter at PCC to mitigate the impacts of renewable generation on the power system grid. Therefore, the case studies will evaluate Load Profile of both simulation results obtained in DIgSILENT and practical model to ensure IEEE Voltage Distortion Limits and currents injection limit are compliant within harmonic standards.

1.8. Research outcome

In this study, the researcher intends to provide a model that will moderate the effects of renewable generation technologies on the power grid. Evaluation of harmonic stability and voltage distortion in case study 2 will provide results that comply with IEEE voltage and current limits.

1.9. Research delimitations

This study focuses on the integration effect of renewable generation on the power quality of grid by modelling harmonics and voltage distortion. Renewable generation technologies currently existing in the fields are of many types, including solar, hydro power, wind power, biomass and methane gas. So, this research is limited to solar and wind for case study on technologies mainly available in South Africa, particularly in the Northern Cape and Eastern Cape where solar and wind power is found in abundance in South Africa.

1.10. Thesis organisation

Chapter one presents the introduction, awareness of the research problem, motivation of the research, research problem and statement. It also highlights the research objective, hypothesis, delimitation and research outline.

Chapter two introduces the literature review, definition of renewable generation, and the development of renewable generation in Africa and South Africa. This chapter further discusses the development of different renewable generation resources available and their potential to mitigate the environmental and economic challenges faced by the world.

Chapter three highlights regional bodies in Africa and their role in accelerating renewable development on the continent. The chapter also takes a comprehensive look at the economic and technical integration challenge associated with renewable generation technologies including the opportunities to increase the development of renewable energy in South Africa and the continent.

Chapter four briefly introduces renewable energy sources and an understanding of what renewable generation is before discussing its effects on the power quality of the grid. The chapter also discusses the power system to understand how addition of renewable generation influences the power quality and all its effects has been discussed in this chapter.

Chapter five briefly looks at power system harmonics, its effect on system stability, and possible mitigation techniques available to limit them. An inverter model is proposed and considered to be harmonic current source in DigSilent to simulate the effects of grid-tied renewable generation technologies. The chapter also presents the harmonic mitigation passive filter design model and simulation results using DIgSILINT as well as and industry standards available to limit harmonic pollution.

Chapter six discusses network design in DIgSILENT, filter design for harmonic mitigation, discussion of simulation of result and analysis of result.

Chapter seven concludes the research and provides recommendations

CHAPTER 2: LITERATURE REVIEW OF RENEWABLE GENERATION

2.1. Chapter Review

This chapter introduces the literature review, definition of renewable generation, and the development of renewable generation in Africa and South Africa. This chapter further discusses the development of different renewable generation resources available and their potential to mitigate the environmental and economic challenges faced by the world.

2.2. Introduction

The worldwide progression of the need energy and the limited reserves of fossil fuel resources have led to intensive use of renewable energy sources (RESs). Other major issues that have strongly the RES development are the ever-increasing impact of energy technologies on the environment and the fact that RESs have today become a mature technology. The necessity for having available sustainable energy systems for substituting gradually conventional ones requires changing the paradigm of energy supply by utilizing clean and renewable resources of energy (Edenhofer et al., 2006).

Among renewables hydro, wind and solar energy characterize as a clean, pollution-free and great energy source, which is abundantly available almost everywhere in the world. These factors have contributed to make these renewable generation energy sources the fastest growing renewable technology in the world (Weedy et al., 2012).

Presently, in South Africa, photovoltaic (PV) generation and wind generation are playing a crucial role as a renewable generation sources application because of their unique benefits such as the presence of fuel cell, high reliability, simplicity of allocation, low maintenance and lack of noise and wear because of the absence of moving parts in photovoltaic (Justo et al., 2013).

The integration of renewable generation resource into the power system grid is becoming today the most important application, gaining interest over our traditional centralized dispatch generation. This trend is being increased due to the many benefits of using RES in distributed (also known as dispersed, embedded or decentralized) generation (DG) power systems (Muruganantham et al., 2017). According to Jacobson and Lauber.,(2006), for example, Germany has phased out some of its nuclear power plants and replaced it with renewable generation power plants. These advantages include the favourable economic and regulatory incentives established in many countries that directly influence the commercial acceptance of grid-connected renewable generation systems.

However, the growing number of distributed generation systems brings new challenges to the operation and management of the power grid, especially when this variable and intermittent energy source constitutes a significant part of the total system generation production (Edenhofer et al., 2006). This imposes the need for an effective design and performance assessment tool of grid-connected renewable generation systems, to accurately predict their dynamic performance under different operating conditions in order to make a sound decision on whether or not to incorporate this technology into the electric utility grid (Zhou et al, 2011).

Therefore, modeling and analysis must be done to identify the current-voltage (I-V) characteristics, transient stability, and the dynamic behavior of the power electronics interface with the power system utility grid, also known as power conditioning system (PCS) required to convert the energy produced into useful electricity and to provide requirements for connection to the grid (Zhong & Hornik, 2013).

The PCS is the key component that enables the provision of a more cost-effective harvest of energy from the sun and to meet specific grid code requirements. These requirements include the provision of high levels of security, quality, reliability, availability and efficiency of the electric power.

This, combined with the accelerated drop of renewable energy technology costs, could create an enormous opportunity for African countries to both transform and expand their energy capacity while providing a pathway for low-carbon economic growth. Figure 2.1 shows a summary of available renewable potential in Africa. Africa holds some of the best renewable energy resources in the world in the form of biomass, geothermal, hydropower, solar and wind which could be economically used to provide energy for the increasing population (Wolfrom et al., 2012).

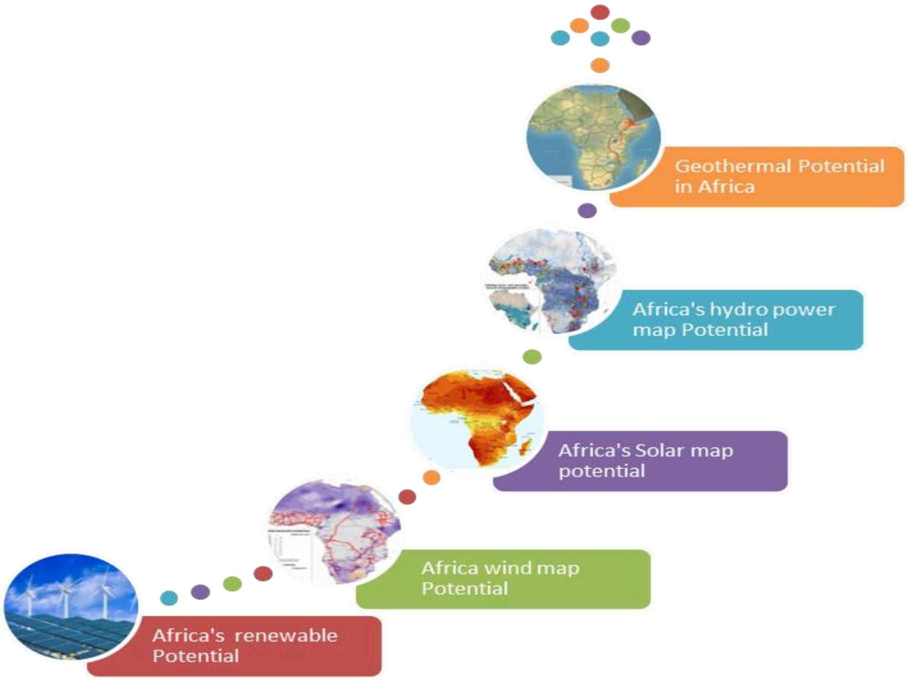


Figure 2.1: Summary of current renewable potential in Africa (SolarGIS, 2013)

2.3. Potential of renewable energy generation in Africa and South Africa

The African Continent is abundantly gifted with immense renewable energy resources enough to meet all its energy needs and yet the potential remains untapped (Fadaeenejad et al., 2014). An evolving concern for carbon emissions and sustainable development has created an opportunity for renewable generation energy on the continent. Currently and in early 2011, the total produced capacity of hydropower in Africa is around 26 GW (Kusakana, 2014). Presently the untapped potential for large hydropower projects is mainly concentrated in the lower Congo River and the upper Nile (Irena, 2013).

According to research by Irena, (2011), DRC's overall hydropower potential is estimated at 100,000 MW, the third largest in the world behind China and Russia, yet only 2.5% of this key resource has been developed. With 40,000 MW of generation potential, Inga is the world's largest hydropower site. Its proper development can make Inga the African continent's most cost-effective, renewable source of energy with an estimated generation cost of US$ 0.03 per kilowatt hour with little or no carbon footprint a significant added virtue (Irena, 2011).

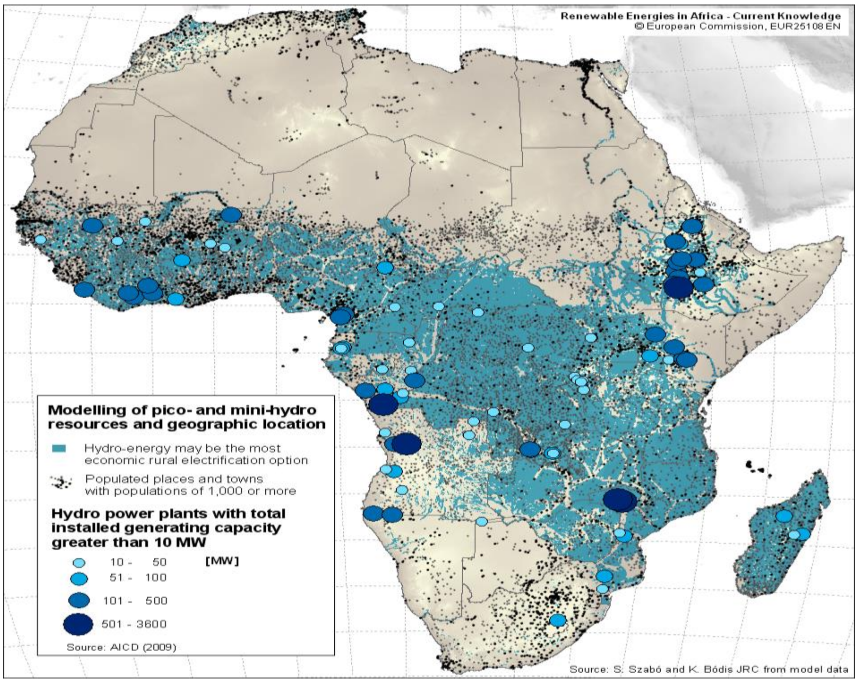


Figure 2.2: Africa’s hydro power potential and total installed generating capacity greater than 10MW (IEA, 2011)

In similar literature done by IEA, (2008), statistics on energy report, Inga Dam, alone on the Congo River, has the capacity to generate 40,000 to 45,000 MW of hydroelectric power, this would be sufficient to supply the electricity needs of the whole Southern Africa region.

The potential on the upper Nile River is also very large, with a potential of 30 GW in Ethiopia alone. Further potential exists in the other tributaries of the Congo (6 GW in Gabon) and the Niger (10 GW in Nigeria), as well as in Angola (18 GW) and Mozambique (12 GW) (Schwerhoff & Sy, 2016).

Small hydropower potential can be found in many hilly locations in West, Central, East and Southern Africa. The economic potential of hydropower is much smaller than the technical potential, but is still enough to allow hydropower to provide a significant share of total African power demand. The benefit of exploiting Small Hydropower Projects (SHP) for example in Rwanda, in 2009 contributed 6.5 MW into the generation capacity of about 43 MW from hydropower (Kaunda et al., 2012). According to Kaunda et al., (2012), in 2009 the total electricity generation capacity in Rwanda was about 72 MW. Rwanda together with Kenya, are the countries where the potential market for micro hydro off-grid electricity is high. The dam-based hydropower potential will, through its electricity storage potential, also play a vital role in facilitating the growth in other variable renewables such as wind and solar energy (Kusakana, 2014).

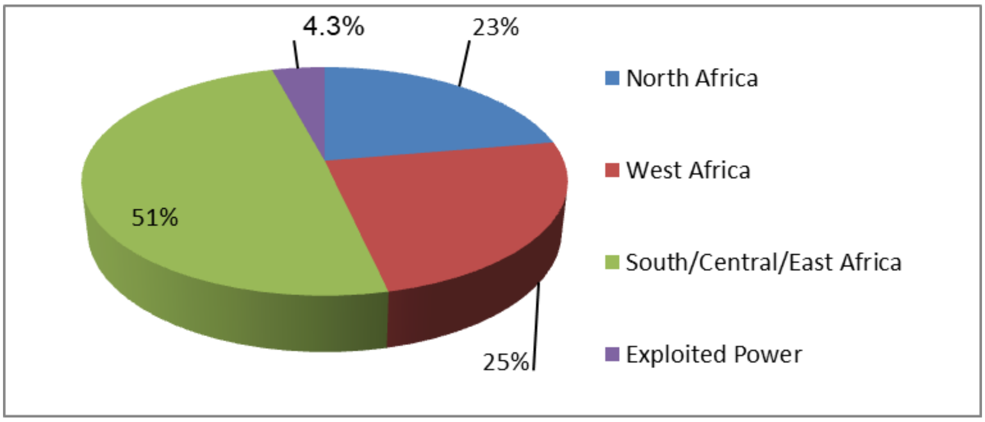


Figure 2.3: Current potential of hydropower in Africa (Kusakana, 2014)

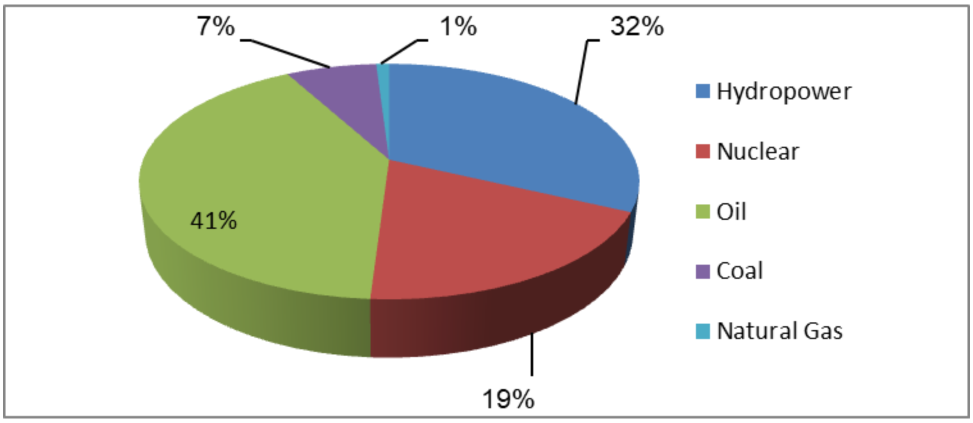


Figure 2.4: Contribution of hydro to Africa's Primary Energy Needs (Kusakana, 2014)

Research suggests that feasible potential production of hydropower in Africa is around 1,750,000GWh/year and only 4.3% has been exploited. Rapid exploitation of hydropower is mainly hampered by low demand and dispersed population. Hydropower in North Africa is estimated at 23%, with West Africa estimated at 25% and South/Central/East Africa estimated at 51% (see Figure 2.3 and 2.4).

Hydropower is contributing more than 50% of electricity in 25 countries, and more than 80% in Angola, Benin, Burundi, Cameroon, Central African Republic, Congo, Democratic Republic of Congo, Ethiopia, Guinea, Lesotho, Malawi, Mozambique, Namibia, Rwanda, Tanzania, Uganda and Zambia (Kusakana, 2014). However, as mentioned above only about 4.3% of this region's technically feasible hydro-potential has been developed, and enormous efforts are now being made across the African continent to create an 'enabling environment' for private investment; this is regarded as the only hope for developments on a large scale (Kusakana, 2014).

The power exploited from hydropower at a particular site is proportional to the product of flow rate and head as given in the following (Kaunda et al., 2012):

$$\mathrm{P} = \eta o \rho g Q H \qquad (1.1)$$

where *ρ* is a density, *g* (m/s2) is the acceleration due to gravity, *Q* (m3/s) is the flow rate, and *H* (m) is the net head available at the inlet to the turbine and *ηo* is the overall energy conversion efficiency (hydraulic to shaft power) (Kaunda et al., 2012). The values for overall efficiencies are higher in large-scale hydropower than small hydropower (SHP) system because, for large scale, the systems are designed with relatively high levels of precision and accuracy (Kaunda et al., 2012). Figure 2.5 below shows a typical hydropower electric dam.

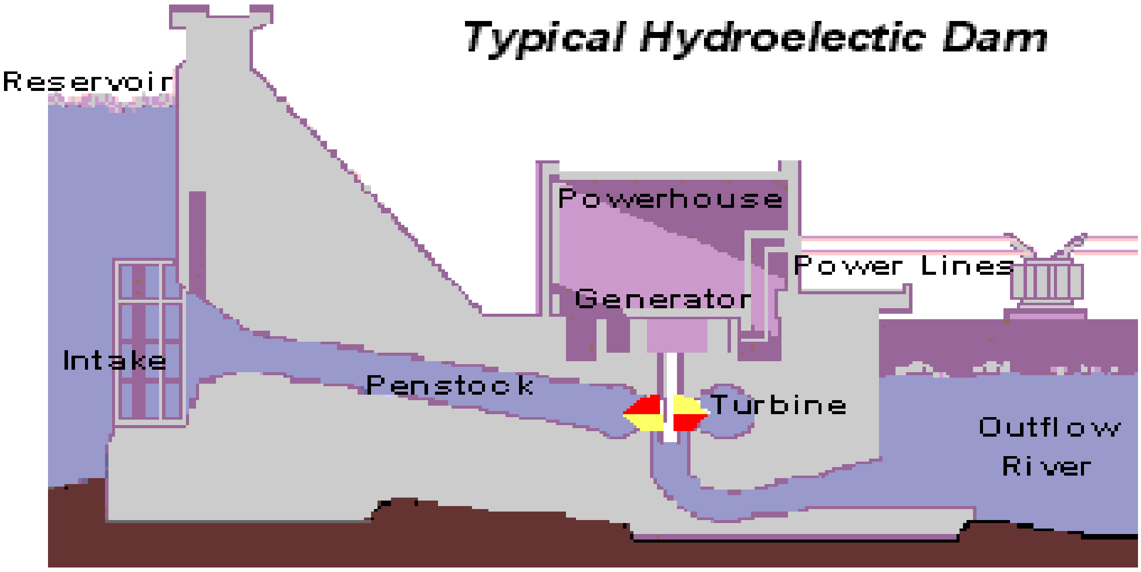


Figure 2.5: Typical hydroelectric dam design components (Laghari et al., 2013)

The technique us dam water falling from a height to turn the turbines of a generator. The mechanical energy is converted into electrical form and fed into the national grid system. Figure 2.5 shows an outline of a hydroelectric power station (Laghari et al., 2013). A dam with a large drop is constructed to raise the potential energy of water. The intake is placed at the bottom where the pressure is highest. Water then flows by gravity through the penstock. At this level, kinetic energy is sufficient to turn the turbines (Laghari et al., 2013).

Hydropower potential if exploited to its full capacity in Africa could provide the basis for industrialization, social and economic development. The benefits include (Mukasa et al., 2015):

- Water supply
- Irrigation
- Navigation
- Fisheries
- Tourism

Large hydropower stations have several advantages. It is a clean and emission free electricity generation technology, and is promoted as an environment friendly energy option. However, hydropower projects in the region are associated with huge loans, which lead to very high external debt levels (Mukasa et al., 2015). Due to the large amounts of capital involved in large-scale hydro projects, these projects are plagued with allegations of corruption (Kusre et al., 2010).

Africa’s solar power potential is another lagging behind in the exploitation of solar natural resource to meet its energy needs. According to Ainah and Folly, (2015) the solar energy reaching the earth on tropical zones is about 1kWh/m2/day in countries within 3200km of the equator. Research suggest that most countries in Africa are situated in the tropical zone of the world, and receive an average of 6-8 kWh/m2/day of solar irradiation which is among the world’s highest (Ainah & Folly, 2015).

The study done by SolarGIS, (2013) shows that Africa is the sunniest continent on Earth, especially as there are many perpetually sunny areas such as the huge Sub-Sahara Desert which is known for having the greatest solar resources than any other part of the continent.

The desert regions are the sunniest while rainforests are considerably cloudier but is still exposed to good global solar irradiation because of the proximity with the equator (SolarGIS, 2013). The distribution of solar resources across Africa is fairly uniform as shown in Figure 2.6, with more than 85% of the continent's landscape receiving at least 2,000 kWh/ (m^2 year).

Figure 2.6 below shows global solar radiation, African solar potential being the highest recorded globally (Africa, 2014).

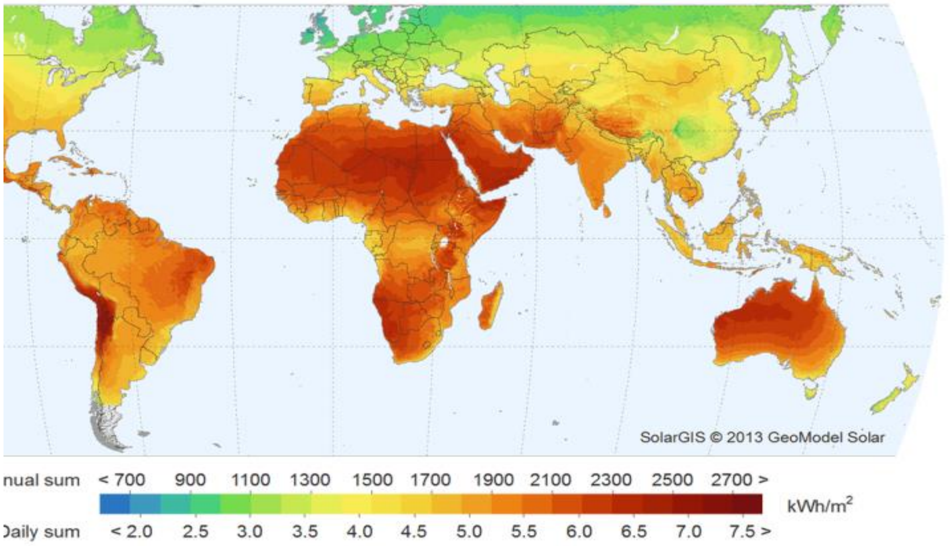


Figure 2.6: World map of global solar horizontal irradiation, (Solar GIS, 2013)

Taking advantage of the readily available solar radiation in the application of DG system can solve the unreliable and epileptic energy scenario in Africa, most especially in the Sub-Saharan African region (Mohammed et al., 2013). Electricity generation in SSA is characterised by acute shortages and high levels of unreliability (Mohammed et al., 2013). In most of the countries in the region, electricity generation capacities are less than 1000 MW, against huge demand for domestic, service, and industrial applications (Mohammed et al., 2013). The installed electricity generation capacity for all 48 countries of Sub-Saharan Africa, excluding the Republic of South Africa is just around 30 gigawatts (GW), which is stated to be almost equal to that of Argentina (Mohammed et al., 2013).

Studies have shown the availability of a significant amount of solar resources for possible renewable generation and Mini Grid (MG) applications in South Africa and Sub-Saharan countries such as Nigeria, Mauritius, Lesotho, Cap Verde, Eritrea Ethiopia and Rwanda (Ainah & Folly, 2015).

The White Paper named “the state of renewable energy in South Africa”, by the South African Department of Energy (2015), indicates how fortunate and rich the country is in terms of natural resources. Above all, other than its rich coal resources, it is also well-endowed with non-depletable RE sources, notably solar, wind and moderate hydro power. The country has an average of more than 2,500 hours of sunshine per year and average direct solar radiation levels range between 4.5 and 6.5kWh/m2 per day, placing it amongst the top-3 in the world (Ohunakin et al., 2014). Figure 2.7, below shows solar resource maps for South Africa, Lesotho and Swaziland (annual sum of direct normal irradiation kWh/m²) (Africa, 2016).

According to Karekezi and Kithyoma, (2014), 18 of the 35 developing countries ranked highest in renewable energy reserves, normalized by annual domestic energy consumption, are located in Africa. Previous studies have documented the required investment to provide adequate generation capacity to power economic development and for widening access to electricity. Nonetheless, Africa and South Africa despite having such high renewable generation potential are still lagging behind in the application of solar technologies to meet its energy needs (Ohunakin et al., 2014). Table 2.2 below shows the number of continents, in their respective regions, with the highest potential in renewable energy. Here, Africa is highlighted as one of the top renewable energy potentials across all sources of energy potential in the world (Edenhofer et al., 2011).

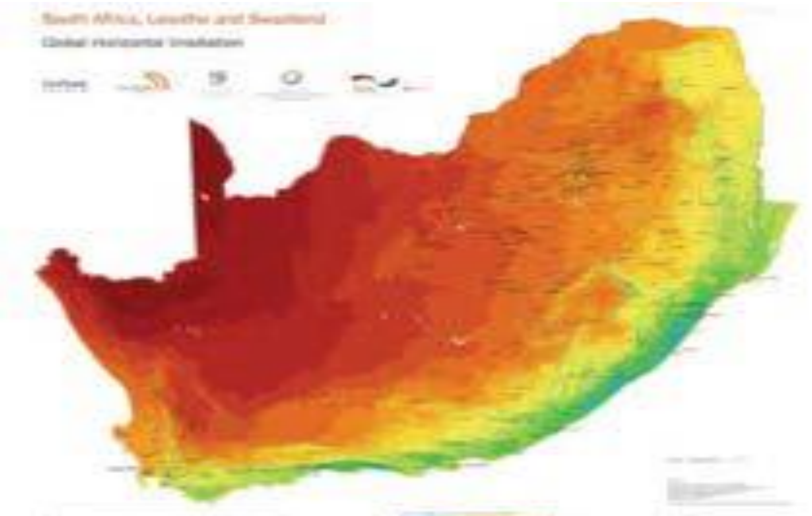


Figure 2.7: Solar resource maps for South Africa, Lesotho and Swaziland (annual sum of direct normal irradiation and global horizontal irradiation, kWh/m²), (Africa, 2016).

In the past, wind energy was considered to be a renewable energy source primarily for developed countries. This is slowly changing. In Africa, the potential of wind energy has started to be recognized in countries like Egypt, Morocco, Tunisia and South Africa in which several wind farms have already been installed. Wind potential in Africa is driven by understanding the distinction between the different potential categories (Coelingh, 1993).

The classification in categories (see Table 2.1 below) has facilitated the study of the constraints that reduce the wind power potential and gives a thorough insight of the important factors affecting potential development of wind (Mentis, 2013).

Table 2.1: Overview of the different potential categories (Mentis, 2013)

Potential Category	**Description**
Theoretical Potential (kWh/annum)	The total energy content of the wind
Geographic Potential	The total amount of land area available wind turbine installation taking geographical constraints into account (km^2)
Technical Potential	The wind power generated at the geographical potential including energy losses due to the power density of the wind turbines and the process of generating electricity using wind turbines (kWh/annum)
Economic Potential	The technical potential that can be realized economically given the cost of alternative energy sources (kWh/annum)
Implementation Potential	The amount of economic potential that can be implemented within a certain timeframe,taking(institutional) constraint, specific legislation framework and incentives into account (kWh/annum)

A study compiled by the African Development Bank (AfDB) to create a wind atlas for Africa also revealed significant potential for wind and the way forward on the continent (AfDB, 2004). Figure 2.8 below shows a study by AfDB which produced a quantitative map of simulated wind speeds on the continent using the Wind Energy Simulation Toolkit model at an altitude of 50m and a resolution of 50 km. The results demonstrated that the best wind in Africa is found in the coastal regions of the continent namely: in the North (Algeria, Egypt, Morocco Tunisia and Mauritania), in the East (Djibouti, Eritrea, Seychelles and Somalia), in the West (Cape Verde) and in the South (South Africa and Lesotho) (AfDB, 2004).

A similar study was done by Ainah and Folly, (2015) on wind resources in some locations in North Africa such as Algeria, and Egypt as well as in some countries in Sub-Saharan Africa such as South Africa, Nigeria, Mauritius, Lesotho, Cap Verde, Eritrea and Somalia amongst others. Recent studies have found that five additional African countries such as Mozambique, Tanzania, Angola, South Africa, and Namibia have potentially large off-shore wind energy resources (Mukasa et al., 2013).

According to Figure 2.8 the general sources show that the highest wind potential exists in coastal areas, which tend also have both on-shore and off-shore potential. An exception is countries like Chad and Ethiopia, whose landscape gives rise to high speed winds in certain high altitude areas, while the rest of land-locked Africa's wind intensity is too low to be harnessed for electric power generation (Mukasa et al, 2013).

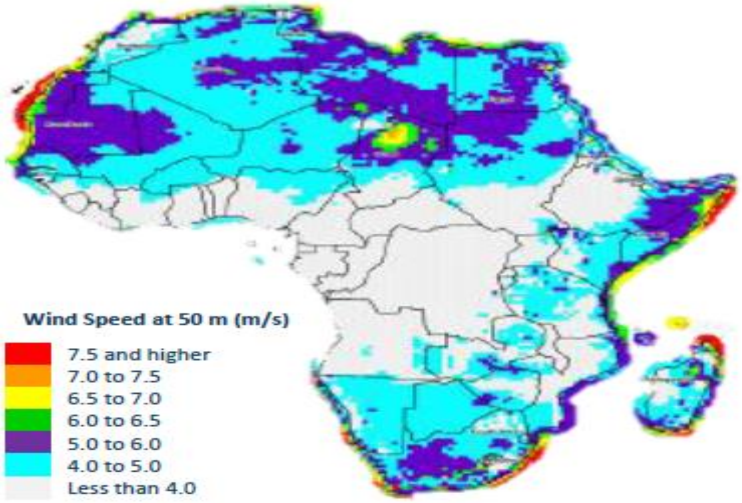


Figure 2.8: Wind speeds in Africa at an altitude of 50m (Mukasa et al, 2013)

Even though North African countries like Egypt, Morocco and Tunisia remains the leading regions in Africa wind energy markets, southern countries such as South Africa and Eastern African countries are expected to reduce the gap, contributing to the energy mix (IEA, 2011).

The South African Wind Energy Association (SAWEA) shows that wind power alone has the potential to generate 62% of South Africa's current energy needs. The above statement is cited in the study prepared by Mentis and Hermann, (2015), titled “Assessing the technical wind energy potential in Africa a GIS-based approach”. Currently in South Africa is capable about 25% of the country’s area is suitable for generating between 5000 and 10000 MWh annually per 1 km^2 (Mentis, 2013).

Like other renewable resources, geothermal energy usage is said to be under-exploited in Africa yet available in an enormous quantity that can provide significant future energy mix in Africa. The East African Rift valley System (EARS) is one of the most important zones in the world where the heat energy of the interior of the Earth escapes to the surface in the form of volcanic eruptions, earthquakes and the upward transport of heat by hot springs and natural vapour emanations (Ohunakin et al., 2014). The EARS appear to possess a remarkable geothermal potential. The eastern Africa branch that forms the Ethiopian and Kenyan rifts possesses, by far, the most extensive geothermal resource base in Africa and one of the most extensive in the world (Ohunakin et al., 2014). Countries such as Djibouti, Uganda, Eritrea and other south eastern Africa countries have smaller yet still important resource bases (Niyimbona, 2005).

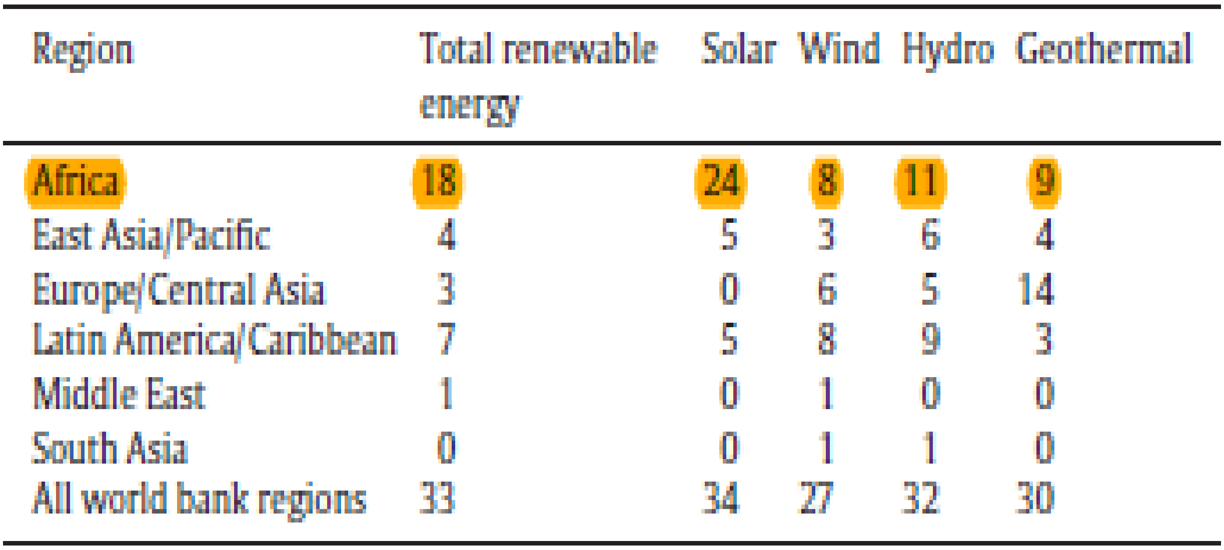
Most of the East African countries with geothermal potential are turning to their own indigenous resources to help them meet their growing energy needs (Niyimbona, 2005). Geothermal energy presents a clean and more environmentally friendly alternative to more traditional fuels (Niyimbona, 2005). Using today's technologies, Eastern Africa has the potential to generate 2,500 to 6,500 MW of energy from geothermal power (GEA, 1999) which if developed would represent from a quarter to three quarters of current worldwide production from geothermal sources (8900 MW total installed capacity). Currently, Kenya is the only country Africa that is exploiting this renewable resource potential, as part of the country's electricity generation infrastructure plan.

However, like anywhere else in the Africa, the progress of development is hampered by a) lack of finance, and b) lack of technical capabilities in some aspects of development (Ohunakin et al., 2014).

Table 2.2: World geothermal Potential (Niyimbona, 2005).

REGION	THEORETICAL POTENTIAL (TWh/YR)	TECHNICAL POTENTIAL (TWh/YR)
AFRICA	10118	3140
N. AMERICA	6150	3120
LATIN AMERICA	5670	3780
ASIA	20486	7530
OCEANIA	1500	390
EUROPE	4360	1430
WORLD	**44280**	**19390**

Table 2.3: Number of continent per developing region with the highest potential for solar, wind, hydro and geothermal energy (Edenhofer et al., 2011).

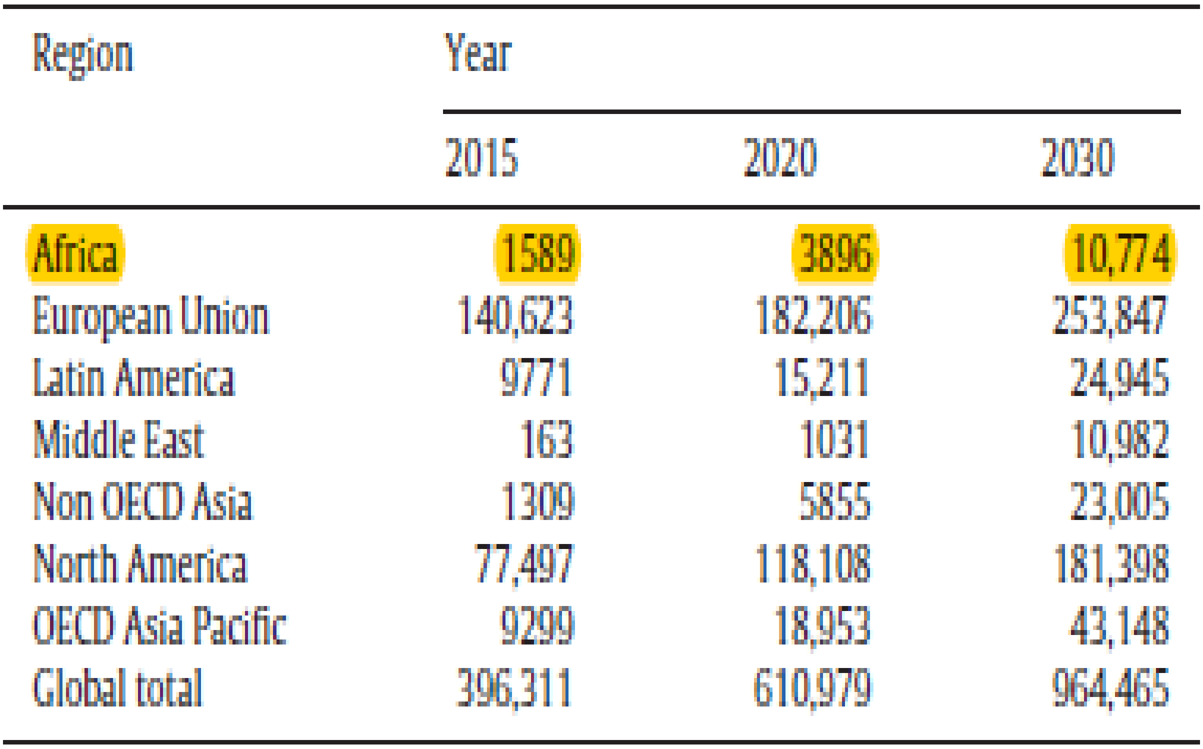


Region	Total renewable energy	Solar	Wind	Hydro	Geothermal
Africa	18	24	8	11	9
East Asia/Pacific	4	5	3	6	4
Europe/Central Asia	3	0	6	5	14
Latin America/Caribbean	7	5	8	9	3
Middle East	1	0	1	0	0
South Asia	0	0	1	1	0
All world bank regions	33	34	27	32	30

For example, according to the African Development Bank (ADB), installed capacity of wind-based electricity in Africa, estimated at 1.1 giga-watts (GW) in 2011, does not exceed 0.5% of the global capacity.

Only 43 megawatts (MW) have been installed in SSA, accounting for a mere 4% of the total installation. Given in the report in Table 2.3, Africa records abundance of wind compared to other countries. In fact, the report from the ADB reveals that Africa's installed capacity was expected to grow to 1.5 GW by 2015 and 3.9 GW by 2020 compared to global wind capacity of 396 GW by 2015 and 610 GW by 2020 (Ainah & Folly, 2015). This lack of harnessing renewable energy resource potential in Africa is mainly due to limited policy interest and investment levels, technical and financial barriers have also contributed to the low levels of exploitation of renewable energy resource on the continent (Ohunakin et al., 2014). Almost €6.3 billion worth of investment would flow into African wind markets every year by 2030, and the sector would employ over 105,000 people (Ainah & Folly, 2015). Table 2.4 shows the Installed wind capacity in MW for selected regions.

Table 2.4: Installed wind capacity in MW for selected regions (Aissa et al., 2014).



Region	Year		
	2015	2020	2030
Africa	1589	3896	10,774
European Union	140,623	182,206	253,847
Latin America	9771	15,211	24,945
Middle East	163	1031	10,982
Non OECD Asia	1309	5855	23,005
North America	77,497	118,108	181,398
OECD Asia Pacific	9299	18,953	43,148
Global total	396,311	610,979	964,465

Tapping into these renewable energy potentials will be a viable alternative for electricity generation in Africa and South Africa (Pegels, 2010). Furthermore, understanding renewable energy sources and their potentials can motivate renewable energy development (Pegels, 2010).

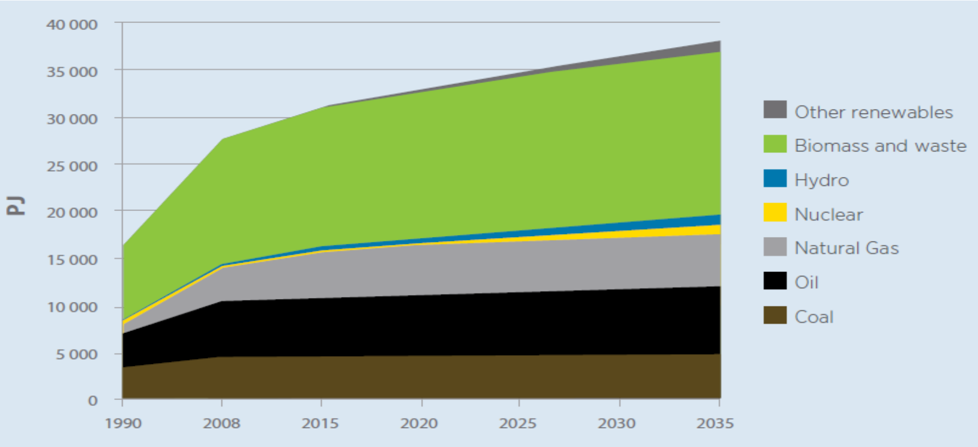


Figure 2.9: Total primary energy demand for energy sources in Africa (IEA, 2010)

Biomass has been used for energy purposes globally for many centuries, and according to Figure 2.9 above, it still is the main source of energy in a number of countries worldwide including the African continent, the use of which is reflected as Africa 39%, East Sahelian Africa 81%, Bhutan 86%, Nepal 97% and Asia 16%, (Anyamba & Tucker, 2005).

In all of the above countries, firewood has been the leading source of biomass energy used mainly for cooking and heating. The type of biomass resources available in Africa varies with climatic region on the continent. For example the rain forest zone will generate the highest quantity of woody biomass while savannah zones will generate more crop residues (Simonyan & Fasina, 2013).

The African Energy Policy Research Network (AEPR) calculates that biomass from agricultural waste alone could meet the present electrical needs of 16 south eastern countries with bagasse-based cogeneration (AEPR, 2011). The suitability of a particular biomass as a renewable generation potential and potential feedstock for bioenergy production depends on various characteristics such as moisture content, calorific value, fixed carbon, oxygen, hydrogen, nitrogen, volatiles, ash content and the cellulose/lignin ratio (Duku et al., 2011).

The drivers for increasing the use of biomass for energy (FAO, 2008) include:

(i) Possibility of reduced carbon emissions and meeting climate change commitments,

(ii) Reduction in fossil fuel consumptions,

(iii) Rural development through employment and increased livelihood and market opportunities,

(iv) Security of supply through local production and / or processing and

(v) Technological developments because bioenergy could be used to bridge the gap between current fossil fuels technologies and future technologies. The conversion of biomass to energy will be rewarding, given the large availability of biomass resources in the continent (Marrison & Larson, 1996).

The African continent features many sustainable energy resources, of which only a small percentage have been harnessed. 5.7% of the continent's hydroelectric potential has been tapped and only 0.6% of its geothermal (Marrison & Larson, 1996).

According to Stephen Karekezi the Director of African Energy Policy Research Network and co-worker Waeni Kithyoma, Africa is the third largest in crude oil reserves (behind the Middle East and Latin America), third largest in natural gas resources (behind the Middle East and Europe), second greatest for uranium (behind Australia), and is plentiful in hydro energy potentials and other renewable energy, such as bio-energy and solar energy. The sugar industry in Mauritius already provides 25% of the country's energy from by-product cogeneration, with the potential for up to 13 times that amount with a widespread rollout cogeneration technology and process optimization.

The International Energy Agency (IEA) projects a decline in the total energy share of biomass and wastes by 2035. However, biomass will continue to remain an important energy resource for Africa in the future (IEA, 2010). The total primary energy demand (TPED) for Africa is predominantly determined by biomass demand with almost half of the energy demand (47.9%) being covered by biomass and waste (see Figure 10).

In South Africa various biomass models exist for the prediction of biomass of different species. A critical review on biomass models in South Africa by Ackerman et al. (2012) showed that a substantial number of biomass models exist for pines and eucalypts.

The most productive biomass areas in South Africa are in KwaZulu-Natal and the wetter land of Mpumalanga (Duku & Hagan, 2011). According to DME, (2003b) the energy potential per hectare extends as high as 1000 GJ/ha/annum and currently there are 4 300 km^2 ha of sugar cane plantation and 13 000 km^2 of forestry plantation in South Africa (SMRI 2004).

The existing sugar mills burn bagasse, and paper and packaging mills use pulp waste to generate process steam and approximately 210 GWh of electricity per year (Duku and Hagan, 2011).

The sugar milling research institute (SMRI, 2013-2014) study indicates a total potential of 12.7 TWh per year from the existing sugar cane, forestry, sawmill, pulp and paper industries. According to SMRI, this study an independent survey of the costs of production of more than 100 global sugar industries producing sugar from cane and beet, South Africa sugar industry consistently ranks amongst the top 15 sugar producers in the world. The research done by the SMRI estimates that gross annual biomass energy production potential for South Africa is about 135 PJ (Pico joule) per cent of available non-crop, non-forest, non-wilderness areas used to produce energy crops.

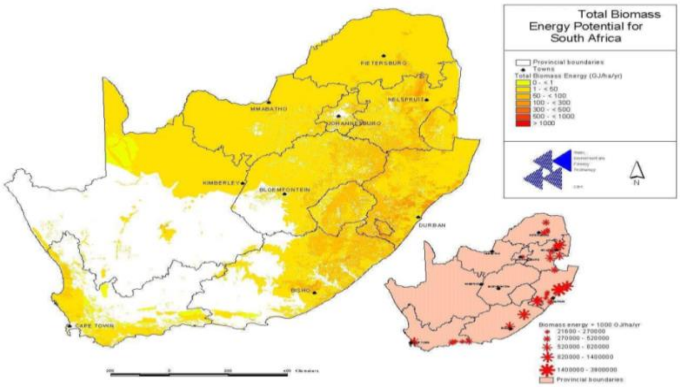


Figure 2.10: South African biomass resources (SMRI, 2013-2014)

Numerous studies on climate change have indicated that forest ecosystems play a major role in carbon seclusion and storage (Phiri, 2013). Carbon from the atmosphere is taken up by vegetation during photosynthesis and stored as plant biomass as part of the carbon cycle process (Samalca, 2000).

2.4. Understanding Renewable generation and Distributed generation concepts

As global energy demand increases, RE provides one means among many of adding energy assets to the system alongside growth of other resources. Due to rapid energy penetration and energy integration, many terms have emerged to describe power that comes from different sources other than from large, centrally dispatched generating units connected to a high-voltage transmission system or network (Sotkiewicz &Vignolo, 2007). To understand the viewpoint of renewable generation, it is important to deal with the well-known concept "distributed generation".

2.4.1. Background of distributed generation

The term distributed generation is not a new concept because originally energy was produced and consumed at the development that required it (Adefarati & Bansal., 2016). However, the definitions used in recent literature with in regards to distributed generation are not consistent. Research shows that most authors define the location of DG at the distribution side of the network, some authors also include the customer's side, and some even include the transmission side of the network. In the literature, a large number of terms and definitions are used in relation to distributed generation. For example Lasseter, (2007) indicates that Anglo-American countries often use the term 'embedded generation', North American countries the term 'dispersed generation', and in Europe and parts of Asia, the term 'decentralised generation' is applied for the same type of generation (Lasseter, 2007).

In other official international documents, different definitions of the term distributed generation (DG) can be found, each referring to various characteristics for the classification: the size of the power plant, its location, the energy source that is converted into electricity, the voltage level of the grid to which it is connected, and the dispatchment methodology (Junior et al., 2013) etc.

Distributed generation sources are normally connected to the main grid or to the load through the interface of power electronics, which manages the power and the output voltage (Chandorkar et al., 2013).

In an amazing book by Lovins et al. (2002), Small is Profitable: The Hidden Economic Benefits of Making Electrical Resources the Right Size (2002), benefits of distributed resources are explored and explained. In his book he defines distributed renewable resources that are relatively small in scale and located somewhat near the end-user. An example of such distributed resources is shown in Figure 2.11. He further states that Distributed Energy Resources (DER), are small-scale power generation sources located close to electricity consumer, providing alternative enhancement of the traditional electric power grid. Distributed resource is a faster and less expensive option to the construct in large, central power plants and high-voltage transmission lines. They offer consumers the potential for lower cost, higher service reliability, high power quality, increased energy efficiency, and energy independence.

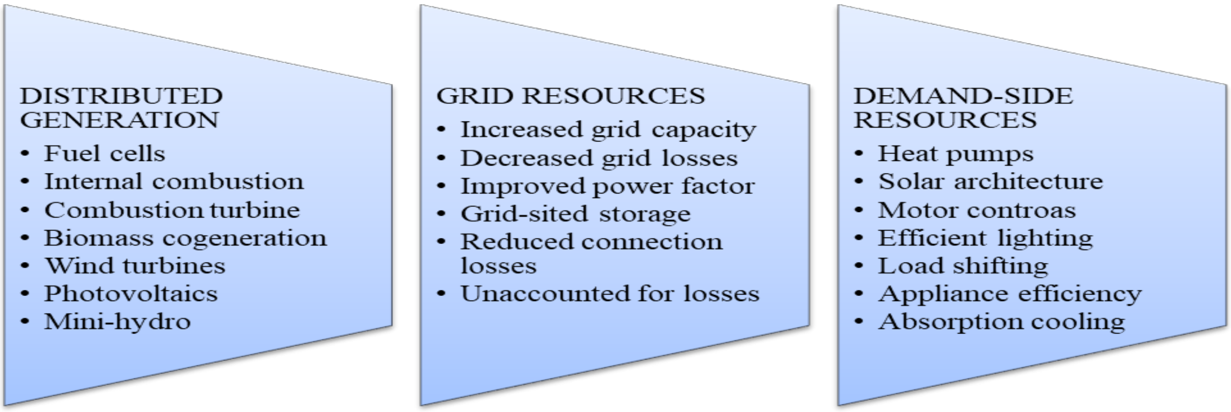


Figure 2.11: Examples of distributed resources (Lovein et al., 2002)

Another basis for classification of DGs is the type of technology involved in the power generation. Therefore, distributed generation technologies can be categorized as renewable and non-renewable as depicted in Figure 2.12.

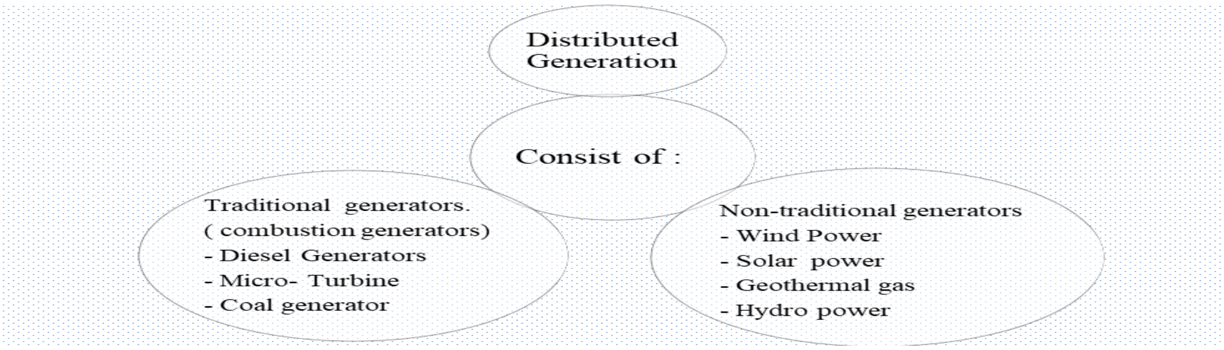


Figure 2.12: Distributed generation classification

Due to the large variations in the definitions used in the literature, the following different approach has been used to define distributed generation more precisely:

- The purpose;
- The location;
- The rating of distributed generation;
- The power delivery area;
- The technology;

- The environmental impact;
- The mode of operation;
- The penetration of distributed generation.

2.4.2. Definition of distributed generation

As mentioned in the previous pages, although distributed generation is not a new approach in the electricity industry, the analysis of recent literature has shown that there is no accepted definition of distributed generation as of yet (Bollen & Hassan, 2011). According to research, distributed generation is an approach that employs small-scale technologies to produce electricity close to the end users of power. The small scale distributed generation is often produced by small modular solar and wind generators, coal generators, hydro, biomass and geothermal etc. Figure 2.12 above shows the classification of some of the distributed renewable generator around the world currently being used to generate power while Figure.2.13 below shows simplified integration of existing distributed power generation to the grid.

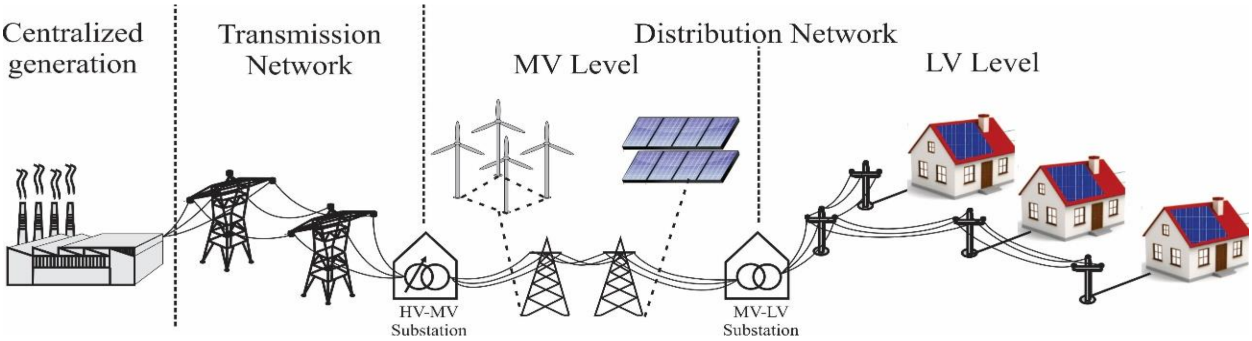


Figure 2.13: Simplified diagram with the most grid-connected DG technology concept (Freris & Infield, 2008)

As a result of many different definitions regarding distributed generation used in the literature and in practice, this study suggests a general definition of distributed generation (Kaunda et al., 2012). Distributed generation is an electric power source connected directly to the distribution network or on the customer site of the meter (Bollen & Hassan, 2011). In most competitive markets such as Europe, USA and Asia, the legal definition for transmission networks is usually part of the electricity market regulation. Anything that is not defined as transmission network in the legislation can be regarded as the distribution network. The definition of distributed generation does not define the rating of the generation source, as the maximum rating depends on the local distribution network conditions, e.g. voltage level. It is useful to introduce categories of different ratings of distributed generation. The following categories are suggested as seen in the table below:

Table 2.5: Distributed generation capacities (Ackermann et al. 2001; El-Khattam and Salama, 2004)

Class	**Power Range**
Micro distributed generation	~ 1W – 5kW
Small distributed generation	5kW – 5MW
Medium distributed generation	5MW – 50MW
Large distributed generation	50MW – 300MW

2.4.3. Renewable generation background

A large amount of research effort has been made in order to diversify the primary energy sources and to accommodate the growth in consumption. This consumption growth, associated to the limited power generation capacity of traditional power plants, is encouraging the development of renewable generation systems. Currently, renewable generation (energy-based) DG has captivated the energy sector and energy economy on a global scale and this has become a leading research area (Adil & Ko, 2016).

Although the existing traditional power grid can maintain an instantaneous balance between supply and demand, it is constantly facing many problems (Adil & Ko, 2016). During the past decades, conventional generation such as diesel and coal has met the problem of energy crisis and environmental pollution. On the other hand renewable generation resources particularly, wind and photovoltaic generations are becoming more cost-effective in South Africa and Africa due to the evolution of renewable technologies and the advances in power electronics solutions (Adil & Ko, 2016).

Although South Africa's journey towards large-scale deployment of renewable energy (RE) technologies has taken slow progress to mature, solar and wind are gaining momentum. Wind and solar photovoltaic (Solar PV) power plants have been the first power plants from the RE portfolio to start operations, steadily contributing additional capacity to the power system with each new successfully commissioned plant, as shown in Figure 2.14 below (SA DOE, 2015).

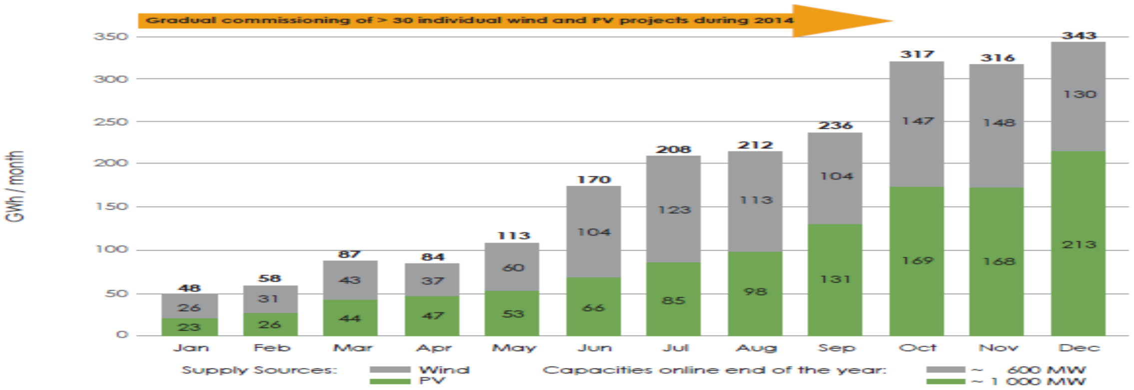


Figure 2.14: REIPP growth in energy produced during 2014 (Eskom, CSIR Energy Centre analysis, 2013)

According to mainstream South Africa (SA), the government's tendering programme (REIPPPP) has already awarded a tender of 848MW of renewable generation to Mainstream for long term development of Solar PV and wind project. The table below shows the summary of renewable generation project currently underway with 318MW generation added on the national grid.

Table 2.6: Summary of renewable generation project in SA, (Mainstream, 2015)

NAME	STATUS	RENEWABLE GENERATION	MW
Jeffrey's bay	Operational	Wind	138
De Aar	Operational	Solar	50
Droogfontein	Operational	Solar	50
Nouspoort	Operational	Wind	80
Khabab	In construction	Wind	140
Loeriesfontein	In construction	Wind	140
Perdekraal East	Contract awarded, nearing financial close	Wind	110
Kangnas	Contract awarded, nearing financial close	Wind	140

Wind and solar power are the focus for two reasons; first they are among the renewable generation types, as wind and solar are subject to natural variability in their energy sources. This variability creates distinct challenges for integration into the larger power system, namely non-dispatchability. Secondly, wind and solar power are relatively mature for use in large capacities and in wide areas, and so have a significant impact on the power grid that is likely to increase over time.

2.4.4. Definition of renewable generation

The term “renewable” generally refers to those energy resources whose common characteristic is that they are non-depletable or naturally replenishable. Therefore renewable generation refers to renewable energy sources that produced electricity at or near the point where it is used. Renewable resources include solar energy, wind energy, hydropower, geothermal energy, biomass and temperature differences in the oceans and the energy of the tides. From the performance point of view, these renewable generations have much in common with conventional utility power plants (Adil & Ko, 2016). Their interconnection to the transmission systems therefore, shall follow the generation interconnection requirements and guidelines.

Enabling renewable generation integration to the power grids has become an essential element of the smart grid roadmap (Gungor et al., 2013).

As electric utilities prepare to meet the Renewable Portfolio Standard goals, advanced sensing and communication technologies can be used to facilitate renewable integration.

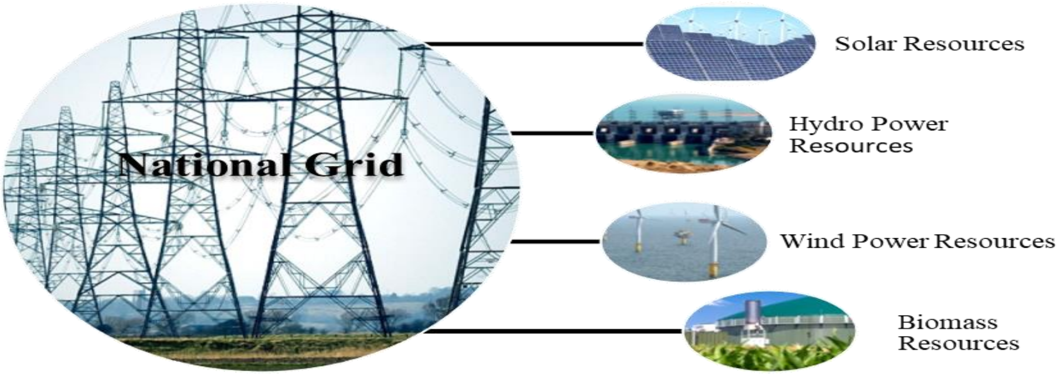


Figure 2.15: Commercially available renewable energy generation resources (SolarGIS, 2013)

Renewable generation technologies consist primarily of energy generation and storage systems placed at or near the point of use. Renewable generation energy comprises a range of resource technologies including biomass, and geothermal. These technologies also involves power electronic interfaces, as well as communications and control devices for efficient dispatch and operation of single generating units, multiple system packages, and combined generating power units.

The primary fuel for much needed renewable generation development in Africa and South Africa is the fast growing economy which requires energy integration to meet the growing demand. Renewable energy technologies—such as solar electricity, biomass power, and wind turbines—are imperative in the energy mix. Figure 2.15 above shows the undergoing major developments in Africa and South Africa.

2.5. Types of renewable energy sources

Renewable generation can be classified into two major groups, namely, inverter based DG and rotating machine DG. Normally, inverters are used in DG systems after the generation process, as the generated voltage may be in DC or AC form, but it is required to be changed to the nominal voltage and frequency (Gungor et al., 2013). Therefore, it has to be converted first to DC and then back to AC with the nominal parameters through the rectifier. In the next pages, some of the presently available renewable generation technologies, for example, photovoltaic systems/solar power, wind turbines, hydro power, biomass, and geothermal and renewable generators are discussed.

Renewable energies are energy sources that are continually replenished by nature and derived directly from the sun (such as thermal, photo-chemical, and photo-electric), indirectly from the sun (such as wind, hydropower, and photosynthetic energy stored in biomass), or from other natural movements and mechanisms of the environment (such as geothermal and tidal energy). Figure 2.16 below shows an overview of renewable energy sources. Renewable energy technologies turn these natural energy sources into usable forms of energy electricity, heat and fuels. Renewable energy markets such as electricity heating and transportation have been growing sharply over the last five years. The deployment of established technologies, such as hydro, as well as newer technologies such as wind and solar photovoltaic, has risen quickly, which has increased confidence in the technologies, reduced costs and created new opportunities.

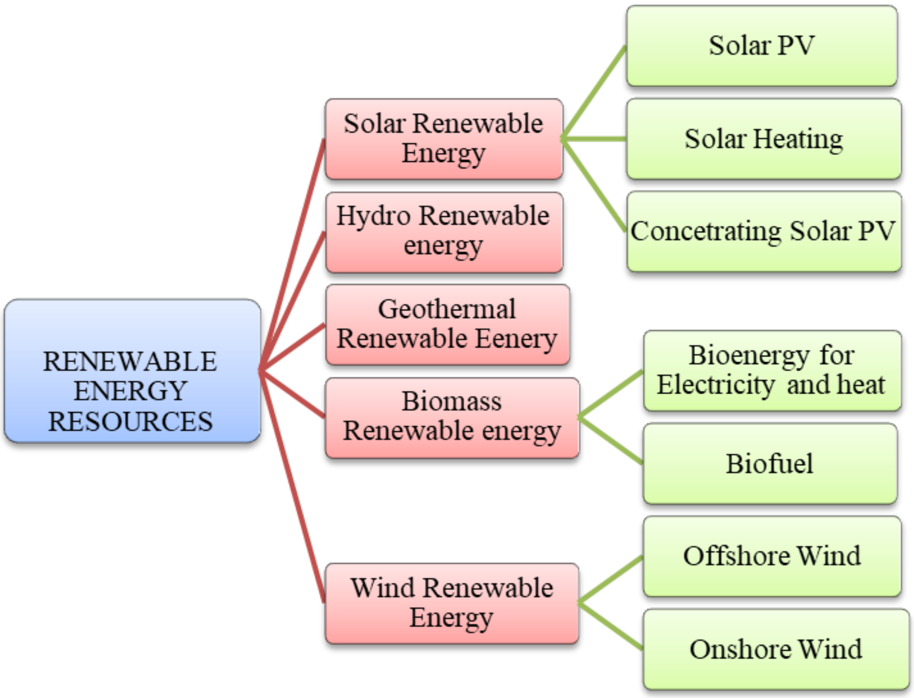


Figure 2.16: Overview of renewable energy sources

2.5.1. Photovoltaic (PV) or Solar Power

A photovoltaic system, converts the light received from the sun into electric energy. In this system, semi conductive materials are used in the construction of solar cells, which transform the self-contained energy of photons into electricity, when they are exposed to sun light (Gungor et al., 2013). The cells are placed in an array that is either fixed or moving to keep tracking the sun in order to generate the maximum power. These systems are environmentally friendly without any kind of emission. They are easy to use, are simple in design and do not require any other fuel save for solar light. On the other hand, they need large spaces and the initial capital is very high (Gungor et al., 2013).

The main components of PV systems are photovoltaic modules and photovoltaic inverter with adequate protective equipment and installation. Photovoltaic modules convert solar energy into DC current, while the photovoltaic inverter adjusts the produced energy in a form which can be submitted to the public grid (Gungor et al., 2013). The AC voltage is supplied to the electricity network through protection and measuring equipment. The photovoltaic inverter is usually located indoors, although there are inverters for outdoor installation, where it must not be directly exposed to sunlight. Inverters produce high-quality AC current of corresponding voltage and are suitable for a network-connected photovoltaic system.

Several large-scale solar power facilities are under development in Africa including projects in South Africa and many other African countries. Although solar power technology has the potential to supply energy to large numbers of people, and has been used to generate power on a large scale in developed nations, its greatest potential in Africa may be to provide power on a smaller scale and to use this energy to help with day-to-day needs such as small-scale electrification, desalination, water pumping, and water purification.

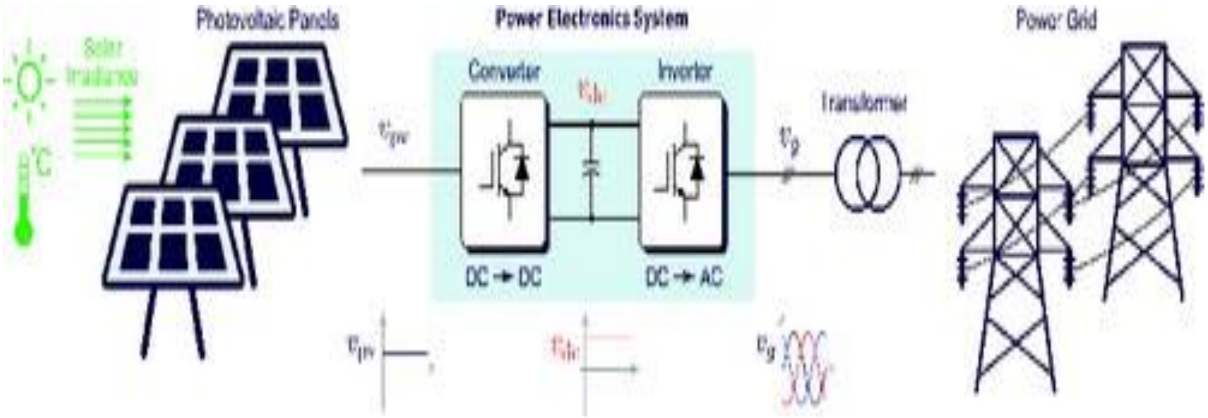


Figure 2.17: Schematic diagram for grid connected PV system (Sipahutar, et al., 2013)

Solar power includes photovoltaic (PV) as well as concentrated solar power (CSP). In South Africa, a 50 MW concentrated photovoltaic (CPV) power plant is being planned in Touwsrivier, in the Western Cape. PV systems generate DC voltage and then transfer to AC with the aid of inverters. There are two general designs that are typically used: with and without battery storages (Reve, 2015).

2.5.2. Theory of Photovoltaic (PV) electricity generation

The photovoltaic effect is the basic physical process through which a PV cell converts sunlight into electricity. Sunlight is composed of photons (like energy accumulations), or particles of solar energy. These photons contain various amount of energy corresponding to the different wavelengths of the solar spectrum. When photons hit a PV cell, they may be reflected or absorbed. Only the absorbed photons generate electricity. When this happens, the energy of the photon is transferred to an electron in an atom of the cell (usually silicon atoms). The electron is then able to escape from its normal position associated in the atom to become part of the current in electrical circuit (Tyagi et al., 2013). The Figure 2.18 below shows that different PV materials have different energy band gaps.

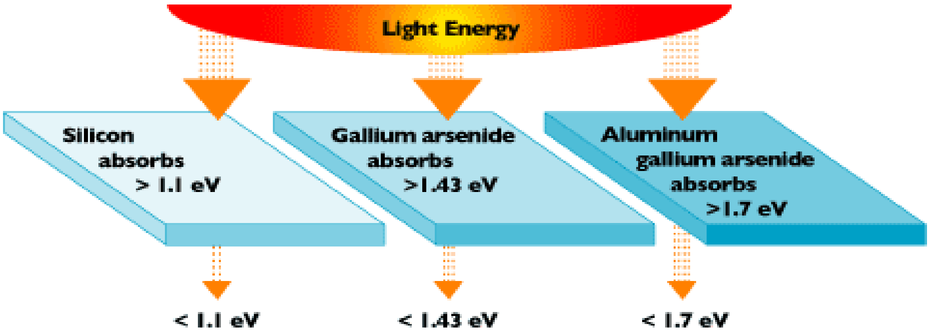


Figure 2.18: Different PV materials with different energy band gaps (Tyagi et al, 2013).

To produce the electric field within a PV cell, the manufacturers create a junction of two different semiconductors (types P and N). The most common way of making P or N type silicon material is by adding element that has an extra electron or has a deficit of an electron. Silicon is the most common material used in manufacturing process of photovoltaic cells. Silicon atoms have 14eletrons, where the four electrons in the last layer are called valence electrons. In a crystal solid, each silicon atom normally shares one of its four valence electrons in a covalent junction with another silicon atom. The silicon crystal molecules are formed of 5 silicon atoms in a covalent junction (Adil & Ko., 2016).

The process of doping introduces an atom of another element into silicon crystal to alter its electrical properties. The element used for doping has three or five valence electrons. Usually phosphorus is used to make the N-type (Boron has 3 valence electrons). In a polycrystalline thin-film cell, the top layer is made of a different semiconductor material than the bottom semiconductor layer.

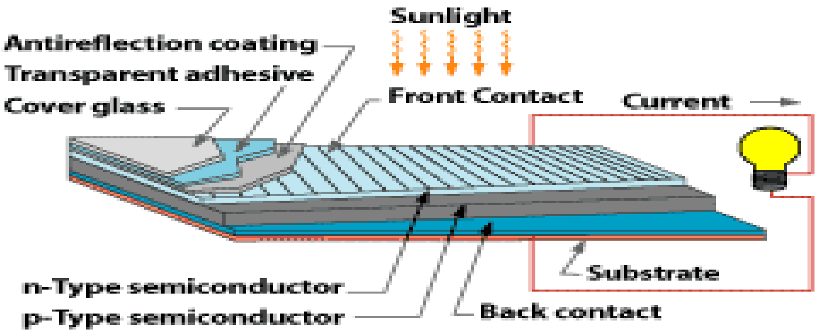


Figure 2.19: What a typical PV solar cell consists of (Tyagi et al., 2013).

2.5.3. Types of photovoltaic systems

Photovoltaic power systems are generally classified according to their functional and operational requirements, their component configurations, and how the equipment is connected to other power sources and electrical loads. Photovoltaic systems can be divided into two basic groups:

1. Photovoltaic systems not connected to the network, stand-alone systems (off-grid)
2. Photovoltaic systems connected to public electricity network (on-grid), of which there are lots of different subtypes of photovoltaic systems according to type and method of connecting to the network, or method of storing energy on independent systems (Claire, 2016).

Sizing of a PV system means to determine how much energy is required to run the system and how many PV modules are needed to generate it. A PV system has to generate enough energy to cover the energy consumption of the loads (lights, appliances, equipment) and energy used by the system itself.

The size and configuration of the solar array is then optimised in order to match the energy yield of the system to the energy consumption of the system. The energy yield of a PV system depends on the type of PV modules, the characteristics of a PV inverter, the orientation of the modules, and meteorological conditions.

2.5.3.1. Stand-alone system

These systems are isolated from the electric grid. Figure 2.20 describes the most common configuration, which is in fact actually one of the most complex and includes the entire element necessary to serve AC appliances in a common household or commercial application. An additional generator (e.g., diesel or wind) could be considered to enhance the reliability. The inverter section of this standalone system will be discussed in more detail in chapter 5 of this thesis.

The number of components in the system will depend on the type of load that is being served. The inverter could be eliminated or replaced by a DC to DC converter if only DC loads are to be fed by the PV modules. It is also possible to directly couple a PV array to a DC load when alternative storage methods are used or when operating schedules are not of importance.

In stand-alone photovoltaic power systems, the electrical energy produced by the photovoltaic panels cannot always be used directly. As the demand from the load does not always equal the solar panel capacity, battery banks are generally used. The primary functions of a storage battery in a stand-alone PV system are:

- To store energy when there is an excess and be available to provide it when required by the load.
- To provide stable current and voltage by eradicating transients (Voltage and Current Stabilization).

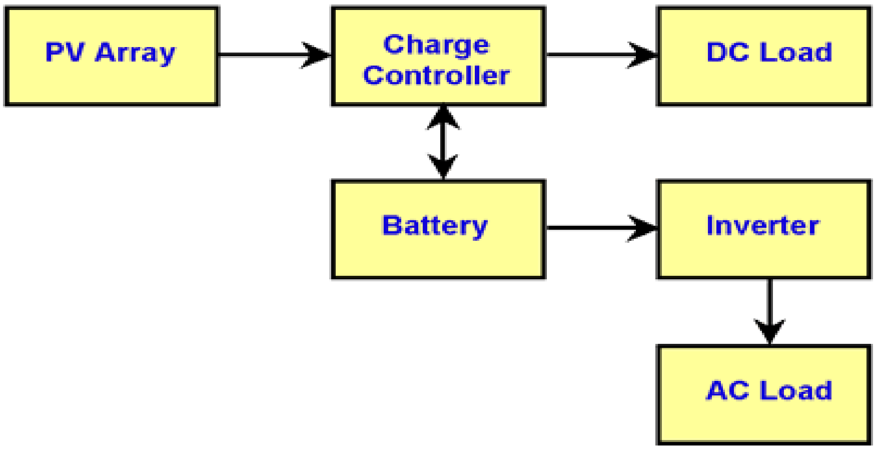


Figure 2.20: Diagram of stand-alone PV system with battery storage powering DC and AC loads

2.5.3.2. Hybrid system

Hybrid systems are mostly combined by both stand-alone system and grid-tied system as an additional connection for reliability and scheduling flexibility of power. Most available reports on PV systems are related to this kind of technology, but the system is only commercially available to commercial consumers and upper class residential consumers.

A hybrid power plant is a complete electrical power supply system that can be easily configured to meet a broad range of remote power needs. Hybrid energy systems combine two or more forms of energy generation, storage or end-use technologies, and they can deliver huge benefits compared with single source systems. In these cases, hybrid energy systems are an ideal solution since they can offer substantial improvements in performance and cost reduction, and can be tailored to varying end user requirements (Chauhan &Saini, 2014).

There are three basic elements to the system –

- The power source unit
- The battery storage unit
- The power management center.

Sources for hybrid power include wind turbines, diesel engine generators, and solar PV systems. The battery allows autonomous operation by compensating for the difference between power production and use. Hybrid systems provide a high level of energy security through the mix of generation methods, however the initial capital is costly. Configurations could include renewable or non-renewable energy sources, electrical and chemical energy storage and fuel cells, often connected via a smart grid (Chauhan & Saini, 2014).

In this scheme below, all DC energy sources (solar) are coupled to the DC bus by proper interfacing circuits. DC loads are directly served through DC bus by using DC/AC converter. AC loads receives energy from converter output AC bus (50–60 Hz). This system eliminates the use of converters (DC/DC) and hence reduces conversion losses in the configuration. As a result, hybrid DC–AC coupled configuration has lower cost and higher energy efficiency as compared to DC-DC coupled with AC schemes. However, the hybrid scheme has relatively complex control and energy management. Hybrid coupled configuration of wind, solar grid based integrated energy system is presented in Figure 2.21 below.

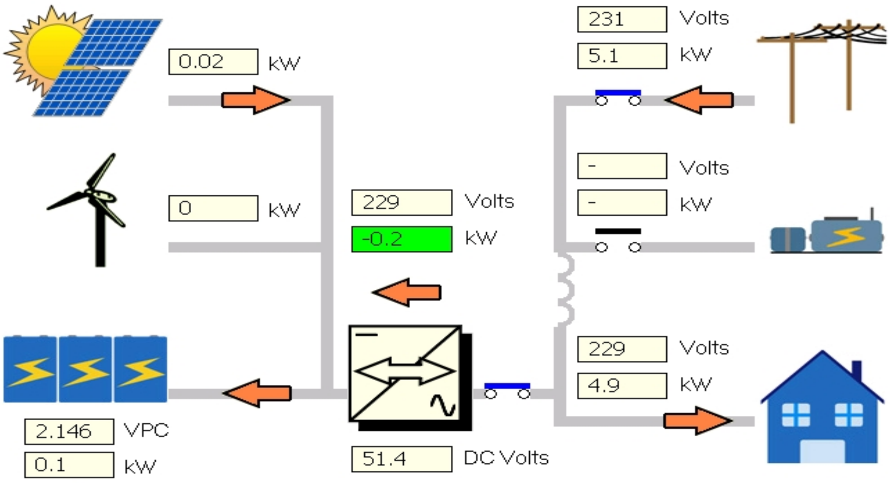


Figure 2.21: Power flow and grid interaction, typical photovoltaic hybrid system (Malengret & Gaunt, 2011)

2.5.3.3. Grid-tied system

These systems are directly coupled to the electric distribution network and do not require battery storage. Figure 2.22 below describes the basic configuration including the grid electric utility. Electric energy is either sold or bought from the local electric utility depending on the local energy load patterns and the solar resource variation during the day. This operation model requires an inverter to convert DC current to AC currents.

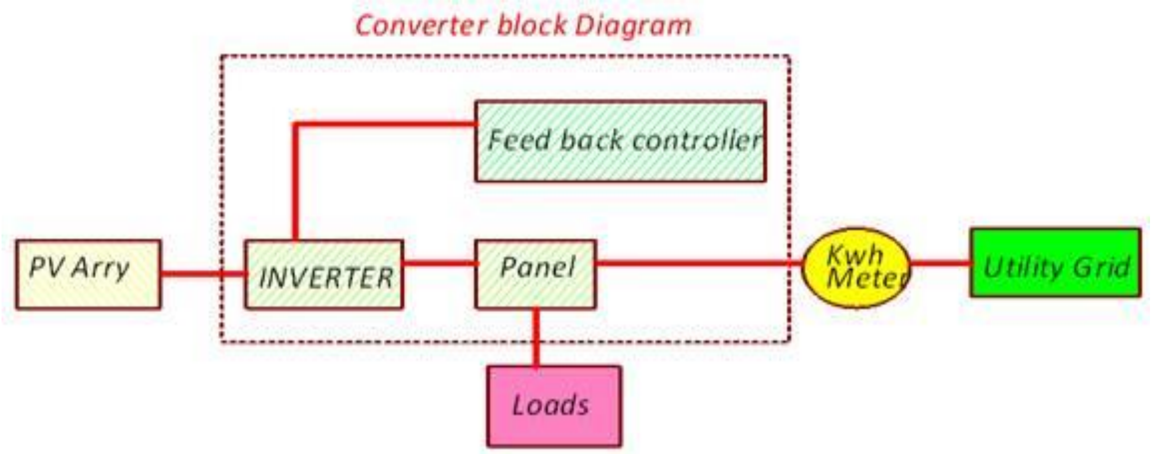


Figure 2.22: Diagram of grid-connected photovoltaic system (Libo et al., 2007).

There are many benefits that could be obtained from using grid-tied PV systems instead of the traditional stand-alone schemes.

- Smaller PV arrays can supply the load reliably.
- Less balance of system components are needed.
- Comparable emission reduction potential taking advantage of existing infrastructure.
- Eliminates the need for energy storage and the costs associated to substituting and recycling batteries for individual clients. Storage can be included if desired to enhance reliability for the client.
- Efficient use of available energy. Contributes to the required electrical grid generation while the client‘s demand is below PV output.

2.5.4. Wind Power sources

Wind power generation is developing fast in South Africa because of its commercial application and large-scale development in future. Recently, wind power generation connected to the grid has become the mainstream, garnering the support of large grid integration.

Wind turbines convert wind energy into electricity. Wind is a highly variable source which cannot be stored, thus, it must be handled according to this characteristic (Blaabjerg & Lonel et al., 2015). A general scheme of a wind turbine is shown in Figure 2.23, where its main components are presented. Figure 2.24 is a schematic representation of a modern power system, which incorporates renewable energy sources, distributed generation, and smart grid functions. Integration is made possible through the extensive use of power electronics. Wind energy is influenced indirectly by the energy of the sun (Burton et al., 2011). Significant quantity of the solar radiation received by the Earth is converted into kinetic energy, the main cause of which is the imbalance between the net outgoing radiation at high latitudes and the net incoming radiation at low latitudes (Burton et al., 2011).

The Earth’s rotation, geographic features and temperature gradients affect the location and nature of the resulting winds (Burton et al., 2011).

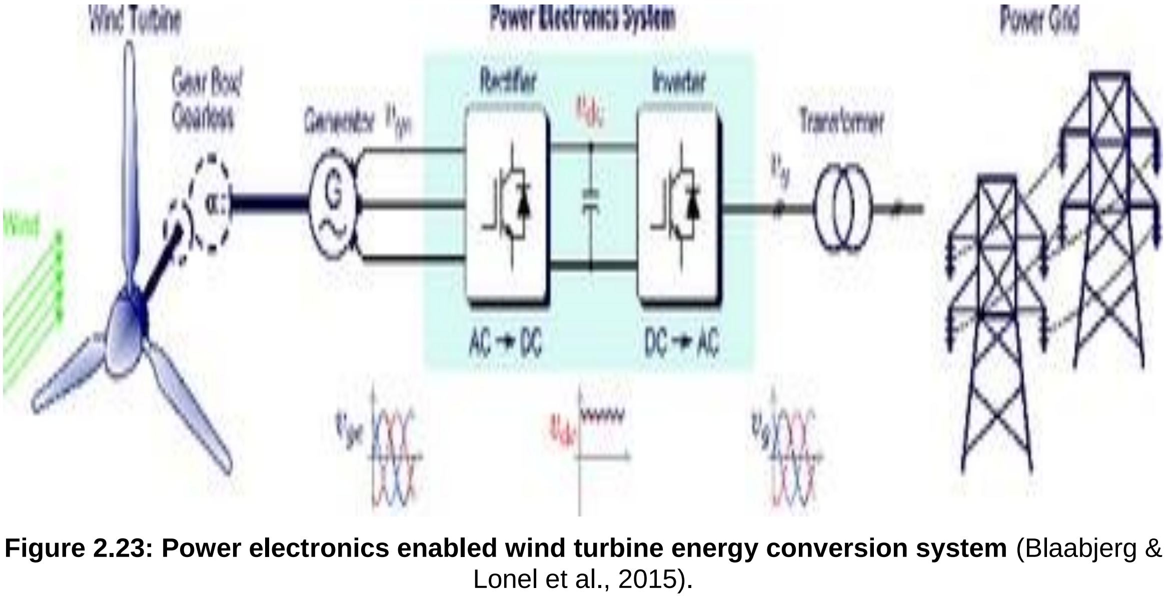


Figure 2.23: Power electronics enabled wind turbine energy conversion system (Blaabjerg & Lonel et al., 2015).

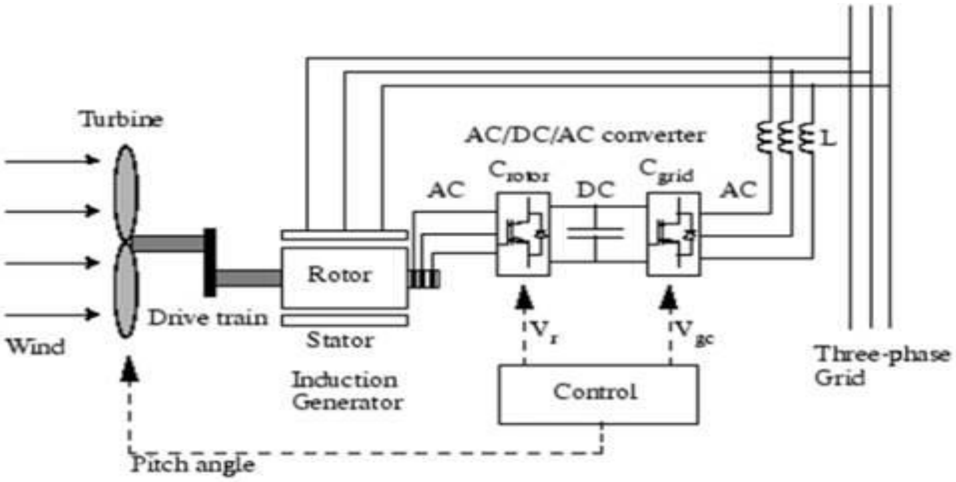


Figure 2.24: Schematic diagram of grid connected wind turbine (Burton et al., 2011)

The use of wind energy requires that the kinetic energy of moving air be converted to useful energy. As a result, the economics of using wind for electricity supply are highly sensitive to local wind conditions and the ability of wind turbines to reliably extract energy over a wide range of typical wind speeds.

Together with hydroelectric and photovoltaic system, wind generation or the direct conversion of wind into electrical energy is one of the cleanest forms of energy conversion available. When the energy crisis in the seventies was occurring, wind generation became very popular as a prospective replacement for fossil fuel electric generation. But, there are several reasons that wind energy generation has not become a major source of energy. However the development of wind has been slow due to high cost and the intermittent nature of winds.

2.5.4.1. Operation of wind turbine

The operation of a wind turbine is characterized by two conversion steps. First, the rotor extracts the kinetic energy of the wind, changing it into mechanical torque in the shaft; and in the second step the generation system converts this torque into electricity (Brent, 2013). The power coefficient, *Cp* gives the fraction of the kinetic energy that is converted into mechanical energy by the wind turbine.

It is a function of the tip-speed ratio and also depends on the blade pitch angle for pitch controlled turbines (Chauhan & Saini, 2014). For the operation of the wind turbine, it is important to take into account the equation of power density. It is used to find which wind site is potentially available to install the wind turbine (Brent, 2013). The expression for kinetic energy in moving air wind is calculated under the following equation:

$$\mathbf{P}_W = \frac{\rho}{2} A V^3 \tag{2.1}$$

Where P = power of a wind flow;

P = Air density [1,225 kg/m3, under usual conditions];

A = the cross-section area of a wind flow;

V = speed of a wind (m/s).

The useful mechanical power obtained is expressed by means of the power coefficient C_P

$$\mathbf{P}_W = C_P \frac{\rho}{2} A V^3 \tag{2.2}$$

The wind velocity suffers retardation due to the power conversion to a speed *V*3 behind the wind turbine. The velocity in the plane of the moving blades is of average value *V*2 = (v1 + *V*3)/2 (Nikolaev et al., 1994)

According to Nikolaev et al., (1994), calculation of useful power is maximum when (*V*3/*V*1) = 1⁄3 and the power coefficient *Cp* ≈ 0.59.

Wind turbines power coefficient maximum values *Cp* max = (0.4 - 0.5). This is because of profile loss, tip loss, and wake rotation loss. Tip-speed ratio is an important parameter of wind turbines. It is the ratio of the ratio of the peripheral velocity of the turbine blade tips and the wind speed (Nikolaev et al., 1994).

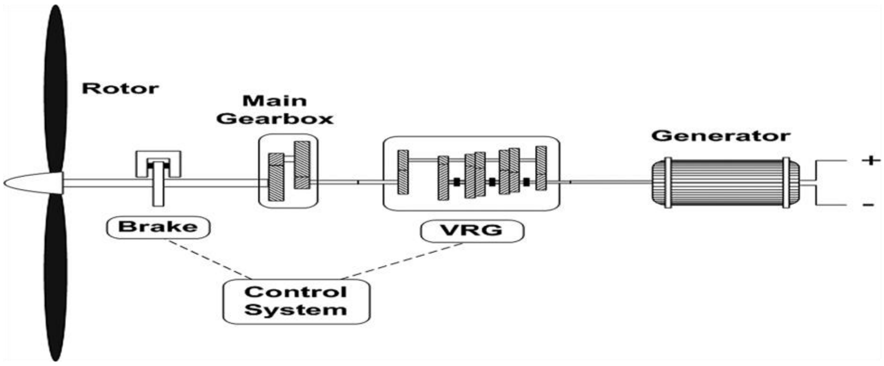


Figure 2.25: Typical diagram of wind turbine (Mentis et al., 2015)

In present wind systems, the generator system gives an AC output voltage that is dependent on the wind speed. As wind speed is variable, the voltage generated has to be transferred to

DC and back again to AC with the aid of inverters. However, fixed speed wind turbines are directly connected to grid (Chauhan & Saini, 2014).

One of the hottest topics for renewable energy is the generation of electricity by means of wind, but since we cannot control wind, a lot of protections have to be taken into account when having wind generators connected to the grid in order to maintain stability and avoid system collapse (Kishore et al., 2013).

2.5.5. Hydro Power source

Hydropower also referred to as tidal power or water power, is power derived from the energy of falling water, which may be harnessed for useful purposes. The early use of waterpower dates back to Mesopotamia, also known as ancient Egypt, where irrigation has been used since the 17th millennium BC and water clocks had been used since the early 2nd millennium BC. According to Wikipedia, (2010), waterwheels, turbines, and mills were built in India: in Imperial Rome, water powered mills produced flour from grain, and were also used for sawing timber and stone. In China, watermills were widely used since the Han Dynasty. In China and the rest of the Far East, hydraulically operated "pot wheel" pumps raised water into irrigation canals (Wikipedia, 2010).

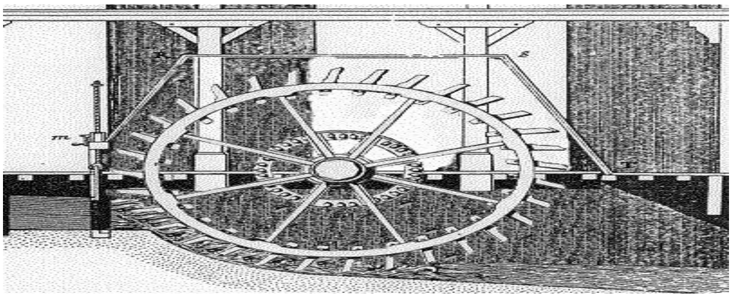


Figure 2.26: Typical ancient water turbine generator in early years in India and China (Wikipedia, 2010)

Hydro power has a long history in the literature, since the early 20th century, the term is used almost exclusively in conjunction with the modern development of hydro-electric power, which allowed the use of distant energy sources (SAAEA, 2012). Among many methods used to transmit energy is a trompe, which produces compressed air from falling water. Compressed air could then be piped to power other machinery at a distance from the waterfall (Mentis et al., 2015).

2.5.5.1. Brief operation of hydro power generation

Newton's law of universal gravitation states, that a particle attracts every other particle in the universe using a force that is directly proportional to the product of their masses and inversely proportional to the square of the distance between their centres. The basic idea behind hydropower comes from the theory of potential energy stored in the gravitational field (Svendsen, 2013). A mass (m) which is contained at a height (h) in a gravitational field with a gravitational constant (g) has a potential energy Ep = mgh. When the mass is released in the gravitational field, the energy will be transformed from potential energy to kinetic energy expressed in terms of the velocity (v) via the relation Ek = ½ mv2.

From the basic physical principal that energy is conserved, all the potential energy will be converted to kinetic energy plus some frictional heat losses due to the falling mass (m) at total height (h). This kinetic energy can be used to drive turbines which, in turn, drive the generators that generate electrical power (Svendsen, 2013). Figure 2.27 and 2.28 illustrates the design and operation of hydro power plant.

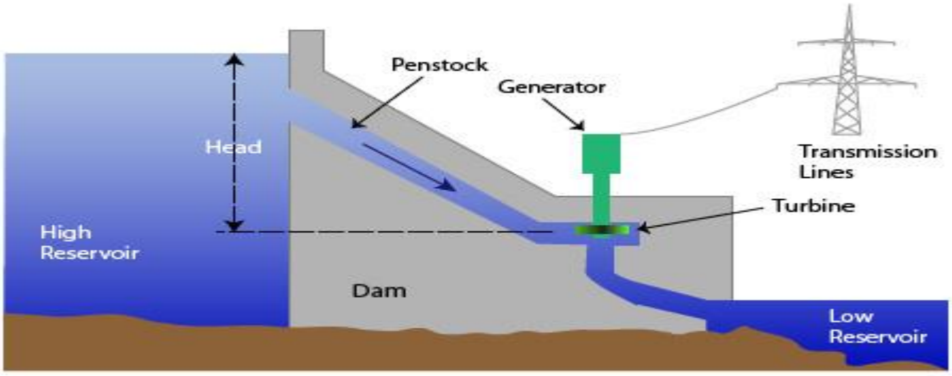


Figure 2.27: Illustration of hydropower conceptual design plan, (Admin, 2013)

Figure 2.28: Image of Inga Hydropower dam in Democratic Republic of Congo (DRC), (SAAEA, 2012)

The water stored behind a dam wall in Figure 2.27 is transported to a hydraulic turbine, which is turned by the force of the water. The turbine drives a generator rotor, to which it is coupled by a shaft, thus generating electricity. After the water has completed its task, it is discharged back into the river downstream of the power station.

Hydropower is one of the most important renewable resources in Africa that is currently under steady development. Research shows that the hydropower resource makes 16% of African power generation mix, and 94% of the continent renewable power production remains untapped (Kaunda et al., 2012). The untapped hydropower potential for large projects is mainly situated in the lower Congo River (INGA) and the upper Nile River (Aliyu et al., 2017).

The economic potential of Africa’s hydro-power is only about a half of the technical potential according to Onyeji. (2014), yet it would be sufficient to provide a substantial share of total Africa power demand. Hydropower provides more than19% of the world's electricity consumption from both large and small power plants. Countries such as Brazil, Uganda, the United States, Canada, DRC, and Norway produce significant amounts of electricity from very large hydroelectric facilities.

Worldwide mini-hydropower or small-scale hydropower projects have become more popular because of their low costs, reliability, and environmental friendliness. Studies show that small scale mini-hydropower generation is economically viable if the projects are combined with the additional benefits of flood and irrigation control as well as encouraging tourism (Aliyu et al., 2017).

2.5.6. Biomass renewable source

Biomass is the term used for all organic material originating from plants, trees and crops, and is essentially the collection and storage of the sun’s energy through photosynthesis. Bioenergy is the conversion of biomass into useful forms of energy such as heat, electricity, and liquid fuels (biofuels) (Phiri, 2013). The biomass renewable resource can also be defined as biological material from living or recently living organisms. Using biomass to generate electricity is technologically well-established, but the price paid for electricity seldom off sets the full cost of the biomass fuel. In South Africa, bioenergy fuels are intensive in the use of inputs, which include land, water, crops, and fossil energy, all of which have opportunity cost.

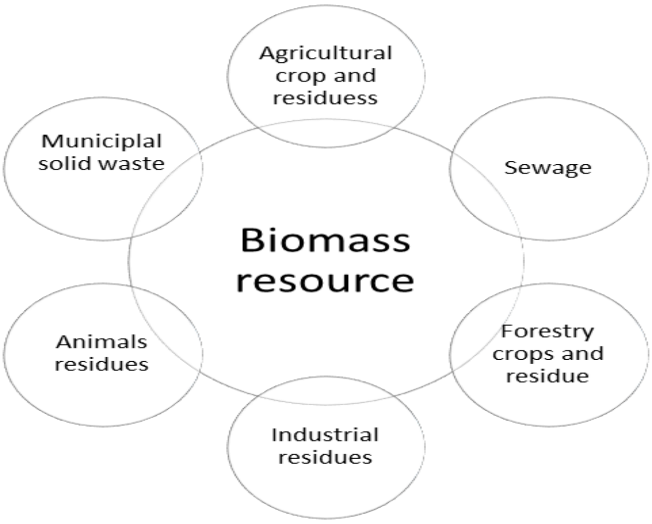


Figure 2.29: Overview of common biomass resources in South Africa (Banks & Schaffler, 2006)

According to the Sustainable Energy and Climate Change Project (SECCP), (2006), biomass energy is currently the largest renewable energy contributor in South Africa, estimated at about 9%, while some data indicates as high as 14%. Most rural households and several hundred thousand low-income urban households rely on fuel wood for cooking and space heating (Banks & Schaffler, 2006). Biomass by-products are used in boilers by the sugar and paper industries to generate electricity.

The South African government and other large stakeholders (e.g. Sasol and PetroSA) are currently developing the capacity to produce liquid fuels from biomass, with an estimated potential of 20% of the national liquid fuels requirement (Banks & Schaffler, 2006).

In the same report by SECCP, production of bio-ethanol, for possible use as a safer household fuel, is also receiving increased attention. In the longer term, SECCP anticipate biomass contributing between 9% and 16% of the energy requirement. The large-scale use of bioenergy would require vast areas of land to be converted to energy crops (Banks & Schaffler, 2006). As an energy source, biomass can either be used directly or converted into another energy product such as biofuel (Haw & Hughes, 2007).

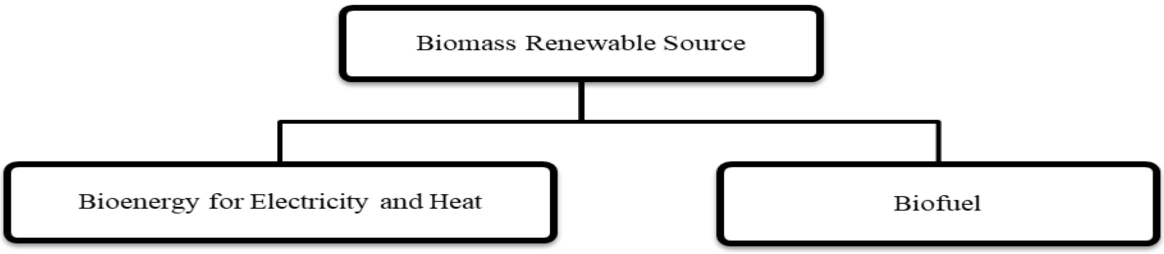


Figure 2.30 Overview of biomass use and different form of energy conversion

Bioenergy comes either directly from the land, such as from dedicated energy crops, or from residues generated in the processing of crops for food or other products (Perlack et al., 2015). Figure 2.29 shows the common overview of biomass resources in South Africa**.** Biomass energy is renewable and sustainable, yet shares many characteristics with fossil fuels. While biomass can be directly burned to obtain energy, it can also serve as a feedstock to be converted to various liquid or gas fuels (biofuels) (Perlack et al., 2015).

Biofuels can be transported and stored, and allow for heat and power generation on demand, which is essential in an energy mix with a high dependence on intermittent sources such as wind (Perlack et al., 2015). Figure 2.30 shows an overview of the use of biomass as well as different forms of energy conversion. These similarities account for the major role biomass is expected to play in future energy scenarios. Therefore a recent emerging strategy is to develop biorefinary and biotransformation technologies to covert biomass feedstock into clean biofuel (Ellaban et al., 2014). Biomass feed stock can be converted into bioenergy via thermo-chemical and bio-chemical conversion processes. These processes include combustion, pyrolysis, gasification, and anaerobic digestion as shown in Figure 2.30 (Perlack et al., 2015).

In contrast to the benefits, there are significant barriers to biomass-to-energy facilities. Biomass fuels have low energy densities, and collection and transportation can be cost prohibitive (Perlack et al., 2015).

2.5.7. Geothermal resources

Geothermal energy has been produced commercially since 1913 for electricity generation, and for four decades on the scale of hundreds of MW both for electricity generation and for direct use (Ellaban et al., 2014). The exploitation has increased rapidly during the last three decades. Geothermal energy is thermal energy generated and stored in the Earth, and originating from the original formation of the planet, from radioactive decay of minerals, from volcanic activity, and from solar energy absorbed at the surface (Ellaban et al., 2014).

The geothermal gradient is the difference in temperature between the core of the planet and its surface; this drives a continuous conduction of thermal energy in the form of heat from the core to the surface (Purschel et al., 2013). The main source of this energy is the constant flow of heat from the earth's interior to the surface. This heat creates the molten rock, or magma, beneath the surface crust (Karekezi, 1994; Karekezi & Ranja, 1997). Volcanoes, geysers and fumaroles are the visible evidence of the great reservoir of heat, which lies within and beneath the earth's crust. The magma heats the surrounding rock structures and when underground water comes into contact with this heat, geothermal fluid is formed (Mariita, 2002; Bronicki, 2001).

This energy can be extracted by drilling wells to tap concentrations of steam at high pressures and at depths shallow enough to be economically justifiable. The steam is then led by pipes to drive electricity-generating turbines (Mariita, 2002; Bronicki, 2001).

Figure 2.31 below illustrates one of the famous geothermal active sites in the Eastern DRC north of Ngoma.

Figure 2.31: Active volcano in DRC is famous for housing the biggest lava lake in the world
(Favalli et al., 2009)

Geothermal power exploitation has numerous advantages over other energy sources. Among the benefits of geothermal power are the near zero emissions (true for modern closed cycle systems that re-inject water back to the earth's crust), and the little space required for geothermal power development compared to other energy sources such as coal fired plants . Geothermal power is mostly concentrated in eastern Africa, but there are many patchy spots of high intensity geothermal potential spread across the continent.

There is enormous potential for geothermal energy in the East African Rift which is roughly 3,700 miles in length (Purschel et al., 2013).

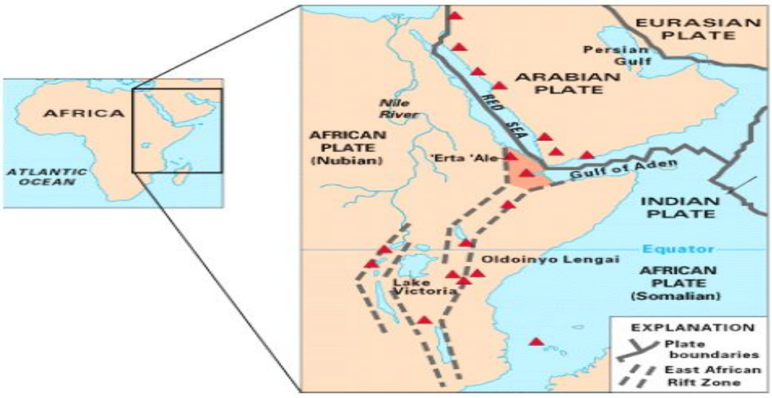


Figure 2.32: Location of geothermal in great East African rift valley system (Purschel et al., 2013)

Figure 2.32 shows East African countries that use and have carried out research on Geothermal Resources which include: Djibouti, Eritrea, Ethiopia, Kenya, Malawi, Tanzania, Uganda and Zambia. The potential to use geothermal energy for grid-connected electrification is imperative and all these countries have the potential to use geothermal energy for grid connected electrification (Purschel et al., 2013).

Geothermal energy is a powerful and efficient way to extract renewable energy from the earth by natural processes. This can be performed on a small scale to provide heat for a residential unit by using a geothermal heat pump, or on a large scale for energy production through a geothermal power plant. Geothermal power is considered a cost effective, reliable, and environmentally friendly energy source (Bertani, 2012).

However, geothermal potential of the country is still untapped for the above mentioned countries. For example, geothermal in potential in Ethiopia estimated at about 5000MW, and no new plant geothermal plant has been commissioned since 1999. According to research, the lack of additional geothermal prospects have been due to the lack of foreign investors, which is the most limiting factor for the future development of geothermal resources in countries (Bertani, 2012).

CHAPTER 3*:* INTEGRATION CHALLENGES OF RENEWABLE GENERATION DEVELOPMENT IN AFRICA AND SOUTH AFRICA

3.1. Chapter review

This chapter has highlighted regional bodies in Africa and their role in accelerating renewable development on the continent. The chapter also takes a comprehensive look on the economic and technical integration challenge associated with renewable generation technologies, including the opportunities to increase the development of renewable energy in South Africa and the continent.

3.2. Awareness of the regional bodies

The future of renewable generation in Africa and South Africa looks bright and this is increasingly powered by micro-grid renewable generation resources. Globally, much of this growth is due to energy security concerns urged by international energy bodies such as IRENA and IEA to look for sustainable sources of energy to replace the depleting fossil fuels of governments of the world. Global environmental and energy security concerns are currently driving penetration of renewable energy alternatives, as these can mitigate the vulnerability of developing economies in energy markets caused by increasing energy requirements and lack of capital.

The increased awareness about fossil-fuel deposits in decline and environmental hazards caused by the burning of fuels is also forcing governments towards exploiting renewable-energy resources as an alternative (Bollen & GU, 2006). This realization by the government has motivated an economic boost and rapid development of renewable technologies.

For example, following the awareness of opportunities and challenges of renewable development in Africa, regional bodies, such as the Economic Community of West African States (ECOWAS), have developed rural renewable energy development agendas (Schwerhoff & Sy, 2016). ECOWAS member countries have established the Center for Renewable Energy and Energy Efficiency (CREEE), forming strategic development deals with several international organizations that include the United Nations Food and Agricultural Organization (FAO) and the United Nations Industrial Development Organization (UNIDO)

(Schwerhoff & Sy, 2016). ECOWAS target is 20 percent for the renewable makeup of energy by 2030, which include off-grid electricity serving 25 percent of the rural population.

The Southern African Development Community (SADC) and the East African Community (EAC) in 2016 agreed to create similar regional renewable energy programs (Schwerhoff & Sy, 2016). In South Africa, the rise of Eskom from darkness in 2008-2010 was massively influenced by government intervention together with the Department of Energy (DoE) to form a consortium that governs renewable energy in South Africa, hence the birth of the Renewable Energy Independent Power Producer Procurement Programme (REIPPPP).

Research done by IEA, (2010a) shows that in terms of Sub-Saharan African countries, South Africa's REIPPPP has been successful. REIPPPP in South Africa together with other organizations like South African National Energy Development Institute (SANEDI) are accelerating the development of renewable generation in South Africa.

In 2012, SANEDI established the South African Smart Grid Initiative (SASGI) to facilitate amongst others the effective strategy of introducing renewable energy feed-in tariff (REFIT) (Fritz, 2012). The objective was to bring certainty and to encourage potential investors to accelerate the introduction of renewable energy generation mix into the grid (Fritz, 2012).

The introduction of private energy generation companies (REIPPPP) offered multiple benefits, such as diversification of supply, skill development, and heavy investments in the South African economy. Renewable energy has become a 'strategic commodity' and therefore any impediment about its development threatens the functioning of the economy, particularly in emerging economies (Kochtcheeva, 2016). Every society requires energy to meet the basic needs. A sustainable social economic development needs secure energy supplies at an affordable rate which have low environmental impacts and low greenhouse gas (GHG) emissions (Kochtcheeva, 2016). This chapter discusses more details on the economic challenges and the technical challenges facing the implantation of renewable generation in South Africa and Africa as a whole. It aims to answer questions such as, what is holding back renewable development technology in Africa and South Africa.

3.3. The challenges associated with renewable generation development

Despite the challenges associated with renewable generation development, renewable energy continues to plays an important role in providing sustainable and clean energy mitigating climate changes. With current technological advancements, the broadened understanding of renewable energy knowledge as well as positive support from governments with favorable promoting policies, renewable generation energy forms are slowly developing to meet energy demands in a cleaner way.

Monopoly utility companies like Eskom who supplies 95% of South Africa’s electricity and own the entire transmission infrastructure and the distribution network are hindering accelerated renewable development (Du Toit, 2014).

It has been argued that monopolistic energy providers in South Africa such as Eskom and Sasol use their influence to protect those of the energy market’s features suited to their core competencies (Bhattacharya et al., 2016). In fact, the structures of the energy sector and regulatory environment have not favored the entry for renewable energy which was acknowledged in the White Paper on the Renewable Energy Policy of the Republic of South Africa (REWP) (Mohammed et al., 2013).

One of the major global challenges is securing energy supply to meet the growing demand, providing everybody with access to energy services, and curbing the contribution to climate change (Bhattacharya et al., 2016). However, for developing countries in Africa, especially the poorest, energy is needed to stimulate production, income generation, social development, and to reduce serious health problems caused by using fuel wood, charcoal, dung and agricultural waste.

Unlike South Africa, most transmission and distribution infrastructure of African countries are virtually non-existent. Building new transmission lines can be difficult due to planning barriers, land use rights and costs. According to Eberhard et al., (2015), the aging utility infrastructure of some African countries presents another challenge that impedes accelerated renewable energy development to help address the urgent energy demand for the growing economy. The question to be answered in this chapter is: "what is delaying accelerated renewable development in Africa and South Africa?" Figure 3.1 shows the main challenges facing renewable development in Africa and Sub-Saharan Africa.

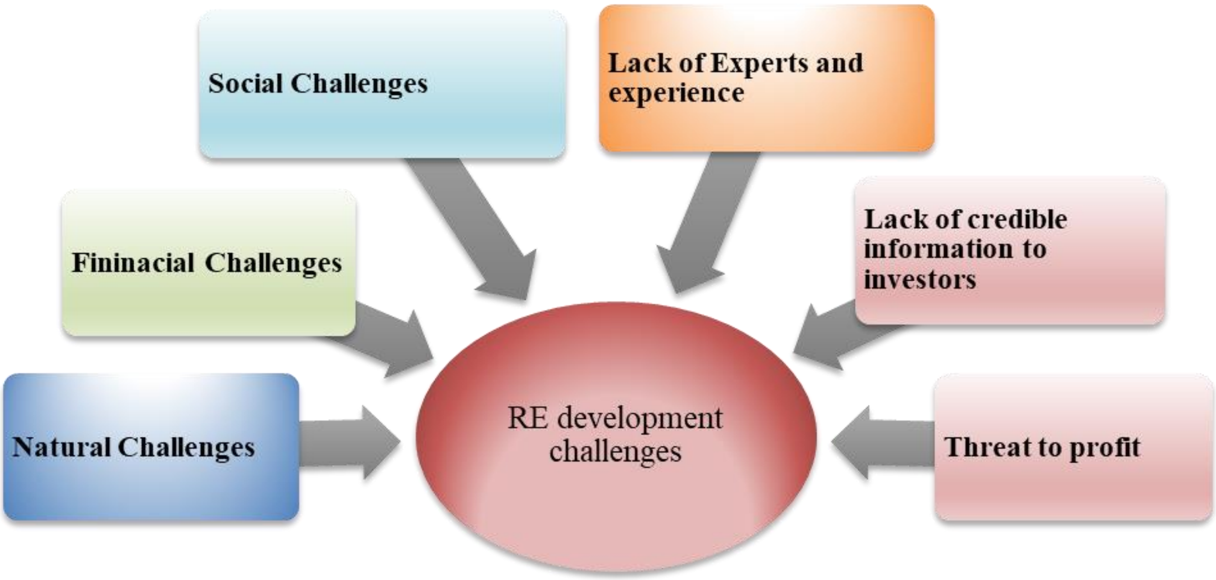


Figure 3.1: Challenges to the development of renewable development in Africa and Sub-Saharan Africa

3.3.1. Natural challenges

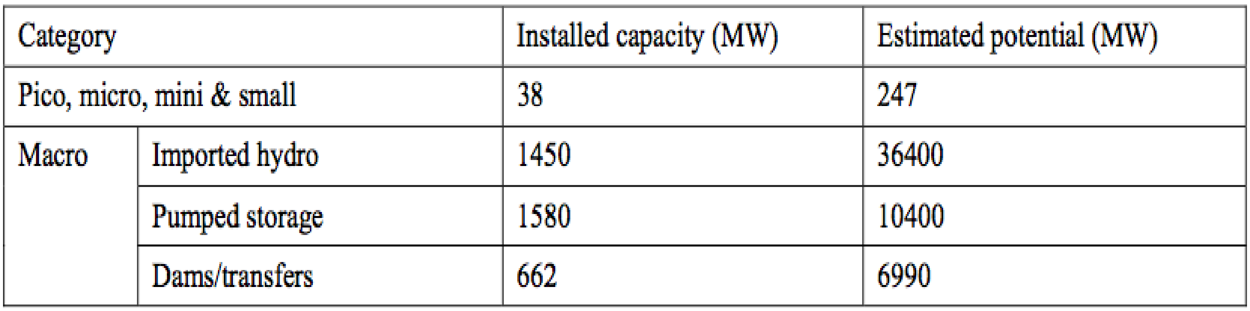
The natural challenges or barriers include the resource availability to develop renewable electricity generation technologies. For example, South Africa is water scarce and hence it has a limitation on the extent to which hydro power can be developed (Musango et al., 2011). The scarcity of water in South Africa and dependency on it for our food and energy industry supply does little to encourage foreign direct investment for potential financial return from small hydropower projects.

Small-hydro plants can be developed within South African borders, however, neighboring countries have significant hydro-electric potential that can be development to benefit the region (Pegels, 2010). According to Musango et al., (2011), the wind resource in South Africa is also mainly concentrated along the coastal areas and hence it cannot be developed in all the provinces of the country. Similarly, all the provinces of South Africa have a potential to develop solar power technologies.

The only solution to natural barrier is highlighted in Chapter 2 of this thesis, utilization of the region potential such as the great Inga in DRC, Zambia and Mozambique for cross border energy market. However, this requires governments to work together to integrate their regulatory frameworks regarding security of electricity supply, and the deeper integration of electricity markets (IEA, 2013).

South Africa hydropower import is shown in Table 3.1 below (Furi, 2009). In certain African countries, the barriers to renewable energy development for hydropower in particular, are the accessibility of sites and the lack of infrastructure availability.

Table 3.1: Hydropower potential in South Africa (Musango et al., 2011)



Category		Installed capacity (MW)	Estimated potential (MW)
Pico, micro, mini & small		38	247
Macro	Imported hydro	1450	36400
	Pumped storage	1580	10400
	Dams/transfers	662	6990

3.3.2. Financial Challenges

The financial challenges to renewable energy development in Sub-Saharan Africa include risk and cost of investment (Pegels, 2010). Currently in South Africa, the lack of financial support and violation of the IPP agreement by the state utility (Eskom) is a barrier to accelerated renewable project undertakings and also intensifies concerns for potential investors of medium to large-scale deployment of the renewable electricity generation. The solution for economic and financial challenges in South Africa was first published in 2009 as Renewable Energy Feed-in-tariff (REFIT), a scheme which was proposed to aid in establishing the RE market and levelling cleaner technology versus the continued financing of coal (Furi, 2009).

The uncertainty of the renewable energy capital return on investment often limits the financial support and mechanisms in the form of grants and loans for the renewable electricity technologies and this is because of an attractive investment particularly due to high interest rate (Musango et al., 2011).

One of the main economic and financial barriers associated with renewable generation development in Sub-Saharan Africa and Africa is the high initial capital of constructing new energy infrastructure; power plants and transmission lines. The increased capital due to lack of infrastructure and increased power reliability problems and power quality in most African countries contributes to the very slow development of renewable energy (Furi, 2009). This concern is complemented by the high cost of developing renewable electricity generation technologies, the use and high-maintenance cost compared to the conventional technologies such as coal or natural gas. In South Africa, the recommendation by Musango et al., (2011) on grid integration and infrastructure improvements need to include improved access to the grid by independent power producers. Energy evolution requires that RE is given priority access to the grid rather than forcing IPP to conform to a currently old and problematic grid.

3.3.3. Policy and regulation challenge

Renewable energy developers have highlighted the lack as well as slow policy regulation on mini-grids as one of the major challenges to successful development of renewable energy and private micro-grids (Schwerhoff & Sy., 2017). Many African countries do not have a renewable mini-grid policy, and, for those that do, the rules for their implementation are often unclear, incomplete, inaccessible, bureaucratic and liable to change (Schwerhoff & Sy., 2017). The main areas of concern are tariffs licensing, permitting requirements, and the expansion of the main grid (Calvin et al., 2016). The regulation of renewable energy mini-grid tariffs and connection fees usually depends on the size of the project. For example, in Tanzania and Cameroon, tariffs for mini-grids below 100kW are exempted from regulatory approval. In many other countries, tariffs for renewable energy development such as mini-grids are not regulated at all (Calvin et al., 2016).

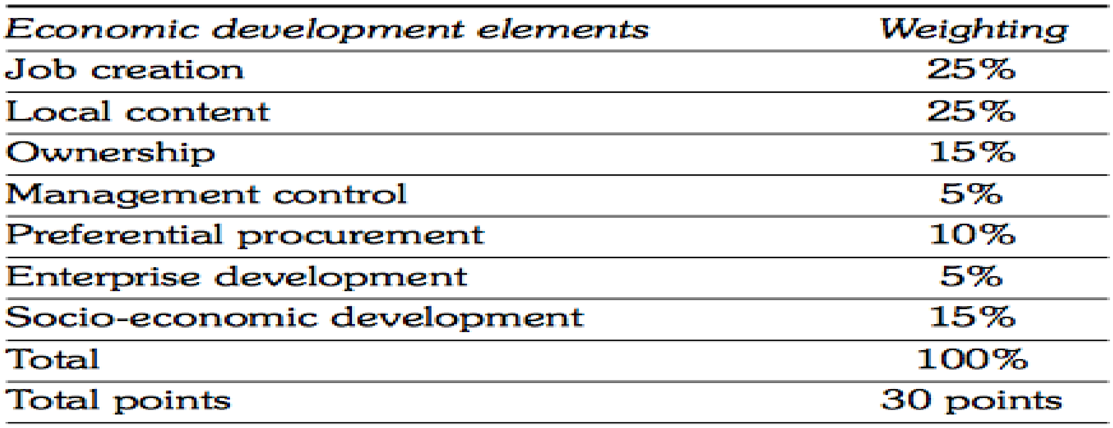
According to Welsch et al.,(2013), bureaucracy and lack of clarity around the licensing and permitting of renewable mini-grids is preventing the much-needed capacity. Depending on the type of project, licences may be required for the generation, distribution and sale of electricity. For larger projects, developers may also need to negotiate a concession contract or power purchase agreement (Welsch et al., 2013).

3.3.4. Social Challenges

According to Amigun et al.,(2011), one of the social barriers of renewable energy development include the possibility of rejection of such projects by the local authorities and communities. There is still an extensive gap of knowledge in potentiality of RE in many African countries. The gap according to Masebinu et al., (2016) is mainly attributed to the lack of information, education, and awareness. Lack of information increases the possibility of new technologies being rejected by the locals due to divergent views of renewable energy generation policies and path dependency problems (Masebinu et al., 2016).

Another social challenge is the land localities issue, such as, cases where the land is communally owned. There is a definite need to gain community acceptance (Masebinu et al., 2016). As observed by Mohammed et al., (2011), land is considered as an inheritance and the successful implementation of renewable energy projects requires the government and project developers to work closely with the communities in the location reserved for renewable energy developments. Therefore, to ensure successful implementation of renewable electricity generation, there is a great need for public awareness. According to Winkler et al., 2005), the department of energy states in the REIPPPP documentation that it recognizes the programme’s great potential to realize positive socio- economic outcomes. These outcomes give greater weighting to the criteria of job creation and local content, followed by local ownership and socio-economic development, management control, and enterprise development (Winkler et al., 2005). The table below presents these requirements

Table 3.2: Requirements for Social Economic development criteria of the RE IPPPP (Winkler et al., 2005)



Economic development elements	*Weighting*
Job creation	25%
Local content	25%
Ownership	15%
Management control	5%
Preferential procurement	10%
Enterprise development	5%
Socio-economic development	15%
Total	100%
Total points	30 points

Social Economic Development (SED) is a plan which was developed by the DoE for the IPP bidder. In the document, SED plans refer to “the plan to be submitted by the bidder on how social economic development will be implemented by the bidder, which will also detail how the targets of the department would be met (Winkler et al., 2005).

3.3.5. Lack of Experts and Experience

According to DuToit, (2014), amongst the major challenge facing accelerated renewable energy generation development in South Africa include: a lack of local experience: difficulties in securing a black economic empowerment [BEE] partner: excessive permitting requirements and sitting restrictions. Furthermore, the public is still not largely informed or aware of the benefits of renewable energy, too many agencies are involved in the approval process, and there is difficulty experienced by IPPs in gaining access to the grid and obtaining the requisite approvals and licenses.

The market for private investment in renewable energy is still relatively immature in Africa, and this is attributed to the lack of skills and experience of public institutions, developers, financial institutions, and local project staff (Welsch et al., 2013). Technical assistance and capacity building are therefore critical if renewable developments in Africa are to be scaled up.

3.3.6. Threat to Profit

The development of renewable energy in South Africa has been argued to have been slowed down by Eskom’s protection of profit interest. Increased renewable generation is reducing the output from sources like such as coal and gas, and causing these sources to export their power.

For example, with reference to Germany’s renewable development, when wind and solar reach very high levels of generation on peak days, this causes electricity market prices to decline such that they reach zero or negative (Foley & Olabi, 2017). Since 2011, South Africa has experienced a surge in renewable energy investment due to the success of its REIPPPP (Eberhard et al., 2014). In just three years, the scheme successfully channelled over 14 billion USD of private sector investment into grid-connected renewable energy technologies (Eberhard et al., 2014).

As this niche in the electricity sector has gathered momentum, it has already begun to disrupt some of the coal-dominated structures in its subsidy regime which has slowed down further accelerated renewable development (Eberhard et al., 2014). This setup of the REIPPPP has altered the prevailing market dynamics within the electricity sector. REIPPPP increased competition and diversity into the traditionally Eskom and coal-dominated electricity market. REIPPPP has undergone several changes during the policy design process, most notably transitioning from a feed-in tariff to a competitive bidding system (Schwerhoff & Sy, 2017). Under the FiT scheme, NERSA would have been responsible for setting tariffs for renewable energy projects (Schmidt et al., 2017). Instead, the competitive bidding process shifted price setting away from centralized control (Foley & Olabi, 2017). The decentralization of price setting, combined with a strategy of procuring renewable energy capacity in multiple bidding rounds, has enabled renewable energy tariffs to drop significantly with each bidding round (Schmidt et al., 2017).

3.4. Technical challenges associated with integration of renewable generation technologies

Previously, distribution networks were considered as passive networks, which have a unidirectional power flow from the source to loads (Revana & Kota., 2017). Introduction of renewable generation technologies such as wind, solar photovoltaic, biomass power plants, especially at high penetration levels, the passive network becomes an active one that has a bidirectional power flow, which happens between the load side and the substation (Huda & Zivanovic, 2017). Figure 3.2 below shows a typical example of the structures of passive and active systems. Previously, the customers such as houses, factories and commercial buildings consumed energy directly from the central power station. Generally, they imported the energy either from the central power station or from an island renewable generation plant such as wind and solar power plants, which are located close to loads (Hung et al., 2016). Today’s power grid is integrated the challenges associated with integration of renewable generation technologies is the high penetration levels together with their intermittency and unpredictability which create a variety of challenges to the distribution system (Hung et al., 2016; Huda & Zivanovic, 2017).

However, the associated benefits of renewable generation integration are that e.g., solar PV or wind units located close to distribution system loads can lead to reliable power flow and loss reductions, voltage profile and loadability enhancement, network upgrade deferral, etc. (Huda & Zivanovic, 2017). Therefore, Integration of renewable generation can become an increasingly viable option. However, this consideration requires mitigation for volatile technical challenges facing the integration on power system grid.

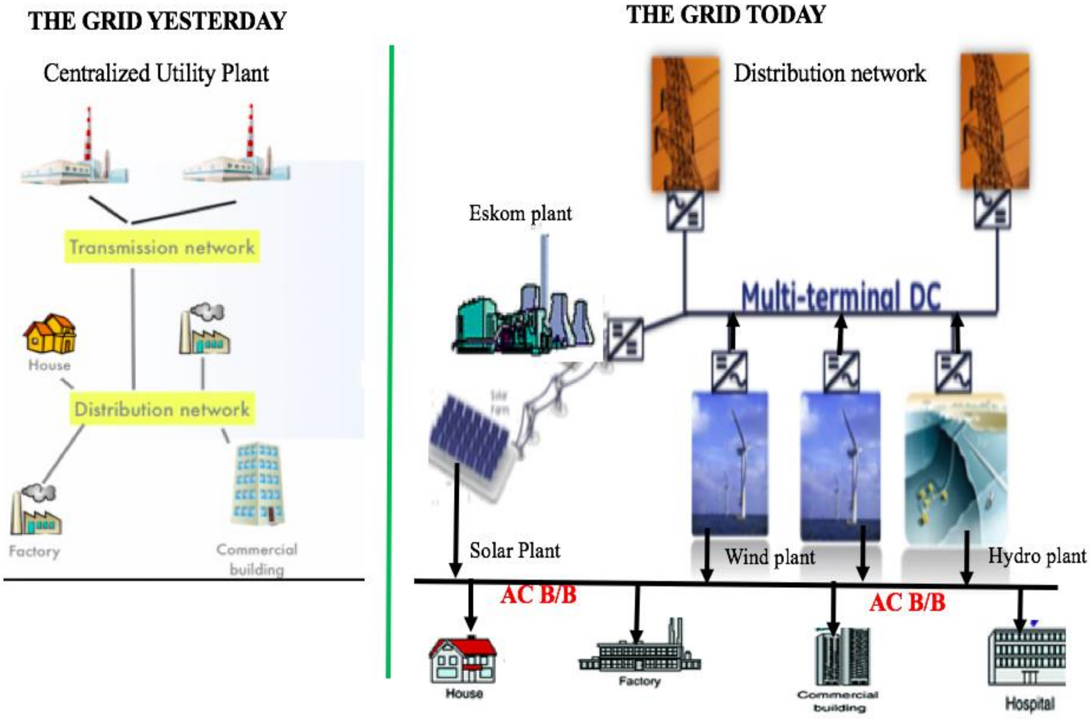


Figure 3.2: Passive power system (left) versus active power system (right) (Kwon et al., 2017)

3.4.1. Power Quality Concerns

Power quality issues, especially harmonic distortion in distribution networks, is major concern for power utilities. The PQ distortions introduced in the power system network by renewable generation technologies can cause major power quality anomalies. The intermittent nature of solar and wind renewable sources contribute heavily to power quality problems such as voltage dips, frequency variations, low power factor, and harmonics. These distortions may occur due to the use of HVDC to HVAC converters such as inverters, and HVAC to HVDC rectifiers (Farhoodnea et al., 2012).

The use of inverters to interface renewable generation technologies and the power grid can produce harmonic currents, thus increasing the total harmonic distortion in the form of voltages and currents at the point of common coupling (Kwon et al., 2017). The harmonic distortion can then result in parallel and series resonances, overheating in capacitor banks and power transformers, and mis-operation of protection devices (Farhoodnea et al., 2012). Voltage harmonics are generally within limits if the network is balanced enough with low equivalent series impedance, whereas current harmonics are produced by high pulse power switching electronic inverters and usually appears at high orders with small magnitudes (Ujile & Ding, 2016). However, variations in solar irradiation and wind variabilities can cause power fluctuations which contribute heavily to poor power quality (Kwon et al., 2017). Harmonics will be discussed in greater details in Chapter 5 of this thesis.

3.4.1.1. Phase Imbalance

Integrating renewable energy in three-phase distribution systems can also develop acute phase imbalance as most PV sources are connected in the form of single-phase units (Huda & Zivanovic, 2017). This phase imbalance could lead to unbalanced voltage profiles among phases and shift the neutral point voltage to an unacceptable and unsafe value (Hung et al., 2016). According to a study by Huda & Zivanovic, (2017), severe phase imbalance due to high renewable penetration integration, exceeding 6% was reported in Freiburg, Germany, while the utility standard is to keep the unbalanced condition within 2.5%. An unbalanced three-phase condition could also influence various instability problems including dynamic voltage instability which can lead to high network losses (Huda & Zivanovic, 2017). This loss, in general, is a concern in distribution systems with high penetration of renewable energy technologies even if the systems are operated in balanced conditions.

The increase in integration of renewable generation technologies will cause increases in reverse power flows from the load side to the substation thus resulting in a higher network energy loss. Such a loss may become very high when compared to those in distribution systems without any renewable energy generation (Hung et al., 2016). In addition, electromagnetic interference of high switching frequency converters such as the inverters is another concern to other circuit elements such as DC links, protection circuit, and capacitor banks which can lead to malfunctions of those devices (Sangwongwanich et al., 2017).

3.4.1.2. Power system grid stability

Power system stability can be generally defined as power system's its ability to remain in operation equilibrium under normal operating conditions and to regain an acceptable state of equilibrium after being subjected to a disturbance (Rahimi & Pamiani. 2009). Following a large disturbance, if the power system is stable, it will reach a new equilibrium state with practically the entire system intact; the actions of automatic controls and possibly human operators will eventually restore the system to normal state (Guerine et al., 2017). On the other hand, if the system is unstable, it will result in a run-away or run-down situation, or equivalently a progressive increase in angular separation of generator rotors, or a progressive decrease in bus voltages (Rahimi & Pamiani. 2009).

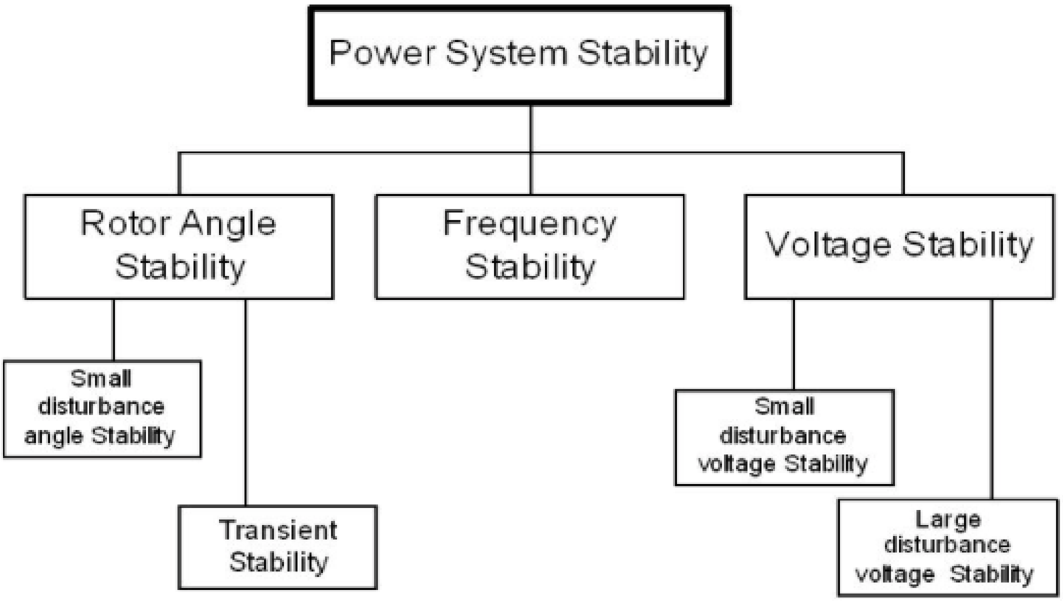


Figure 3.3: Classification of power system stability (Rahimi & Pamiani. 2009)

As indicated in Figure 3.3, the power system stability can be classified as:

Rotor angle stability

Frequency stability

Voltage stability

Small signal stability

Rotor angle stability is concerned with the system's ability to maintain the equilibrium between the electromagnetic torque and mechanical torque of each generator in the system.

Instability that may result occurs in the form of increasing angular swings of some generators, which lead to their loss of synchronism with other generators (Rahimi & Pamiani. 2009).

These different viewpoints are introduced concerning the power system stability issues raising different types of stability problems. With the integration of renewable energy, especially based on inverters and other small-scale generation with synchronous or asynchronous machines, distribution systems could possibly be considered as small power systems with rich dynamics and complexities (Shah et al., 2017; Kwon et al., 2017). The dynamics of the technologies combined with the intermittent nature of the output of generation could lead to several instability problems, including static and dynamic voltages as well as modal interactions that may lead to resonances (Shah et al., 2017). The primary reason for voltage instability in distribution systems is normally considered due to the lack of reactive power support (Huda & Zivanovic, 2017). In a distribution system, voltage instability could possibly be affected by both real and reactive power imbalance, as it’s resistance to the reactance ratio is quite high.

A study (Shah et al., 2017) has reported that static voltage stability in a distribution system, which is typically evaluated by loadability, can improve because of the rooftop PV integration in the system. However, with renewable generation technologies that are unevenly distributed among phases, a more unbalanced three-phase condition in a distribution system may occur (Shah et al., 2017). This could lead to poor loadability and less static voltage stability margins. Dynamic voltage stability is defined as the system’s ability to maintain acceptable voltages following an event or a change in system conditions such as faults. It be could be severely affected by small scale embedded generation technologies such as rooftop PV units (Yaghoobi et al., 2015). Due to passing clouds, no wind, faults in the system, and the consequent tripping of PV units, voltages can drop below a given limit in a PV integrated distribution system (Hung et al., 2016).

Another stability issue that has attracted great attention in terms of distribution systems is called small signal stability (Hung et al., 2016).

Small signal stability is the ability of the power system to restore its equilibrium state under small disturbances. Such small disturbances occur continually due to loading or generation which are small variations. It is worthy to note that, the classification of power system stability has been based on several considerations to make it convenient for identification of the causes of instability, the application of suitable analysis tools, and the development of corrective measures appropriate for a specific stability problem (Rahimi & Pamiani. 2009).

When a distribution system is purely a passive system, the issue of small signal stability may not be a concern (Revana & Kota.2017). However, with the integration of renewable generation through power electronic interfaces and their associated controllers, the stability of the system operating point when subjected to small disturbances became a major concern (Sangwongwanich et al., 2017).

3.4.1.3. Voltage stability

Voltage stability is concerned with the ability of a power system to maintain a steady voltage at all buses in the system under normal operating conditions, as well as after being subjected to a disturbance. Instability that may result occurs in the form of a progressive fall or rise of voltage of some buses. Research suggests that due to the distinct characteristics of renewable generation technologies or small scale embedded generation controllers involved in the voltage stability of the system can be significantly affected by the system penetration integration (Hung et al., 2016). The effect of high penetration on the voltage magnitude and stability of the distribution and transmission systems has been studied in the literature by using both deterministic and time series analyses (Shah et al., 2012; Vittal et al., 2010). The impact of renewable generation technologies on the voltage stability of real power systems, such as in Germany’s system, has been analysed using real wind data to find out the possible adverse effect and the solution of the voltage instability problem that may be incurred (Hung et al. 2016).

3.4.1.4. Frequency stability

Frequency stability refers to the ability power system has to maintain steady frequency within a nominal range following a severe system upset, which results in a significant imbalance between generation and load. This depends on the ability to restore balance between the system generation and load, with minimum loss of load. It is of importance to note that, severe system upsets generally result in large excursions of frequency, power flows, voltage, and other system variables. In practice, there always exists a mismatch between generation and load in the power system. This mismatch results in frequency variation or frequency instability. System operators are always aim to match the generation to the load so that the frequency can be as close as possible to 50Hz. The system operators are to balance the generation and load by varying the output of proper generating units based on the system frequency (Jenkins & Ekanayake, 2017). Variation of frequency is further increase by the addition of renewable generation, such as solar and wind. Figure 3.4 below is an example of the rule for frequency control with an example of actual variation (Pimentel et al., 2002).

According to Revana & Kota.,(2017), with high penetration of renewable generation technologies, a significant number of synchronous generators in the system would be replaced by renewable generation technologies, thereby resulting in the reduction system inertia (Jenkins & Ekanayake. 2017).

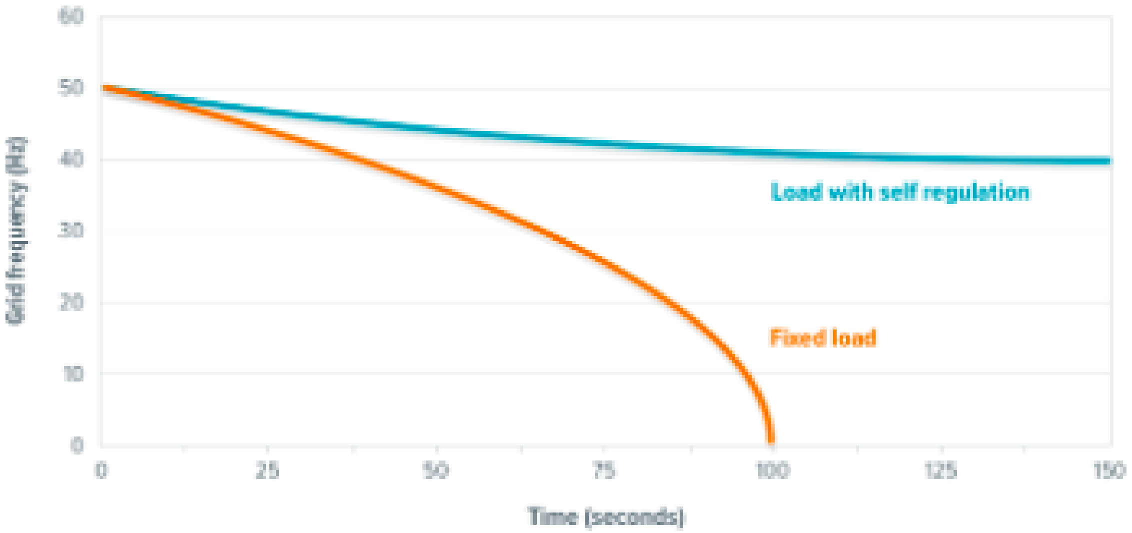


Figure 3.4: Mitigation of the decrease in frequency due to self-regulation of grid load in the case of a 50 MW initial unbalance between generator output and load (Pimentel et al., 2002)

Any power system is required to maintain the frequency within the desired limits. Any large variation from 60Hz will cause unwanted system instability and can bring the entire system down (Jenkins & Ekanayake. 2017). Due to high penetration of zero inertia generators such as PV and full converter wind turbines, the conventional generators that are co-existing with these generators will be forced to provide torque and inertia to mitigate any instability events, which could lead to the frequency instability problem (Revana & Kota. 2017). It is believed that high penetration of zero inertia generators such as a PV unit with a higher ramp rate could adversely affect the frequency stability of the system according to Yan et al., (2015). Similar findings have been found that display the impact of high penetration of solar and wind on the frequency stability of the South Australian power system (Yan et al., 2015).

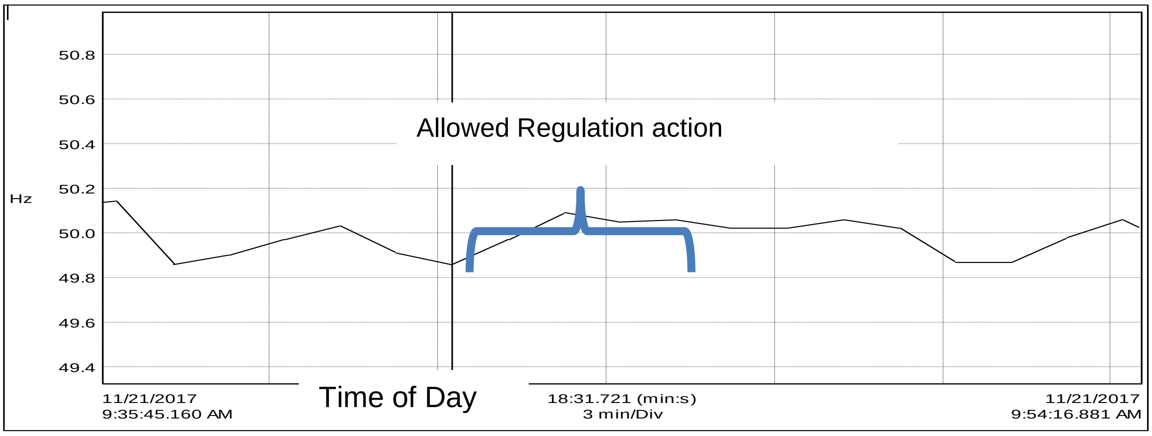


Figure 3.5: Example of the rules for frequency control, with an example of actual frequency variations frequency data source

When renewable generation is in operation, the mismatches between the generator and load are also caused by the variability of the generation. Figure 3.6 below shows the variation of the power out of 50MW load with 1.5MW solar PV rooftop plant over four days in November 2017 for rooftop solar PV system at Langerberg mall in mosselbay. The variation can be seen widely experienced over the whole course of the day.

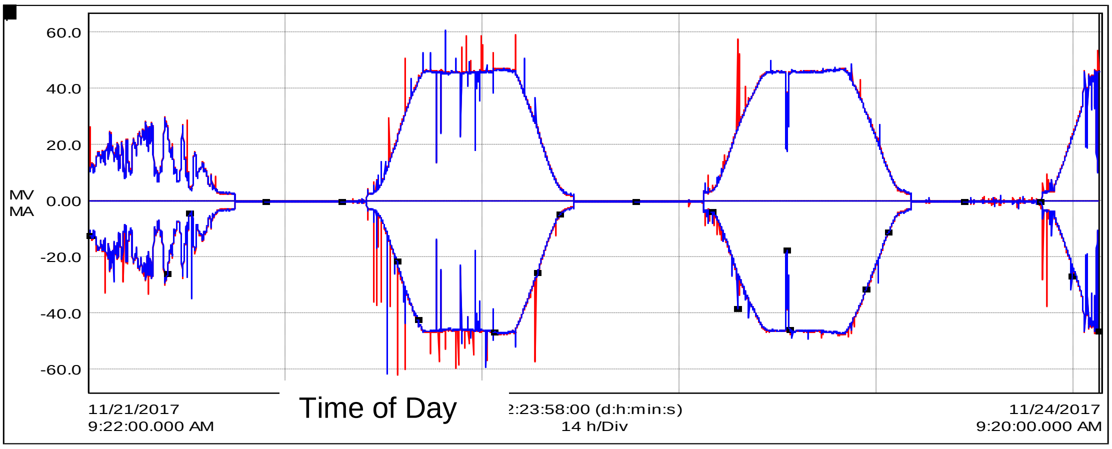


Figure 3.6: Output variation of 50 MW load with 1.5MW Solar PV plant in Mosselbay

3.4.2. Intermittency of generation

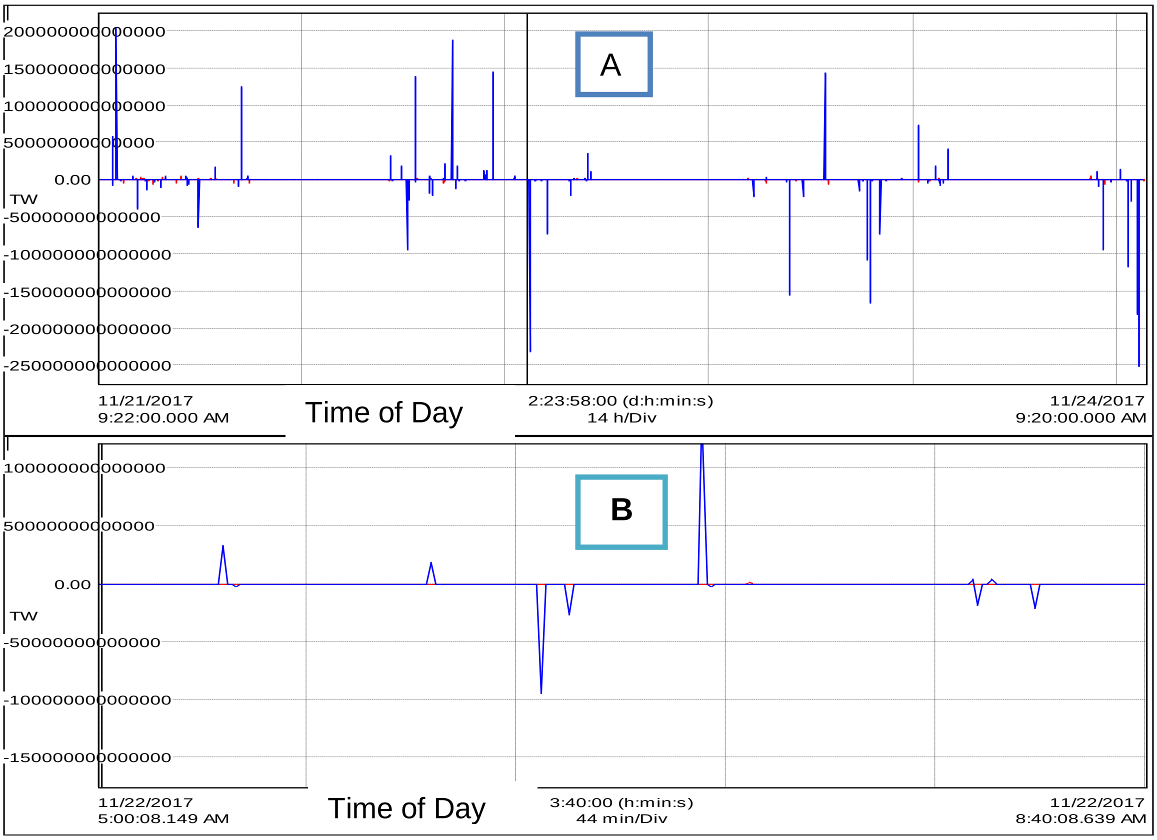


Figure 3.7: 3.7 (a) and 3.7(b) presents typical Intermittent of instantaneous output power of solar PV of Langerberg mall grid-tied system in Mosselbay

Although solar energy is abundant and inexhaustible, it is weather-dependent, intermittent and unavailable during the night. Figure 3.7a and 3.7b is an example of solar PV showing the instantaneous power output. As shown in the figures, the intermittency of PV generation due to moving clouds frequently experienced, even within an extremely short time period during the day. For a grid integrated solar PV system this could be severe for voltage control, grid stability and poor power quality. Such fluctuations might result in low system stability and poor power quality. Although used as a viable solution to eliminate PV intermittency, battery energy storage is limited in terms of high investment costs (Yan et al., 2015).

3.4.3. Change in standard load patterns

High penetration of domestic rooftop solar PV systems in recent years has changed the standard load curves of a characteristic distribution system (Revana & Kota, 2017). This change is most apparent during the middle of the day when the sun’s radiance is at its highest and causes a significant load reduction. For instance, Figure 3.8 shows the impact of PV on practical feeder load profiles where the drop-in demand during the middle of the day has risen from an increasing PV capacity on the feeder. The day load has dropped below the night-time trough; however, the night peak load requirement remains unchanged.

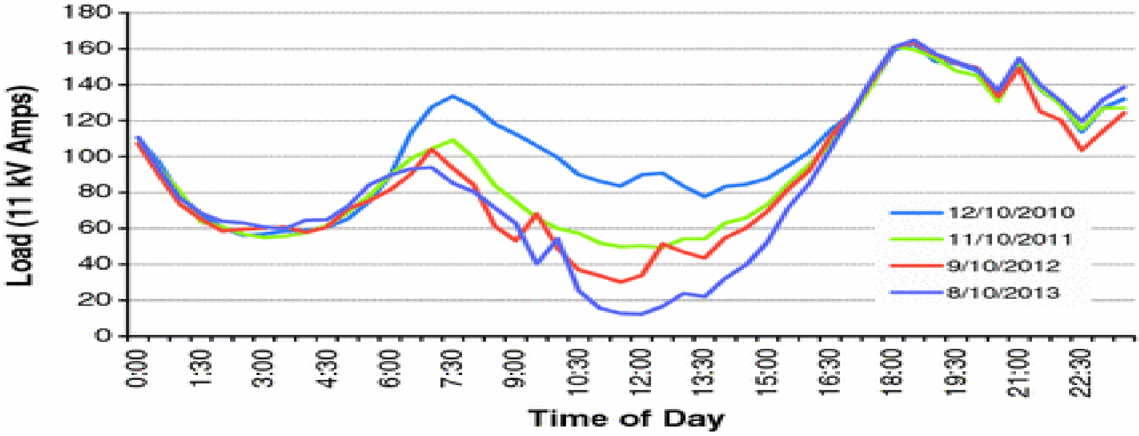


Figure 3.8: Practical PV impacts on Currimundi feeder network on the load profiles (Jackson et al., 2014)

3.4.4. Reverse Power Flow and Voltage Rise

Previously power flow in the distribution system is traditionally unidirectional from the medium voltage (MV) to low voltage (LV) networks. See Figure 3.8. However, when the total amount of PV generation is larger than that of load demand, reverse power flows occur on the feeders, flowing from the LV to MV sides (Yeh et al., 2012). The reverse power flows may lead to complexity in operations of voltage control devices such as switched capacitors; automatic voltage regulators and on-load tap changers (Huda & Zivanovic. 2017). The increasing shift from minimum to peak load as well as the inherently intermittent power supply of solar PV panels can cause unexpected issues associated with voltage regulation on power distribution feeders with high solar PV penetration (Katiraei & Aguero, 2011).

However, the high penetration of intermittent renewable generation sources at the distribution system level has adverse impacts on power quality, especially the voltage rise which normally occurs due to reverse power flow when the generation of PV exceeds the local demand (Katiraei & Aguero 2011). Depending on the capacity, the generation of PV can reduce the stress on the distribution system and enhance its performances, for instance in the case of power losses and voltage profiles (Yeh et al., 2012; Hung et al., 2014).

3.4.5. Security and Risk

Grid integration with renewable resources can significantly improve the energy security of power systems as primary sources are diversified and renewable energy resources are available locally. However, a very high penetration level of renewable energy in power grids can bring operational security concerns and risks (Jenkins & Ekanayake, 2017). Moreover, a very high penetration level is only possible for large-scale plants such as wind and solar farms in the range of hundreds of megawatts, located far away from potential load centers. The challenges can lead to a variety of instability and operational security problems, covering voltages, angles and frequency issues, due to lack of reactive and real power (inertia) support (Jenkins & Ekanayake, 2017).

The risk related to system security with wind and PV technologies has been assessed in several studies (Preece & Milanovic, 2015; Katiraei & Aguero, 2011). To prepare for the high penetration of RPPs in both transmission and distribution systems, power system operators should thoroughly explore the subsequent risks associated with the power systems static and dynamic operations. Power system operators should regularly perform security analyses to ensure that the network does not operate beyond the acceptable limits of operation (Katiraei & Aguero, 2011).

3.5. Opportunities for increased integration of renewable generation

To support the development of active distribution networks and extract corresponding benefits associated with an increased amount of renewable generation, new commercial arrangements need to be developed. Although the cost associated with the operation of active distribution networks is still a concern, Pinto et al., (2016), suggests that the integration benefits are likely to outweigh the cost of its implementation considerably. Case studies have indicated that the active management of distribution networks can enable significant increases in the amount of renewable development that can be connected to the existing networks (Baker & Sovacool, 2017). Experience in the last decade has shown that to accelerate the connection rate of renewable generation, it is necessary to either provide incentives to renewable DG developers and network operators or alternatively to mandate the connection of renewable generation technologies under a regime of preferential feed in tariffs like the case of Germany (Baker & Sovacool, 2017).

- For various legitimate reasons renewable generation technologies are still relatively

> expensive sources of energy and moreover tend to disrupt the normal way that power systems are used to operating. And yet, they are desirable technologies that must be supported because they are good for the environment and contribute to sustainability and energy security objectives (Baker & Sovacool, 2017).

In the long-term, there is no doubt that these technologies will become competitive as the price of fossil fuels rise due to ever-growing demand worldwide especially in the growing Asian economies such as China and India (Peskett, 2011).

In South Africa, for example, the entry of independent power producers broke Eskom's market power and provided rapid roll out and legal connection of privately owned generating capacity opportunities due to the large power projects owned by Eskom taking years before commissioning (Eberhard et al., 2014). These developments have undermined the political and bargaining power that Eskom has previously enjoyed, as it can no longer claim to be the most competent power provider of low-cost electricity for the population.

According to Aliyu et al., (2017), Africa has enormous potential for cleaner energy in the form of natural gas, hydro, solar, wind, and geothermal power, and therefore, we should seek ways to move past the barriers facing the accelerated development of these technologies.

Although some countries have responded positively to the development of these technologies the trajectory of its development is still slow on the continent (Aliyu et al., 2017). Kenya for example is now the world's ninth largest producer of geothermal energy. According to reports (Tech Central, 2015), Kenya is expected to have doubled this capacity by the end of 2016 by expanding the Olkaria plant. Ethiopia is praised to have tackled the impact of falling water levels in the dry season by moving into wind power. It now boasts one of Africa's largest wind farms, the 120MW, 84-turbine farm plant (Tech Central, 2015). Furthermore, Ignite Power is the first part of an ambitious plan aimed at achieving universal access to clean energy coverage in Rwanda. It brings together local and international organizations and has developed a template for connecting all households and beyond the grid (Tech Central., 2015). These initiatives and many more in Africa need to be supported and funded by the governments to provide the needed energy capacity on the continent through the sensitizing of renewable development.

Lastly, the opportunities for increased renewable generation technologies may be realized directly, for example, through the imposition of carbon taxes on fossil energy sources in countries considering fossil as the cheapest and sustainable energy means on the African continent. Additionally, the implantation of regime policies such as tax incentives, government renewable incentives, market design, demystifying the base load challenge and sizing policy that will contribute to accelerated development of RGT on the African continent (Jackson et al., 2014). For developed countries this is realized directly, for example, through the imposition of carbon taxes on fossil energy sources or indirectly, through payments for "offset" emissions due to the substitution of renewable energy for fossil fuels as implemented in the Clean Development Mechanism (CDM) within the UN's Kyoto Protocol for GHG control (Gabriel, 2016).

3.5.1. Tax incentive

Renewable energies are seen as the long-term future to the planet's energy demands because of the increasing effects of climate change due to the long-term use of fossil fuels (Welsh et al., 2013). However, renewable energy projects and initial set-up costs are very expensive (Aliyu et al., 2017). As a result, the government has introduced many tax incentives in the renewable energy sector (Cuamba et al., 2013). According to Cuamba et al., (2013), some of the incentives or mechanisms which have been introduced are focused on reducing carbon emissions, however, carbon tax still has to be introduced in South Africa. The 2016 Draft Taxation Laws Amendment Bill, (Draft TLAB 2016) intends to introduce the latest renewable energy incentives (Gabriel, 2016).

The Explanatory Memorandum to the Draft TLAB 2016 states that large-scale renewable energy projects are currently not sufficiently catered for due to the capital-intensive nature of the supporting infrastructure whose tax treatment would need to be specifically targeted (Gabriel, 2016). Although the increase of renewable energy tax incentives is most certainly welcome, it remains to be seen whether the recent round of proposed amendments will have a positive effect on the uptake of large renewable energy projects. Nevertheless, such an amendment may have a much larger impact on the feasibility of sorely needed large-scale renewable energy projects (Musango et al., 2011). The tax incentive and carbon taxation aim is to internalize the negative impacts arising from climate change by putting a price on carbon while also leveraging the price for renewable technologies.

3.5.2. Government renewables incentives

A paper by Lopes et el., (2007), validates that some form of renewable incentive schemes are in existence in countries like the UK, Spain, Germany, Sweden, Netherlands, Norway, and many other EU countries. Most of the incentives benefit distributed renewable generation (Lopes et el., 2007). To this end the South African government is offering an energy efficiency incentive for every kWh saved. The energy efficiency incentives are well promoted in the demand side management (DSM) report on energy efficiency pragmmes as a means to safeguard the security of supply. The renewable energy mix in South Africa is seen as a part of the DSM solution to increase the peak demand and unless this project is seen as a separate power generator which can increases the supply, the issue of power monopoly played by Eskom and its politics will continue to challenge the integration of energy in South Africa. The government of South Africa, together with Eskom, must develop renewable incentive schemes to allow for the competitive integration of energy, and this goes for all African countries that have not adopted this widely-used model in Europe. In Spain, for example, income from environmental incentives comes from a combination of renewable energy premium, subsidies and tax concessions (Lopes et el., 2007).

3.5.3. Sensitizing Policy Makers in Africa

According to the IEA, (2015) report on Africa’s energy outlook on the issues facing the financing of accelerated renewable development in Africa, senior executive in financial institutions positions have limited knowledge and awareness about the impact and the opportunities of financing renewable generation technologies. In another the report by IEA, (2015), most decision-making staff of financial institutions in Africa have very limited or no knowledge about the technology, impact and opportunities available in financing renewable generation technologies and projects. Gabriel. (2016), adds that the non-traditional financing sector should also be encouraged to develop schemes to support the renewable generation industry.

Moreover, funding should be channelled into improving the research and development into production techniques on the continent and governments should support investors in these areas with attractive tax packages. Gabriel. (2016) proposes that production of solar technology, for example, must be localized, and the desired market created for solar energy systems. He also indicates that policy makers are hesitant about renewable energy because they have not been well exposed and sensitized on the impacts that renewable energy has made in other countries. Thurs policy makers should be exposed to the impacts of renewable energy in other countries through study tours documentaries and workshops.

3.5.4. Baseload myth

Renewable energy projects continue to face significant challenges such as integration into an undercapitalized and Eskom-controlled grid, a perception that it is inadequate to provide baseload power, a lack of clarity in the local content requirements and difficulties building the technological capabilities needed for localizing low-carbon industries (Baker & Sovacool, 2017).

Renewable energy deployment in SA has set in motion dynamics that can potentially break the lock-in of directly and indirectly subsidized coal-powered generation; undermining the economic rationale for centralized coal-fired power, which erodes the market power of Eskom and other energy-intensive local industries, and building political support for a greener growth trajectory (Baker and Sovacool, 2017).

3.5.5. Amendment of policy and energy regulation

Countries such as Zambia, Kenya, Rwanda, and Tanzania, have reduce the complexity of procedures, rules and regulations usually associated with obtaining the required approvals, as well as permits and licences for investors in the electricity sector. Its mandate includes solicitation and evaluation of proposals, negotiation and awarding of contracts, and finalization of the implementation agreement, as well as representing the interests of government and co-ordination with other government agencies. In order, to accelerate renewable energy development in Africa energy policy and regulations must favour the objective to increase electricity access, increase the efficiency of the electricity sector and to promote private-sector involvement in the development of renewable generation schemes.

3.5.6. Market Design

The last opportunity discusses market issues and the question asked are: who should bear the cost and responsibility of sustainability and the grid integration costs on the Africa continent for countries that cannot afford connectivity? This is the major concern for both investors and developers on the continent. How are the markets defined and how largely are they influencing the development and the sustainability of renewable generation technologies? How does the resource regulator design a regulatory regime to promote renewable resource development? These questions were not discussed but are raised in thesis as an indicator of the imminent challenge for the development of renewable energy sources on the continent.

According to Romero-Cadaval et al., (2015), the potential for renewable energy can be realized at a reasonable cost. Market research shows that many customers will purchase renewable power even if its cost is more than conventional power. In South Africa, customers in the past had no choices about the sources of their electricity. However, electricity deregulation has opened the market so that customers now have a variety of choices (Aliyu et al., 2017). Start-up companies must communicate the benefits of renewables to customers to persuade them to switch from traditional sources. Public education will be a critical part of a fully functioning market if renewables are to succeed the traditional energy sources (Aliyu et al., 2017).

Economies of the larger market are likely to lead to cost reduction for wind, solar and biomass technologies. Unfortunately, if the markets remain small, few units are produced and prices will remain high. This leads to low demand and therefore low production volumes (Spiess & Sousa, 2016).

Market design must create skills development to allow for competitive installations as well as the operation and maintenance of new technologies on the African continent. Renewable technologies need operating experts such as trained installers to operate and maintain the plants.

South Africa is an example of a volatile market, with a high number of company start-ups and technology development (Spiess & Sousa, 2016). However, beyond government programmes, private sales have been slow due to affordability constraints, a hugely successful grid extension programme, and consumer expectations of universal grid access (Aliyu et al., 2017).

Lastly, for the African continent to reach its electricity target and maintain prevailing markets for investors there should be frameworks of dedicated markets and favourable policy reform which results in continuously lowered technology costs as calculated on a complete life cycle of generation systems (Kouro et al., 2015).

CHAPTER 4: EFFECT OF RENEWABLE GENERATION TECHNOLOGIES ON POWER QUALITY OF THE GRID

4.1. Chapter Review

Chapter four briefly introduces renewable energy sources and an understanding of what renewable generation is before discussing their effect on the power quality of the grid. The chapter also thoroughly discusses the power system to understand how the addition of renewable generation influences the power quality of the grid. Power quality and all its effect have been discussed in this chapter.

4.2. Introduction

The mixture and transition of the energy system that is largely based on renewable energy sources (RES) are one of the greatest challenges of our time. Integration of large amounts of intermittent renewable energy poses fundamental challenges to the operation and reliability of the power system grid. The main RES integration challenges relate to the fundamental characteristics that the most widespread RES technologies, such as wind and solar possess namely; variability and uncertainty. These RES characteristics are often summarized in the notion that of intermittency causes power quality issues which influence technical and financial operation when integrating them into the energy system.

The increasing reliance on renewable generation energy sources for large fractions of the electricity production in power systems introduces new challenges such as controllability and flexibility as well as power quality problems in terms of power system planning and operation (Gautan et al., 2009). PQ used to be the ability of the electric utilities to provide electric power without interruption.

Therefore, PQ problems as a result of the introduction of intermittent RES cannot be ignored, considering the high penetration levels of RES into today's electric grids. Many international scientific works have explored the possibility of achieving high levels of renewable electricity penetration (Hand et al., 2012; Mai et al., 2014) and a survey of several successful cases of countries with a high level of variable renewable energy in their grids is presented in (Cochran et al., 2012).

4.3. Brief review of the impact of renewable generation technologies

According to research, there is clear theoretical power utility operator evidence that PQ problems increase with the increase of RG technologies integration across the network which increases PQ problem and this causes uncertainties in the feeder as well as in the DN and LV network (Braun & Strauss, 2008). This study also investigates possible mitigation measures to effectively optimize and reduce the adverse impacts of integrating large-scale RG technologies into the electric grid network.

Today, power quality encompasses any deviation from a perfect sinusoidal waveform. This includes electromagnetic interference (EMI) and radio frequency interference (RFI) noise, transients, surges, sags, black outs, RG technologies, and any other distortions to the sinusoidal waveform (Jackson et al., 2014). One distortion to the sinusoidal waveform which has dangerous consequences is harmonics. The integration of large-scale renewable energy sources such as wind and solar energy into the grid introduces current and voltage harmonics due to the power electronics devices as well as the inverter connected for energy conversation (Ackermann & Knyazkin, 2002).

The effect of harmonics and its mitigation will be discussed in greater detail in Chapter 5. The focus of this chapter to investigates the general potential impacts to power system grid as a result of the high penetration of renewable generation technologies.

4.4. Brief review and definition of renewable generation

Renewable generation which was discussed in Chapter 2 of this thesis refers to an approach that employs small scale technologies to produce electricity for distribution and close to end users of the power. The technologies often consist of renewable energy sources or generators sources. Renewable generation refers to renewable technologies such as solar panel and wind turbines while distributed generation refers to combined heat and power and emergency generators (Gautan et al., 2009).

Renewable generation or distributed generation can serve a single structure, such as a home or business, or it may be part of a micro-grid (a smaller grid that is also tied to the larger electricity delivery system), such as at a major industrial facility, hospital facilities, or large government and university facilities.

The definition that was suggested in Chapter 2 looks at an approach towards a general definition of distributed generation or renewable generation. The general definitions for distributed generation suggested here are: *Distributed generation is an electric power source connected directly to the distribution network or on the customer site of the meter. Another proposed definition of DG can be defined as, electric power generation within distribution networks or on the customer side of the network* (Braun & Strauss, 2008). The International Conference on Large High Voltage Electric Systems (CIGRE´) defines DG as smaller than 50MW, and because of different government regulations, the definition of the rating of each distributed power station also varies between countries.

In the residential generator, common renewable generation or distributed generation systems include the following (Braun & Strauss, 2008):

- Solar photovoltaic panels
- Small wind turbines
- Natural-gas-fired fuel cells
- Emergency backup generators, usually fueled by gasoline or diesel fuel

In the commercial and industrial generators, renewable generation or distributed generation can include resources such as (Braun & Strauss, 2008):

- Combined heat and power systems
- Solar photovoltaic panels
- Wind plant
- Hydropower plant
- Biomass combustion
- Geothermal plant
- Fuel cells fired by natural gas or biomass

- Hybrid system or island grid (Solar photovoltaic and wind plant, Reciprocating combustion engines, including backup generators, which may be fueled by oil).

4.5. Overview of Power System grid

The electrical power grid is an interconnected network that delivers the generated power to the consumers. The power grid consists of generating stations that produce electrical power, high voltage transmission-lines that carry power from distant sources to distribution centers, and distribution lines that connect individual customers to the grid. The general structure of the electric power system as treated in previous research on power systems is as shown in Figure 4.1. The electric power is generated in large power stations at relatively small different locations. This power is then transmitted and distributed to the end-users, typically simply referred to as load/consumers (Bollen & Gu, 2006).

In South Africa, the power grid consists of the generating station (generation plant), transmission system, distribution system, and reticulation network. Power generating stations are situated at a feasible location closer to the availability of the source. In all industrialized countries, this remains the structure of the power system (Bollen & Gu, 2006). Hence, the generation plant is often located relatively away from populated areas. This is practical because the transmission of electrical power over longer distances is considered more economical (Bollen & Gu, 2006).

The electrical source includes a hydroelectric power plant, off-shore wind farm, and more centralized generation such as coal and nuclear plants. At transmission system is therefore used to transmit generated electrical power over long distance to populated cities. A world-wide transmission system connects the large generator stations. The transmission system allows the sharing of the resources from the various generator stations over large areas.

Distribution system and reticulation are used to distribute the power to consumers at appropriate voltages. Similarly, distribution networks transport the electrical energy from the transmission sub-stations to the various loads. There is no complete criteria to distinguish between distribution and transmission networks. Some countries use the term sub-transmission networks or an equivalent term to refer to the networks around big cities that have a distribution system structures (Bollen & Gu, 2006).

Figure 4.1: Traditional power grid, characterized by generation, transmission, distribution and reticulation of electricity to end-use consumers. Image Source (EPRI, 2014)

Due to several developments during the last decade, the model in Figure 4.1 no longer fully holds. In most countries, generation is completely integrated and deregulate as in the case of USA and Europe. This is, intended for effective management of the energy economy. Transmission and distribution are often split into separate companies. Each company is economically independent, even where it is electrically an integral part of a much larger system.

The need for environmentally friendly energy has led to the introduction of smaller generator units. Clean renewable generation technologies or embedded generation or distributed generations are often no longer connected to the transmission system but to the distribution system. A more modern way of looking at the power system resulting from these developments is shown in Figure 4.2 below. The electric power network no longer only transports energy from generators to end-users but instead enables the exchange of energy between Independent Power Producer (IPP) and the national electrical grid.

The downstream of network in Figure 4.2 could be a transmission network or a distribution network or an industrial network or any other network owned by a single company. In South Africa, IPP’s are currently part of the distribution system generating electricity for distribution at different generation sites and are integrated to the electrical grid to increase generation capacity. However, in countries like Rwanda and other African countries, IPP's are generating electricity for transmission and distribution to meet the national energy capacity demand programs. This disparity in T&D exhibits the clear needs for robust and efficient networks.

The aim of the T&D network is to only transport the electrical energy, or in economic terms, to enable transactions between generators and consumers. The diverse role of renewable generation integration plays a major role in T&D systems of the electricity energy market economy. However, the major concern which places enormous constraints on the development of REG in Africa is the limited ability of the network to transport electricity. According to Eberhard, (2015), the lack of generation capacity is due to aging networks and virtually none existent networks in many African countries and is a relating deficiency to Africa's energy market economy.

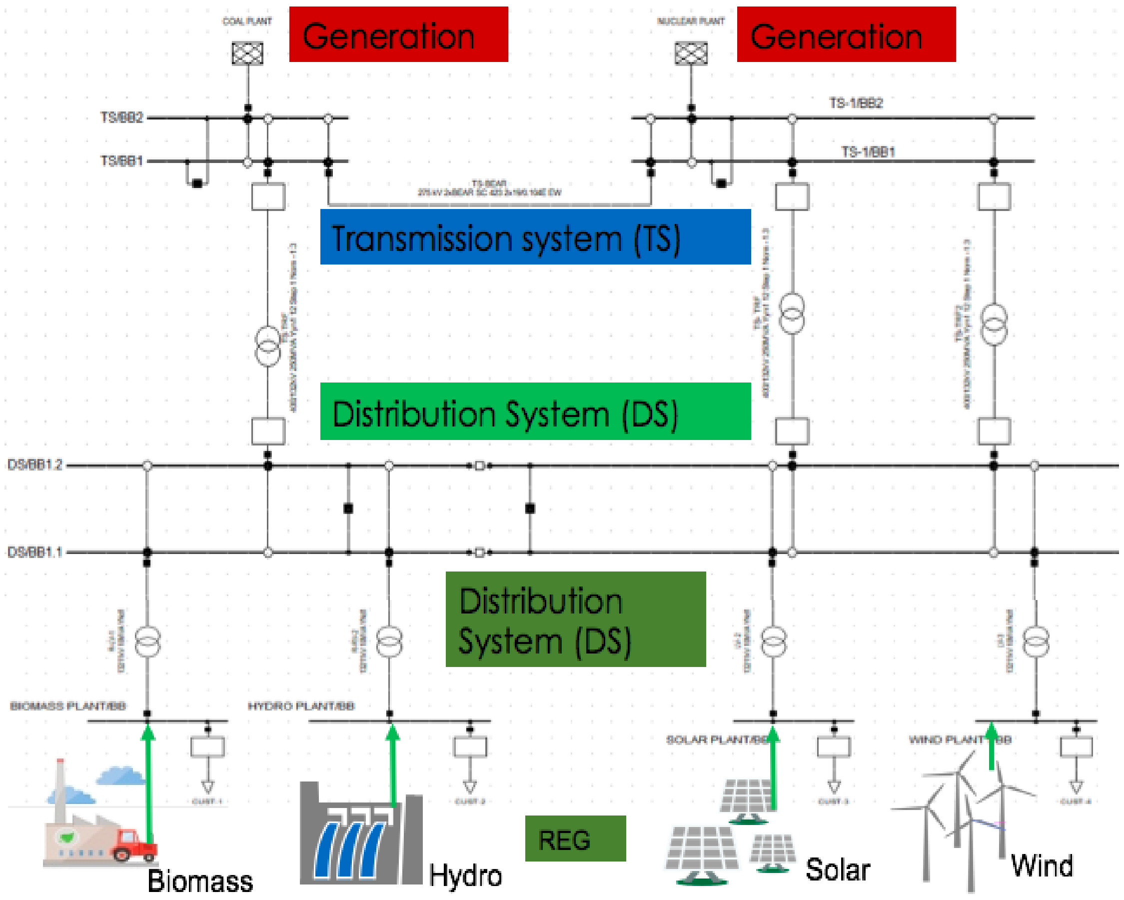


Figure 4.2: Concept of integrated grid with multiple renewable generation sites for distributed energy resources, networked with other points of generation as a distributed energy network.

Moreover, research by Passey et al., (2011), suggests that effective and significant utilization of intermittent renewable generation located away from major load centers cannot be accomplished without significant additions to the transmission system.

As renewable generation integration continues to develop, the clear solution to integration impact will be found in collaboration between the network service providers (NSP) and IPP operator considering various technical and economic constraints (Eberhard, 2015). Another possibility for an effective electric T&D system is the modernization of the network which is impacted by the economic cost.

4.6. Power Quality

The increased amount of activities on the power system electrical grid in recent years has caused a growing emphasis on the quality of power delivered to consumers. As result, the modern-day power system has become complicated networks due to hundreds of interconnected generating plants and thousands of loads centers interconnected through long power distribution system (Brenna et al., 2014). The basic structure of the power system is shown in Figure 4.3 below, containing generating plants, transmission system, distribution system and the consumer load. According to Key (1987), questioning the definition of power quality in early 2000 was awkward due to the meagre research and papers published at the time.

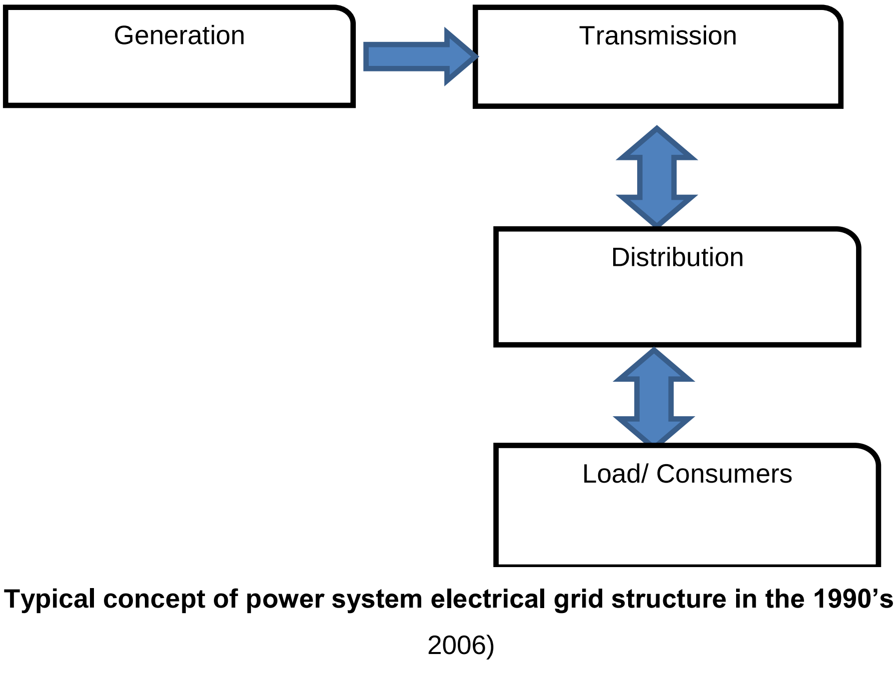


Figure 4.3: Typical concept of power system electrical grid structure in the 1990's (Bollen & Gu, 2006)

The application of power electronics and high penetration of SSEG technologies to our power system grid has increased power quality abnormalities. The modern power system structure is shown in Figure 4.4, which contains several interconnected generation plants at the distribution system. However, high penetration levels of renewable generation technologies or SSEG, is on the LV side of the power system's network. Power system overall structure seen Figure 4.4 below demonstrates the need for recent developments in power quality mitigation. The increase in network development in recent years has resulted in new ways of qualifying power quality disturbances produced by factories, commercial companies, and residences which was an insignificant issue in the past. The main concern for power suppliers and consumers is the quality and reliability of power supplies at various load locations.

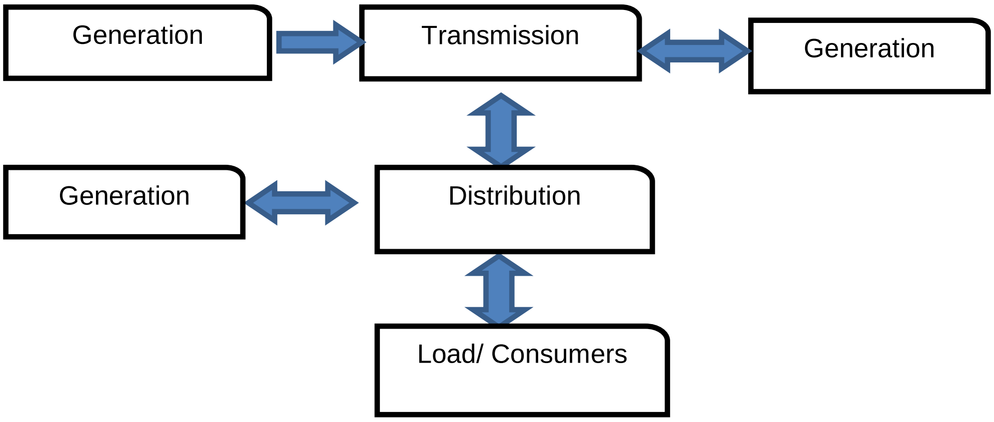


Figure 4.4: Typical concept of modern Power system of electrical grid structure (Bollen & Gu., 2006)

One of the biggest problems in power quality is the presence of harmonics in the electrical system. Generally, harmonics may be divided into two types: voltage harmonics and current harmonics (Javadi et al., 2017). Current harmonics is usually generated by harmonics contained in the voltage supply and depends on the type of load, such as resistive load, capacitive load, and inductive load. Both harmonics can be generated at by either the source or the load side.

To improve power quality, the sources and causes of the disturbances must be known before appropriate mitigating actions can be taken. A feasible approach to achieve this goal is to incorporate detection capabilities into monitoring equipment so that events of interest will be recognized, captured, and classified routinely. Therefore, good performance monitoring equipment must have functions which involve the detection, localization, and classification of transient events and harmonics (Heydt, 2005). When the disturbance type has been classified accurately, the power-quality engineers can define the major effects of the disturbance at the load and analyse the source of the disturbances so that an appropriate solution can be formulated.

In a modern power system, the objective of continuous supply of electric energy has made power quality become an issue of utmost importance. To maintain an expected level of electric power quality, some practices have been suggested to help to restrict the ever-increasing level of waveform distortion caused by the increased levels of nonlinear loads.

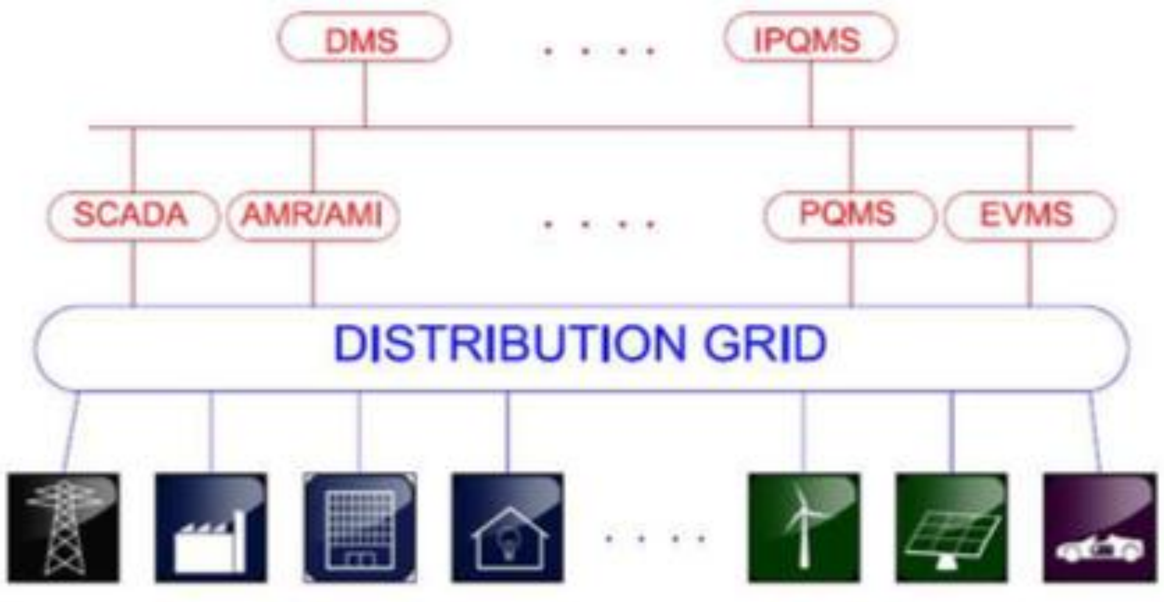


Figure 4.5: The Principle concept of the smart distribution grid PQMS (Music et al., 2012)

Due to the awareness of power quality, utility companies have installed dedicated monitoring devices such that the warning alarms can be earlier acquired to detect all possible power-quality issues. Figure 4.5 above shows the principle concept of the smart distribution grid, with some of the characteristic consumers and generators connected to it. To measure the power quality and power flow in the network, the smart grid needs adequate observability and controllability, which are enabled by various measurement and control devices (Music et al., 2012).

4.6.1. Reasons for increased interest and development of Power quality

Power Quality has become an interesting issue in the power industry and energy economy. It has affected both electrical distribution utilities and electrical power end-users all over the world. The increased interest in power quality in recent years can be explained by the major reasons below:

1. Increased awareness- Electricity consumers such as industries, factories, commercial companies, and residences are becoming better informed about power quality issues. In addition, many governments and energy regulators have revised their policies to regulate electric utilities to improve power quality within the set standards and limits. The case model in South Africa is the demand side management (DSM) programme which was designed to encourage action by customers to modify the electrical usage to meet some goals in energy demand and cost.
2. Newer generation- The increased developments of renewable generation technologies or distributed generation interconnected in the electrical network, such as solar and wind energy system has created new power quality problems, namely voltage variations and waveform distortion. Most interfaces with renewable energy sources are sensitive to voltage disturbances, especially voltage dips. However, such interfaces may be used to mitigate some of the existing power quality disturbances (Bollen & Gu, 2006).
3. Energy efficiency programmes- Increased importance on the overall power system efficiency has resulted in growing applications of high-efficiency devices, adjustable-speed motor drives, and shunt capacitors for power factor correction and the reduction of losses. Consequently, increased harmonic levels on electrical power systems have threatened the operability, reliability and safety of the system. Chapter 5 will go more in depth regarding the applications of energy efficiency in terms of power quality and harmonic mitigation techniques.

4. Increased sensitive equipment- Equipment produces more current disturbances than it used to do. Both low- and high-power equipment is more and more powered by simple power electronic converters which produce a broad spectrum of distortion. There are indications that the harmonic distortion in the power system is rising, but no conclusive results are available due to the lack of large-scale surveys (Bollen & Gu., 2006).
5. Metering and Protective relay: Poor power quality can affect the accuracy of utility metering and cause protective relays to malfunction.
6. Downtime: Poor power quality can result in equipment downtime and/or damage, resulting in a loss of productivity.
7. Cost: Poor power quality can result in increased costs due to the preceding effects.

4.6.2. Definition and background of Power Quality

Previous research suggests that the term “power quality” originated in 1968 from a U.S. Navy study, after specifications for the power required by electronic equipment, used for monitoring which presented a good overview of power quality in the field (Martzloff & Gruzs., 1988). Power quality has since evolved with the ever-increasing demand for energy.

The main aim of PQ industry development is to understand the causes of PQ degradation, their origins, their consequences for equipment, and the main solutions. The development offers a methodology for measuring PQ in accordance with set standard limit measures. The question stands: “what is power quality?” Several researches suggest varying and sometimes conflicting definitions of power quality.

For example, the Institute of Electrical and Electronics Engineers (IEEE) dictionary states that “power quality is the concept of powering and grounding sensitive equipment in a manner that is suitable to the operation of that equipment (Bollen & Gu, 2006).” One could, conclude from this definition that harmonic current distortion is only a power quality issue if it affects sensitive equipment.

According to Jay and Goetz, (1988), the definition of power quality by the International Electrotechnical Commission (IEC) is stated as follows: “Characteristics of the electricity at a given point on an electrical system, evaluated against a set of reference technical parameters." This definition of power quality is related not to the performance of equipment but to the possibility of measuring and quantifying the performance of the power system.

Some authors use the term 'voltage quality' and others use 'quality of supply' to refer to the same issue of power quality. Power quality in the power system is defined and documented in established standards as reliability, steady state voltage controls and harmonics (Bollen & Gu, 2006).

According to NERSA, power quality is defined as voltage quality in this subset, in that power quality referrs to steady-state voltage quality i.e. voltage regulation (magnitude), voltage harmonics, voltage flicker, voltage unbalance, and voltage dips (Dzobo et al., 2012).

The definition suggested in this chapter for Power quality is the combination of voltage quality and current quality.

Voltage quality is concerned with deviations of the actual voltage from the ideal voltage. Current quality is the equivalent definition for the current (Heydt, 2005). "A power quality problem is defined as any manifested problem in voltage/current or leading to frequency deviations that result in failure or mis-operation of customer equipment (Heydt, 2005)."

The power quality of the system is essential because most grid connected equipment and devices are designed to operate under certain specified voltage and frequency conditions and any deviation from these may result in a malfunction or damage of the equipment (Larsson, 2000). Considering the above definitions of power quality, the next section of this chapter introduces the more common power quality terms along with definitions of these terms and explanations in details where necessary. However, firstly, grid code will be discussed (Larsson., 2000).

4.6.3. **Grid code analysis and definition**

Grid codes are the technical, operational, and planning requirements and rules for power systems, such as generator interconnection and operation, grid operation, generation and transmission planning, and market rules for balancing, congestion management, and capacity allocation (Martinot, 2016). For power quality reliability, grid codes are designed by the utility regulators to check if the power plants are compliant with grid code connection requirements.

The primary objective of grid code connection is to specify the minimum technical and design grid connection requirements for Renewable Power Plants (RPPs) connected to or seeking connection to electricity transmission systems or distributions (Setati et al., 2002). Grid code is meant to cover all material and technical aspects relating to the connections, and the operation and use of the electricity transmission or distribution network of a certain utility (Setati et al., 2002).

The analysis of the literature of grid interconnection standards have shown that the most developed standards are found in the leading wind energy countries, namely Germany, Denmark, Spain and Ireland (Fagan et al., 2005). The South African Electricity Regulation Act (Act 4, 2006), states that it is mandatory for all Renewable Power Plants (RPP) connecting on the transmission or distribution grid to comply with the requirements of the South African Renewable Energy Grid Code (SAREGC). The SAREGC was first published in 2010 and has since evolved into the current version 2.8 of the grid code released (Sewchurran & Davidson., 2016).

SAREGC is applicable to all RE technologies, namely: photovoltaic plants, concentrated solar power plants, small hydro power plants, landfill gas power plants, biomass power plants, biogas power plants and wind power plants (Magoro & Khoza, 2012). The SAREGC requires that all testing of RPP compliance be done at the Point of Connection (POC) and not at the generator terminals as required by some international grid codes (Magoro & Khoza, 2012).

4.6.4. Power quality concerns with renewable generation integration

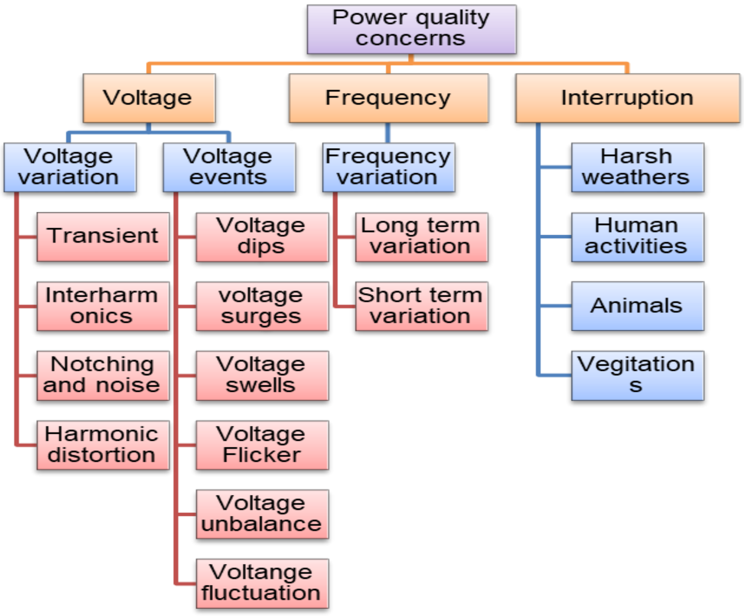


Figure 4.6: Classification of power quality concerns (Larsson, 2000).

Now that we have discussed power quality briefly, various possible power quality problems and power quality phenomena shall be presented. The main power quality problems can be expressed in terms of **voltage**, **frequency,** and **interruptions**. The next section of this chapter highlights general power quality problems such as voltage flicker, voltage dip (sags) and swell, EMI, transients, and voltage sag in the power system (Larsson, 2000). All electrical devices are prone to failure or malfunction when exposed to one or more power quality problems. The electrical device might be an electric motor, a transformer, a generator, a computer, a printer, communication equipment, or a household appliance (Larsson, 2000). These devices and others react inefficiently to power quality issues, depending on the severity of problems.

Generally, electrical utilities strive to meet the power demand of their customers with consistency under all conditions. Without proper power, an electrical device may malfunction, fail prematurely, or not operate at all (Larsson, 2000). There are many ways and causes in which electric power can be of poor quality and many more causes of such poor-Power quality.

According to Larsson, (2000), the quality of the voltage must fulfil the requirements stipulated in the national and international standards. In the standards, voltage disturbances are subdivided into voltage variations, frequency, and interruption. Grid connected renewable plants do affect the power quality of the grid. The power quality of the grid depends on the interaction between the grid and renewable generation technologies.

4.6.4.1. Voltage dips/sags

Voltage dips are short duration under-voltages which is also referred to as **Voltage Sags**. A voltage sag is a reduction in the supply voltage magnitude followed by a voltage recovery after a short period of time. According to the NRS 048-2 (Standard, 2004), voltage sags or dip can be described as a short-term reduction in RMS voltage for a period of between 20 milliseconds to 3 seconds. The duration of the voltage dip is the time measured from the moment the R M S. voltage drops below 0.9 per unit of declared voltage up to when the voltage rises above 0.9 per unit of the declared voltage (Standard, 2004).

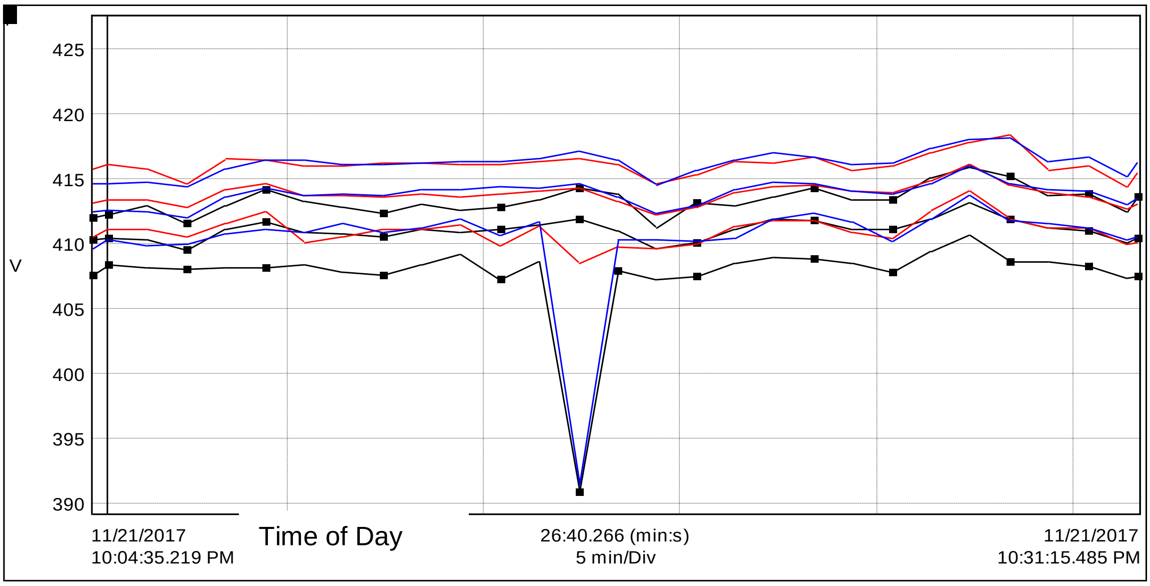


Figure 4.7: A voltage dip caused by a cloud which causes shading on solar panel cell of the on grid tied solar system

The major cause of voltage dips on a supply system due to a fault on the system, for instance. A fault on the transmission or distribution network or increased load demand and transitional events such as motorized starting of large machines and the occasional start-up of wind turbines which may not have a generator soft start (Venkatesh et al., 2008). The impact on consumers may range from the annoying light flicker to the serious tripping of sensitive loads and stalling of motors. Figure 4.7 gives an illustration of a voltage dip caused by cloud shading of cells which resulted in a sharp dip on a power system. For instance, Figure 4.7 shows that when a dip occurs on the network after 0.15 seconds, the voltage level drops to about 6% of the nominal voltage before the system recovers.

4.6.4.2. Voltage surges/spikes

These are instantaneous interruptions in the form of spikes or surges that have very fast variation of the voltage value for a duration from several microseconds to a few milliseconds. Voltage spikes are also defined as electrical transient characterized by a sharp increase in voltage (Venkatesh et al., 2008). Figure 4.8 below displays unknown power spikes captured by using power quality meter recorder on the system, and reveals a sharp increase in the apparent power due to an increase in voltage above nominal voltage for a few milliseconds on Laingsburg electrical grid.

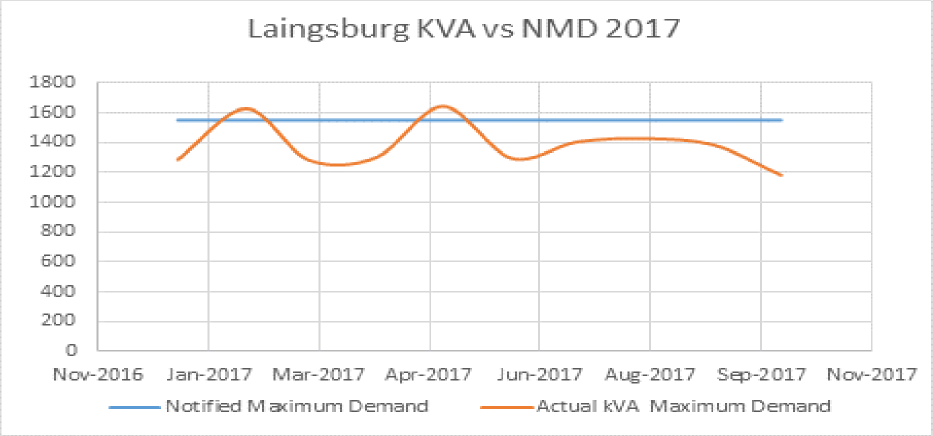


Figure 4.8: Illustrates peak spikes caused by unknown voltage spikes on Laingsburg electrical grid

However, the power spike occurred during low peak period, the increase in voltage is associated to the grid tied solar plant. The most common cause is the switching of heavy line electrical equipment such as power factor correction capacitors as well as the disconnection of heavy loads. During these conditions, the destruction of component and insulation of material can occur. Computer systems and other high-tech equipment can experience flickering lights, electromagnetic interferences and data processing errors or memory loss (Venkatesh et al., 2008). Possible solutions include surge suppressors, voltage regulators, uninterruptable power supplies, and power conditioners.

This voltage transient may be responsible for disturbing sensitive equipment connected to the same grid. The connection of shunt line capacitor banks leads to a large inrush peak current occurring as shown in Figure 4.8 (Venkatesh et al., 2008). Shunt capacitor banks are usually installed to control the line voltage by reducing the reactive power which, in turn reduces voltage drop on the line.

4.6.4.3. Voltage Swell

Electrical transients are characterized by high-voltage swells which occur when there is a sudden voltage peak outside tolerance with the duration of more than one cycle and typically less than of second (Larsson, 2000). These swells are usually the result of nearby lightning strikes.

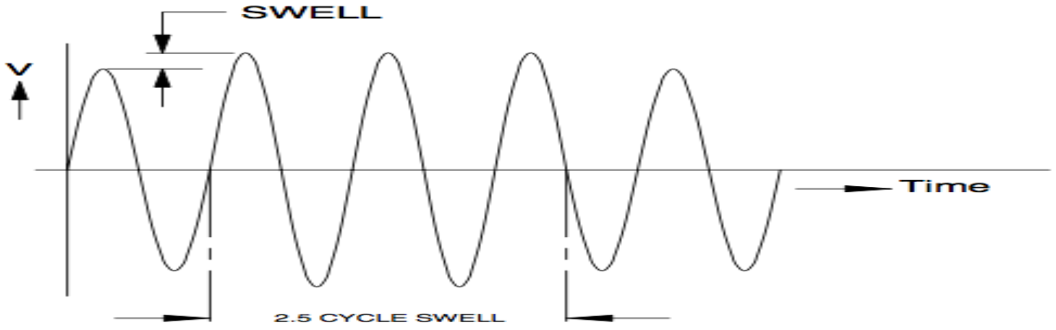


Figure 4.9: Swell of 2.5 cycles (Larsson, 2000)

The other cause related to voltage swells could be due to the starting and stopping of heavy loads, poorly regulated transformers, and poorly dimensioned power sources (Larsson, 2000). The effects on vulnerable electronic systems can include the loss of data and burned circuit boards. Possible solutions are using surge suppressors, Voltage Regulators, uninterruptable power supplies, power conditioners (Larsson, 2000). Usually, excessive network loading results in the opposite of a voltage swell i.e. under voltage. Under voltage can result in the loss of generation as we as voltage regulator malfunctions. Loads with a poor power factor or a general lack of reactive power support on a network are also contributors to this phenomenon. Under voltage can also indirectly lead to overloading problems as equipment takes an increased current to maintain power output (Heydt, 2005).

4.6.4.4. Voltage flicker

Flickers are short-duration voltage changes, resulting from switching, short circuits, and load changing. Basically, flicker is an old way of quantifying voltage fluctuations (Favuzza et al., 2004). The method is based on the measurement of variation in the voltage amplitude i.e. the duration and the magnitude of the variation (Favuzza et al., 2004). The permissible magnitude of light flicker is regulated by International Standards based on perception criteria (Blavette et al., 2016). A flicker-meter is used to measure flicker. The method used to measure it is based on measurements of voltage variations in the voltage magnitude (Favuzza et al., 2004).

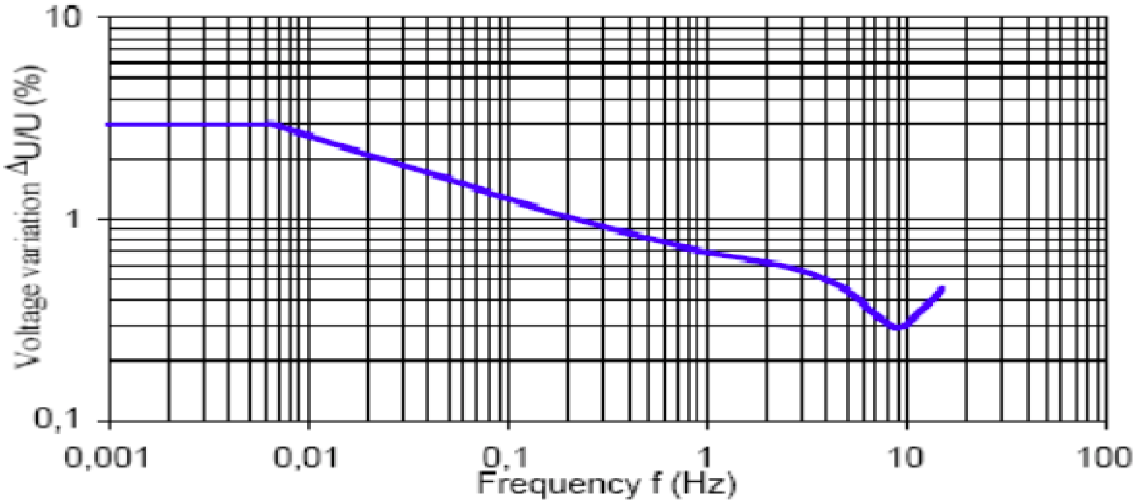


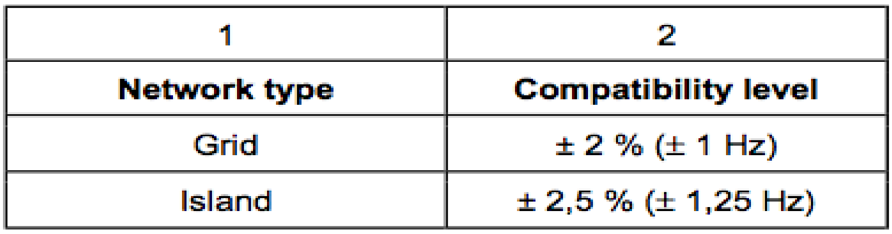
Figure 4.10: Flicker curve according to IEC 60868 (Favuzza et al., 2004).

The measurements and determination of flicker are normally given in the IEC 60868 Standard and Amendment 1 (Favuzza et al., 2004) for most European utilities, and in South Africa, the NRS 048-1, 2 standards (Standard, 1996). The above curve, in Figure 4.10 gives an illustration of the magnitude of the allowable voltage limits for a sinusoidal curve with respect to the number of voltage changes per second as given in the IEC 60868 standard and NRS 084-1,2 (Favuzza et al., 2004). Figure 4.10 is normally referred to as a flicker curve and commonly it normally represents “the short-term flicker values of 1.0 for various frequencies of rectangular voltage fluctuations”

4.6.4.5. Frequency variation

A frequency shift either upwards or downwards in a power system is the main indicator of the temporary imbalance between generation and demand (Short et al., 2007). If at any instant the power demand exceeds the supply, then the system frequency falls. Similarly, if the power supply exceeds demand, frequency rises (Short et al., 2007). The system frequency fluctuates continuously in response to the changing demand and due to the practical impossibility of generation being controlled to instantaneously track all changes in demand (Short et al., 2007). According to NRS 048-2:2003, the standard and maximum deviation frequency limits are stated in Table 4.1 and Table 4.2 below (Standard, 2003).

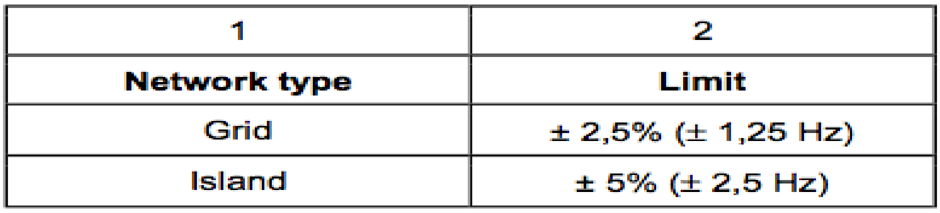
Table 4.1: Deviation from standard frequency (Standard, 2003)



1	2
Network type	**Compatibility level**
Grid	± 2 % (± 1 Hz)
Island	± 2,5 % (± 1,25 Hz)

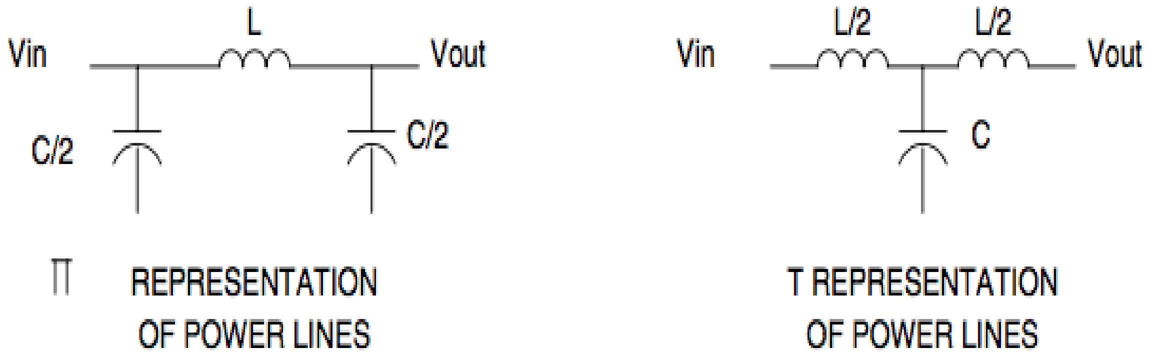
Table 4.1 for illustrates the standard deviation limits from supply the frequency while Table 4.10 illustrates the maximum deviation limits from the supply frequency (Standard, 2003).

Table 4.2: Maximum deviation from standard frequency (Standard, 2003)



1	2
Network type	**Limit**
Grid	± 2,5% (± 1,25 Hz)
Island	± 5% (± 2,5 Hz)

Frequency deviation in a power system may be caused by the erratic operation of emergency generators or unstable frequency power sources. For sensitive equipment, the results can be data loss, program failure, equipment lock-up, or complete shutdown (Dugan et al., 1996). Possible solutions are using voltage regulators and power conditioners (Dugan et al., 1996). To obtain higher accuracy as the frequency goes up, the constants are divided up and grouped to form the PI or T configurations shown in Figure 4.11. Although the computations may get tedious, more accurate results are obtained (Short et al., 2007).



Π REPRESENTATION OF POWER LINES

T REPRESENTATION OF POWER LINES

Figure 4.11: Representation of power lines at high frequencies where L is the total inductance and C is the total capacitance of the power lines (Short et al., 2007)

4.6.4.6. Transients

Power system transients are fast, short-duration events that produce distortions such as notching, ringing, and impulse (Dugan et al., 1996). The mechanisms by which transient energy is propagated in power lines, transferred to other electrical circuits, and eventually dissipated are different from the factors that affect power frequency disturbances (Dugan et al., 1996). Transients are also defined as the change in a system variable that disappears during transition from one steady- state operating condition to another. A transient may generate in the system itself or may come from the other system. For transients to occur there must be a cause. Although they may be many, the most common causes of transients are highlighted below (Larsson, 2000):

- Atmospheric phenomena (lightning, solar flares, geomagnetic disturbances)
- Switching loads on or off
- Interruption of fault currents
- Switching of power lines
- Switching of capacitor banks

The connection of shunt capacitor banks leads to a large inrush peak current occurring as shown in Figure 4.12 (Larsson, 2000).

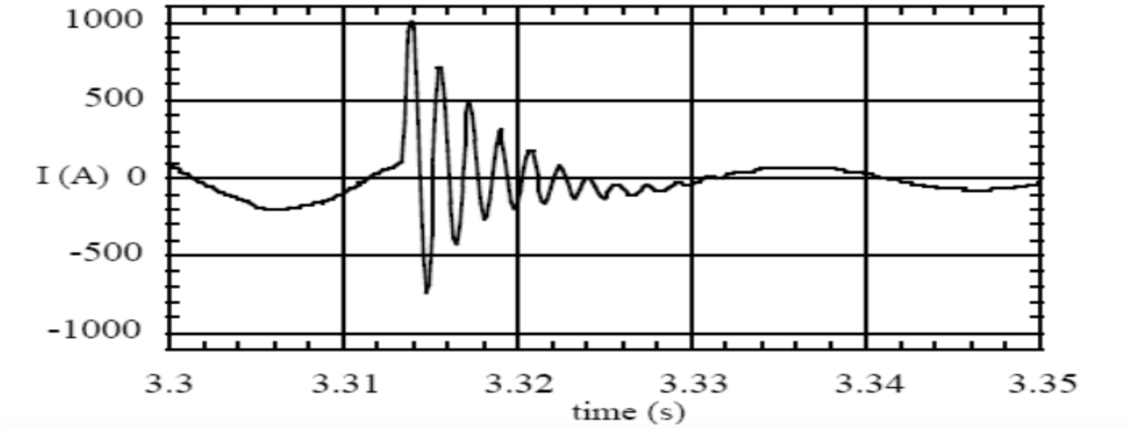


Figure 4.12: Transient current caused by connection of a shunt capacitors during start-up of a 225kW wind turbine (Larsson, 2000).

4.6.4.7. Electromagnetic interference

EMI refers to the interaction between electric and magnetic fields and sensitive electronic circuits and devices. Electricity and magnetism are related and exist in a matching fashion (Bollen & Gu, 2006). Any conductor carrying electrical current has an associated magnetic field (basic machine theory) (Bollen & Gu, 2006). A magnetic field can induce voltages or currents in a conductive medium exposed to the field. The term EMI is commonly associated with high-frequency noise, which has several possible power quality causes. Figure 4.13 describes how EMI may be generated and conveyed to equipment (Bollen & Gu, 2006).

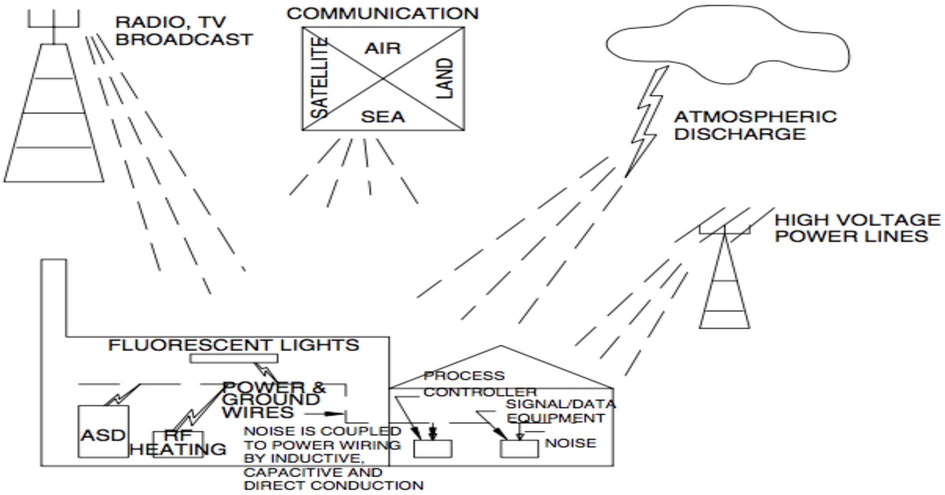


Figure 4.13: Common electromagnetic interference (EMI) sources (Short et al., 2007).

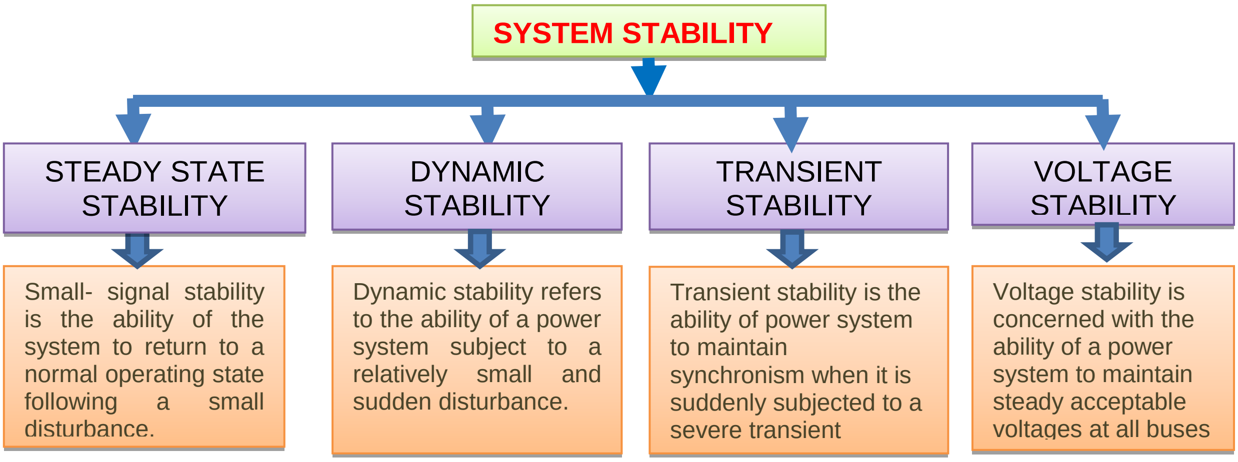
The most common high-frequency EMI sources are radio, television, and microwave communication towers; marine or land communication; atmospheric discharges; radio frequency heating equipment; adjustable speed drives; fluorescent lighting; and electronic dimmers. These devices produce interference ranging from a few kilohertz to hundreds of megahertz and perhaps higher (Bollen & Gu., 2006).

4.6.5. Power Quality Mitigation Techniques

Grid stability and the security of supply are two important aspects for in terms of energy supply. In order to avoid power outages it is necessary that power generating plants should have control capabilities and protection mechanisms. To improve the electrical power quality especially of low voltage (LV) distribution systems, several solutions have been proposed in the literature (Roncero-Sanchez & Ach, 2015).

The integration of renewable energy source has sighted power problems like synchronization, power quality, protection, load sharing, and grid instability increasing (Tareen et al., 2017). Their influence on voltage quality and power quality has seen the use of custom power devices such as: DVR, SVR, D-STATCOM, and AUTO transformer which are being developed and improved in their design in order to mitigate PQ problems.

Custom devices are designed to improve voltage quality and current in non-linear loads as well as to compensate voltage in the traditional grid and micro grid hybrid systems (Roncero-Sanchez & Ach, 2015). The aforementioned custom devices are briefly discussed in this thesis.



Small- signal stability is the ability of the system to return to a normal operating state following a small disturbance.

Dynamic stability refers to the ability of a power system subject to a relatively small and sudden disturbance.

Transient stability is the ability of power system to maintain synchronism when it is suddenly subjected to a severe transient

Voltage stability is concerned with the ability of a power system to maintain steady acceptable voltages at all buses

Figure 4.14: The initial operating condition considered with large renewable generation integration

Power quality studies aim to achieve the stability of an electric power system. Figure 4.14 above illustrates the initial operating condition considered with large renewable generation integration to achieve an equilibrium state.

4.6.5.1. Distribution Static Synchronous Compensator (D-STATCOM)

Distribution static synchronous compensator (DSTATCOM) is one of the shunt connected custom power devices used to improve PQ, voltage, and reactive power support, as well as to increase the capability of the auxiliary service for the utility grid (Roncero-Sanchez & Ach, 2015).

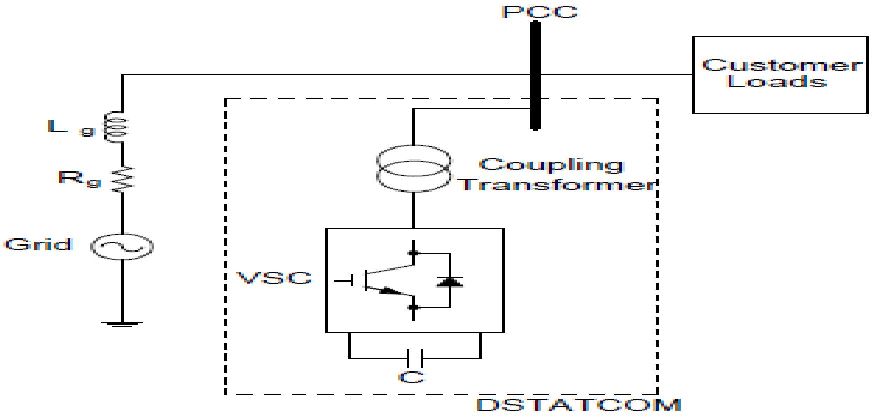


Figure 4.15: Scheme of a DSTATCOM connected to the point of common coupling (PCC)
(Tareen et al. 2017)

D-STATCOM, which is schematically pictured in Figure 4.15, consists of a two-level voltage supply convertor (VSC), a DC energy memory device, and a coupling electrical device connected in shunt to the distribution network through a coupling electrical device (Elango and Sekaran., 2011). The VSC converts the DC voltage across the memory device into a collection of three-phase AC output voltages. These voltages are a unit in part and paired with the ac system through the electrical phenomenon of the coupling electrical device. Appropriate adjustment of the part and magnitude of the D-STATCOM output voltages permits the effective management of active and reactive power exchanges between the DSTATCOM and also the AC system (Elango & Sekaran, 2011).

Main tasks of the D-STATCOM (Tareen et al., 2017):

- It must compensate voltage sags by injecting reactive power into the grid.

- The DC capacitor must be charged to a necessary voltage level to avoid the over modulation region.
- D-STATCOM are also employed to compensate poor load power factors for low and medium power applications.
- A D-STATCOM can also be used for Reactive Power Compensation in 1∅ operation of micro-grid. The placement and current ratings of these devices are optimization problems and various techniques are available for solving it.

The increasing number of Renewable Energy Sources (RES) and Distributed Generation (DG) requires new techniques for the operation and management of the electrical grid to enhance the power supply reliability and the power quality, such as D-STATCOM (Tareen et al., 2017).

4.6.5.2. Low-voltage ride through (LVRT)

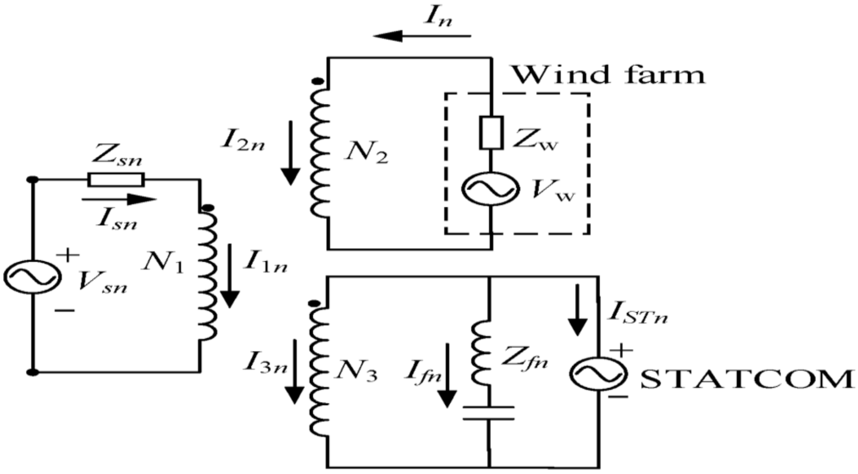


Figure 4.16: A single-phase equivalent-circuit model of the new grid-connected transformer with fully-tuned (FT) branches (Tareen et al. 2017).

Low-voltage ride through (LVRT) is the capability of electric generators to stay connected during short periods of lower electric, network voltage due, to sporadic, disturbances such as voltage dips. It is needed at the distribution level such as in wind plants and PV system plants to prevent a short circuit at the HV or EHV level from causing a widespread loss of generation. Low-voltage ride through (LVRT) capability enhancement of wind farms integrates system by means of an inductive filtering method, especially if it contains a grid-connected transformer, a static synchronous compensator (STATCOM) and fully-tuned (FT) branches (Tareen et al., 2017).

Short-term voltage dips may occur, for example, when large loads are connected to the grid or as a result of grid faults like lightning strikes or short-circuits. In the past, renewable generating plants such as wind turbines were allowed to disconnect from the grid during such a fault and then try to reconnect after a certain period of time (Mittal et al., 2009). Today, because of the significant share of renewable generations, such a procedure would be fatal. If too many generating plants disconnect at the same time, the complete network could break down, a scenario which is also called a “blackout” (Mittal et al., 2009). Due to this, the LVRT requirement has been established intended to guarantee that the generating plant stays connected to the grid as well as ensure stability.

4.6.5.3. Dynamic Voltage Restorer (DVR)

Dynamic Voltage Restoration is a method and apparatus used to sustain, or restore, an operational electric load during sags, or spikes, in voltage supply. It employs a series of voltage boost technology using solid state switches for compensating sags/swells (Golovanov et al., 2013).

The DVR is a series-connected power electronic device used to inject voltage of the required magnitude and frequency. The basic structure of a DVR is shown in Figure 4.15 and contains the following components-:

- Voltage Source Inverter (VSI)
- DC storage unit
- Filter circuit
- Series Transformer

Considerations for the control system of a DVR include: detection of the start and finish of the sag, voltage reference generation, transient and steady-state control of the injected voltage, and protection of the system (Tareen et al., 2017).

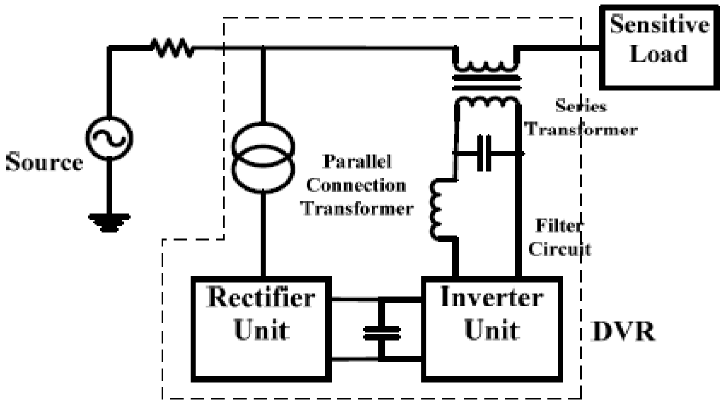


Figure 4.17: Basic Structure of DVR (Tareen et al. 2017)

The operation of the DVR is to inject the voltage of the required magnitude and frequency when desired by the power system network. During normal operation, the DVR will be in stand-by mode. During the disturbances in the system, the nominal or rated voltage is compared with the voltage variation and the DVR injects the difference in voltage that is required by the load.

4.6.5.4. Auto-Transformer

An auto transformer is a single winding transformer where there is no isolation between the primary and secondary windings (Tareen et al., 2017). This device requires less conductor material in its construction and is of less size and weight when compared to the normal two winding transformer. It can be used in mitigating the voltage sag when controlled properly.

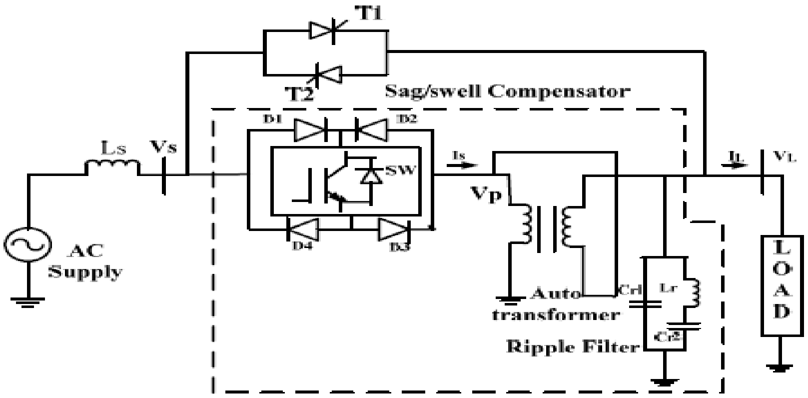


Fig.4.18 Voltage sag mitigation scheme using auto transformer (Abdelrahem & Kennel, 2016)

The function of the control strategy is to control the pulses generated to the IGBT switch such that the auto-transformer generates the desired voltage to mitigate the voltage sag (Abdelrahem & Kennel, 2016). The RMS value of the load voltage is compared with a reference value (Vref). Under normal operating conditions there is no error and no pulses are generated to the IGBT switch and auto-transformer does not work. However, when there is voltage sag, then an error occurs and based on the error value the PMW generator generates pulses to the IGBT switch (Abdelrahem & Kennel, 2016).

4.6.5.5. Static VAR Compensator (SVRs)

A static VAR compensator is a set of electrical devices for providing fast-acting reactive power-on high-voltage electricity transmission-networks. The Static VAR Compensator is one of the shunt-connected flexible alternating current transmission system (FACTS) devices which are based on power electronics (Peng et al., 2016).

In order to stabilize the intermittent voltage in distribution systems, electrical static VARs compensators are employed to control voltages with reactive power.

An SVR, mainly used in the conventional voltage control is connected in series connection equipment, and regulates voltage by switching the tap of a transformer.

SVR can help in:

- Voltage regulation,
- Reactive power control and
- Improving the transient stability of the system.

The voltage regulation by SVC is done, by controlling the amount of reactive power injected into or absorbed from the power system (Peng et al., 2016).

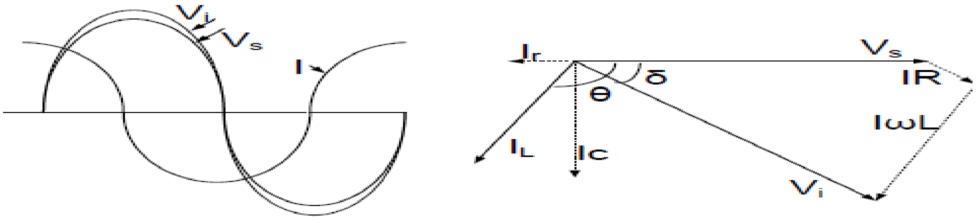


Figure 4.19: Input Voltage is greater than System voltage, Current leading (Peng et al., 2016)

When the system voltage is low the SVC generates reactive power (capacitive mode).

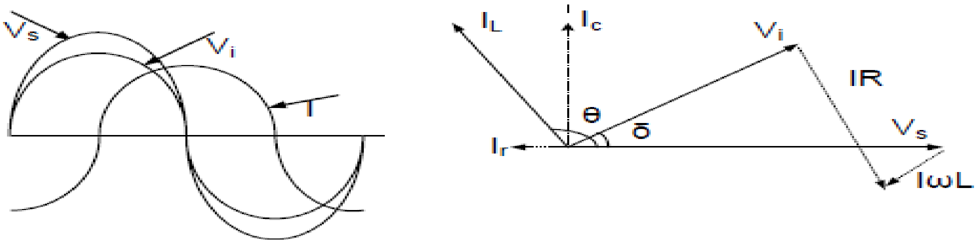


Figure 4.20: Input Voltage is less than System voltage, Current lagging (Peng et al., 2016)

When the system voltage is high, the SVC absorbs reactive power (inductive mode).

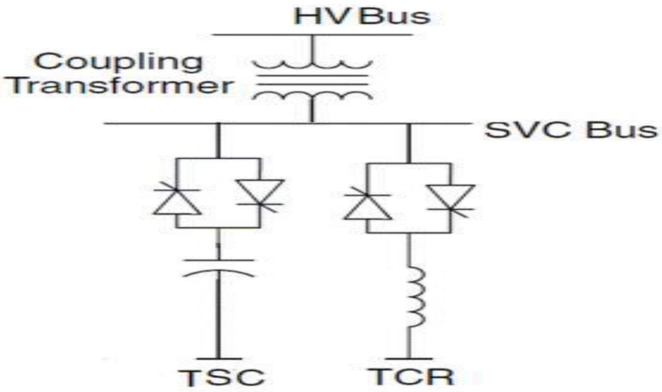


Figure 4.21: Typical SVC configuration employing a thyristor switched capacitor a thyristor controlled reactor (Peng et al., 2016).

By connecting the thyristor-controlled reactor, which is continuously variable, along with a capacitor bank step, the net result is continuously variable leading or lagging power.

In industrial applications, SVCs are typically placed near high and rapidly varying loads, such as arc furnaces, where they can smooth the flicker voltage (Peng et al., 2016).

CHAPTER 5: HARMONIC MITIGATION TECHNIQUES AND SYSTEM STABILITY

5.1. Chapter Review

This chapter looks at power system harmonics briefly, its effect on system stability, and possible mitigation techniques available to limit them. An inverter model is proposed and considered to be harmonic current source in DigSILENT to simulate the effects of grid-tied renewable generation technologies. The chapter also presents harmonic mitigation passive filter design model as well as simulation results using DIgSILINT and industry standards available to limit harmonic pollution.

5.2. Introduction

Research shows that the integration of concentrated grid-connected renewable generation technologies and huge facilities that use a large amount of electrical power, concerns power quality of the grid and the consumers electrical equipment connected on the grid. The consequences of this concern are reduction of power system efficiency and system stability. Power quality used to be to the ability of the electric utilities to provide electric power without interruption (Passey et al., 2011). Today, power quality encompasses any deviation from a perfect sinusoidal waveform. This includes electrical magnetic interference (EMI) and radio frequency interference (RFI) noise, transients, surges, sags, flickers, black outs, and any other distortions to the sinusoidal waveform (Passey et al., 2011). One distortion to the sinusoidal waveform which has dangerous consequences is harmonics.

The general awareness of PQ harmonics and their causes and effects especially related to renewable generation technologies and methods to control them will aid improving system the stability and PQ of the grid. It is therefore essential to understand the causes of these concerns and how to deal with them (Kazma et al., 2017).

5.3. Harmonics Definition

IEEE 519-1992 defines harmonics as a sinusoidal component of a periodic wave or quantity (for example voltage or current) having a frequency that is an integral multiple of the fundamental frequency. In power systems, harmonics can be described as a sinusoidal section of a periodic wave having a frequency that is an integral multiple of basic frequency (Enslin &Heske, 2004). A distorted periodic wave of any possible shape might be generated by utilizing distinctive harmonic frequencies with different amplitudes. Any distorted periodic wave could be disintegrated into a basic wave and a set of harmonic waves (Enslin &Heske, 2004).

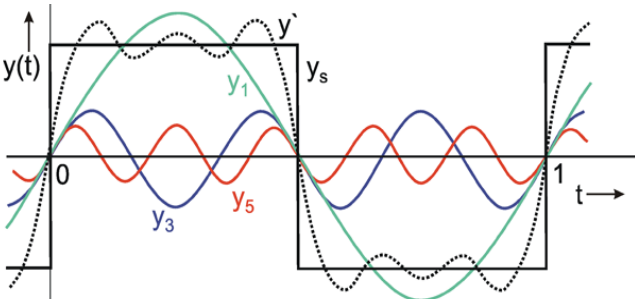


Figure 5.1: The graph above shows how a fundamental frequency and several harmonics combine to produce a resultant (Silas & Madubuike, 2016).

A sinusoidal waveform with a frequency that is an integral multiple of the fundamental 60 Hz frequency is shown in figure 5.1:

- 60 Hz fundamental
- 180 Hz 3rd harmonic
- 300 Hz 5th harmonic

This disintegration process is called a Fourier Series Expansion. Fourier analysis is a mathematical technique for finding the amplitudes, frequencies, and phases of the components of a given waveform. The equations below shows the discrete Fourier sum for f (t) before letting ᴛ approach infinity (Silas & Madubuike, 2016). figure 5.1 is the expansion of graphs, showing the influence of non-linear loads in the power system grid.

5.4. Power system stability

Over the years many different definitions of power system stability have been proposed. The most recent one, is the result of a joint IEEE/CIGRE working group activity: “Power system stability is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact” (Subhani et al.2017). Such a disturbance could for example, be the power quality related issues discussed in great details in Chapter 4. The behaviour of the system after this disturbance depends on the extremity of the disturbance on the system. The ability to maintain system stability is therefore vital and can be achieved maintaining power quality problems, particularly those hosting higher intermittent capacity such as renewable energy sources, from power interruptions, voltage sag, and spikes etc (Kazma et al., 2017).

5.5. Harmonic generation in renewable systems

Static power converters are the equipment that utilize power semiconductor devices for power conversion from AC-to-DC, DC-to-DC, DC-to-AC and AC-to-AC; and constitutes the largest non-linear loads connected to the electric power systems. These converters are used for various purposes in the industry, such as adjustable speed drive (ASD) or variable frequency drives (VFD), uninterruptable power supplies (UPS), and switch-mode power supplies (SMPS) etc. These static power converters used in a variety of applications draw non-linear (i.e. non-sinusoidal) currents and distort the supply voltage waveform at the PCC (Kazma et al., 2017). Renewable energy generation systems based on the renewable energy sources, such as solar photovoltaic, wind power, and geothermal power are increasingly the integrated to national grid. The grid-connected inverter is an important power electronic device used to convert DC-to-AC to integrate with the national grid.

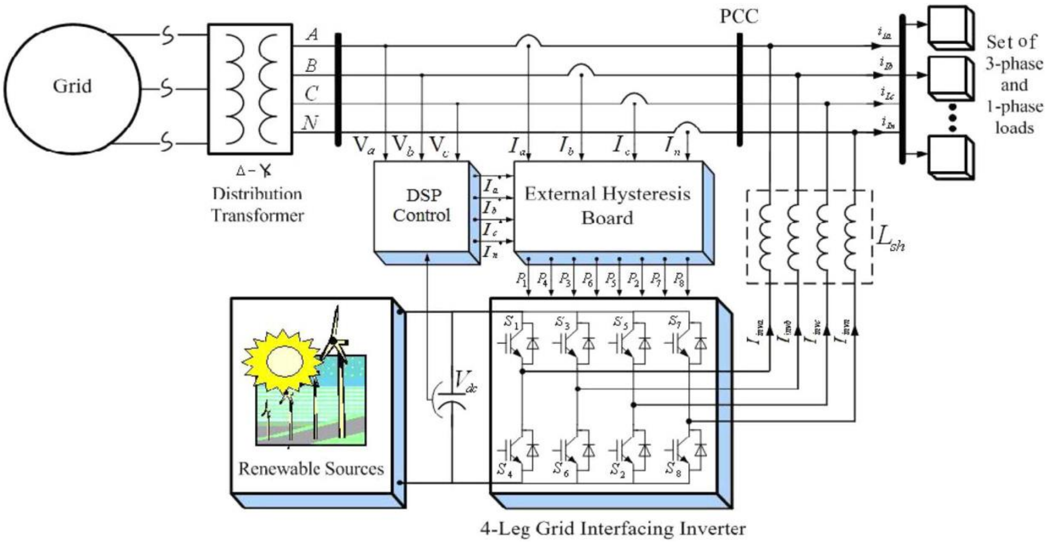


Figure 5.2: Schematic of proposed renewable based distributed generation system (Pradhan et al., 2014)

This phenomenon is explained using Figure 5.2 above. The PCC is a point between the system owner or operator and end- users connects to the grid. The PCC is usually taken as the point in the power system closest to the user where the system owner or operator could offer services to another user (Tareen et al., 2017). In general, the PCC is a point on a public power supply system, electrically nearest to a particular load, at which other loads are, or could be connected and is located on the upstream of the considered installation (Pinto et al., 2016).

Theoretically, there are both even and odd numbered harmonics. Typically, in an AC power system even harmonics are absent. Our concern is mostly old harmonics, which are present in an AC power system network and do contribute to total harmonic distortion (THD) (Pinto et al., 2016).

Odd harmonics that are a multiple of three in a three-phase power system are called triplen harmonics, however triplen harmonics are virtually absent in a balanced a three-phase power system. However, balanced system is rarely the case in a power system (Kazma et al., 2017). In three-phase circuits, the triplen harmonic current (3rd, 9th, 15th, etc.) add instead of cancelling. Being three times the fundamental power frequency and spaced in time by 120 electrical degrees based on the fundamental frequency, the triplen harmonic currents are in phase with each other, and add in the neutral circuit (Abdel-Salam et al., 2011).

5.6. Understanding power system harmonics

To understand power system harmonics, all electrical power is generated and distributed in the form of a sinusoidal voltage wave form. To understand harmonics and their effect it is always necessary to look at the fundamentals of power generation and how harmonics are generated in the network (Mantilla, 2015). There are a lot of good reasons to understand harmonics, their effect, and how to mitigate them. When an electrical load is connected to the voltage sources, it draws current to perform work. If the current follows the voltage wave form in some sinusoidal patterns, then the load is said to linearly follow the voltage. The figure 5.3 below illustrates the two sources of harmonics i.e. voltage source non-linear load and current source nonlinear load (Subhani et al., 2017).

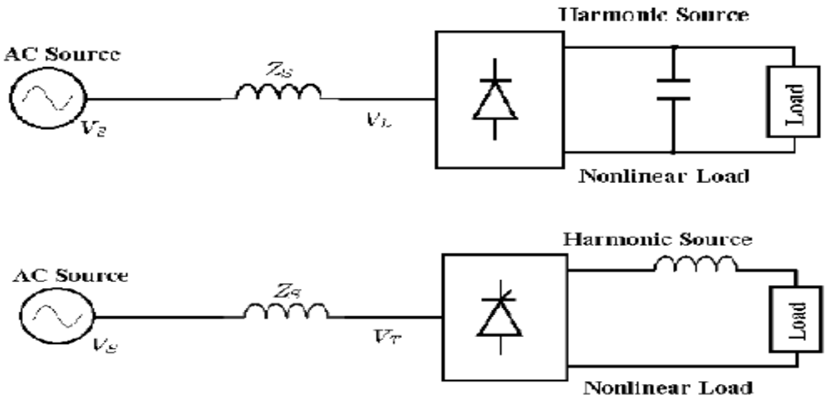


Figure 5.3: Voltage source non-linear load and current source non-linear load (Subhani et al., 2017)

An example of voltage and current waveforms of a linear load is shown in Figure 5.4 below. However, if the current does not linearly follow the load, it is a called non-linear load. Non-linear loads cause stress and many other effects on the transformers, generators and other electrical equipment's that make up the electrical grid system.

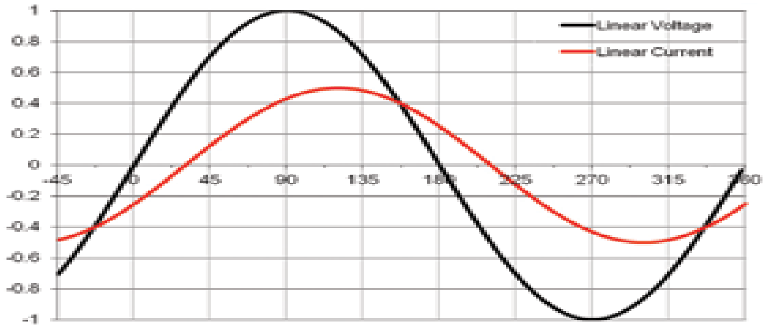


Figure 5.4: Example of Voltage and Current waveforms of linear load (Subhani et al., 2017)

The stress or the effects of the non-linear loads have been found to be thermal in nature. Although the load that is doing the work can be very efficient, the overall work required to perform work done by the non-linear load is much greater than the linear load (Subhani et al., 2017). The distorted current that is drawn by the non-linear load is local in nature and flows only into the non-linear loads consuming that current, however, the distorted current produced by grid-tied renewable generation technologies is transported along the power system grid and it causes voltage distortion. An example of a voltage and current wave form of a non-linear load is shown below in Figure 5.5 which illustrates the measurement of current drawn by a non-linear load.

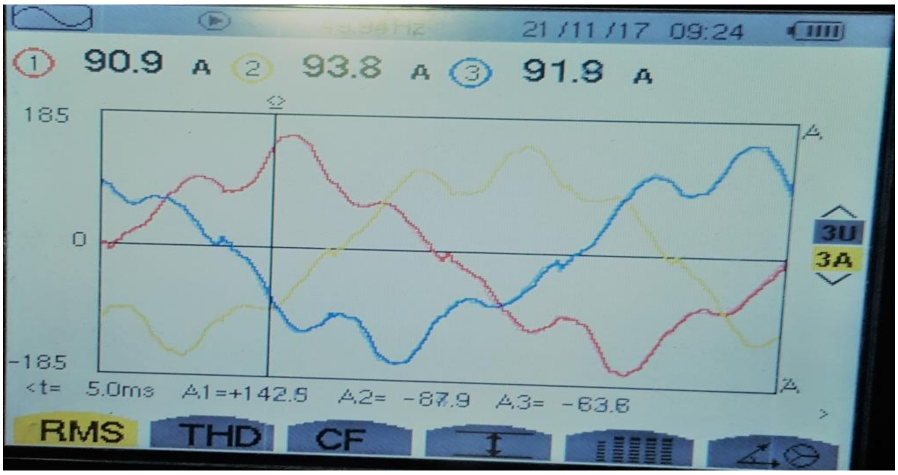


Figure 5.5: An example of a voltage and current wave form of non-linear load

It should be understood that voltage is all common to all users national wide, and by distorting voltage can create wide-spread causes that may result in the faulty operation of many types of electrical equipment. To mitigate or reduce the levels of distorted voltage, it is important to limit the flow of the distorted current. Some inverter topologies such as the inverter topology below are designed to inject the compensating current into the grid to filter the load current harmonics. Figure 5.6 below illustrates an AC–AC inverter topology with the pulse width modulation voltage source inverter connected in parallel with the DC-link capacitor (Javadi et al., 2017). These non-sinusoidal currents contain harmonic currents that interact with the impedance of the power distribution system to create voltage distortion that can affect both the distribution system equipment and the loads connected to it (Abdel-Salam et al., 2011).

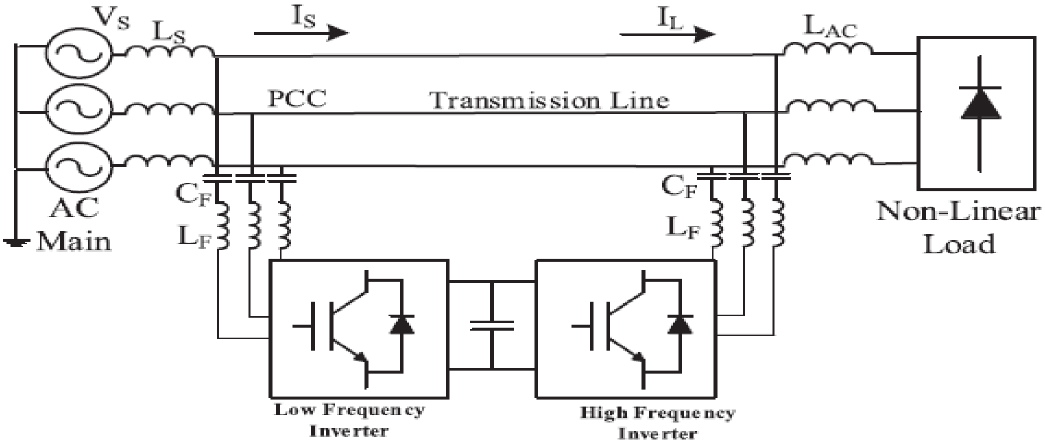


Figure 5.6: AC–AC inverter topology (Revana & Kota, 2017)

5.7. Harmonic Source

The harmonics in renewable generation technologies are normally produced by non-sinusoidal power electronic converters, transformer flux distribution in the air gap, and by flux saturation. However, in practical terms, the content of harmonic voltage produced by renewable generators may be neglected in harmonic propagation studies. The descriptions of DG harmonics are focused on transformer magnetizing currents and power conversion devices. In general, the harmonic sources can be classified according to their physical cause as (Javadi et al., 2017):

(a) Magnetizing currents, e.g. transformers and saturable reactors.

(b) Flux distribution, e.g. synchronous generators.

(c) Power conversion applications, e.g. power control (inverter and UPS) and computers.

(d) Arc processes in arc furnaces.

5.7.1. Magnetizing currents

Transformers: Due to the curve of the hysteresis loop for iron and steel, transformers give rise to harmonic magnetizing currents. These currents do not normally cause any wave distortion of consequence. An exception would be when high voltages occur due to a system upset. Exciting currents increase very rapidly with an increase in voltage.

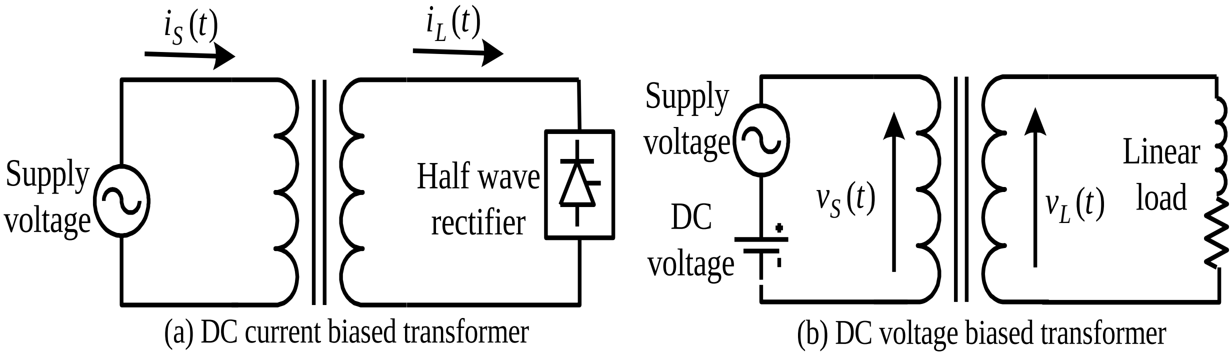


Figure 5.7: Saturated DC-biased transformers (Javadi et al., 2017)

5.7.2. Power conversion devices

With the development distributed generation (DG) and solid-state technology, more and more power electronic devices are used in power grids to convert AC power to DC power or different amplitude, different frequency AC power. In the electronic converting process, the converter breaks or chops the AC current waveforms by allowing the current to flow during a portion of the cycle. The AC current is determined by the characteristics of the converter, e.g. type of connection, control, characteristics of the supply network, and nature of the load. They can be classified according to the solid-state devices used (Javadi et al., 2017):

(a) They includes variable speed drives (VSD), AC/DC converters, computer power supply, cycloconverters, and superconducting magnetic energy storage (SMES).
(b) Thyristor-based power conversion devices, such as line commutated converters, cycloconverters, integral cycle controllers, and statistic VAR compensator
(c) IGBT, GTO, CMOS-based power conversion devices, such as PWM converters.

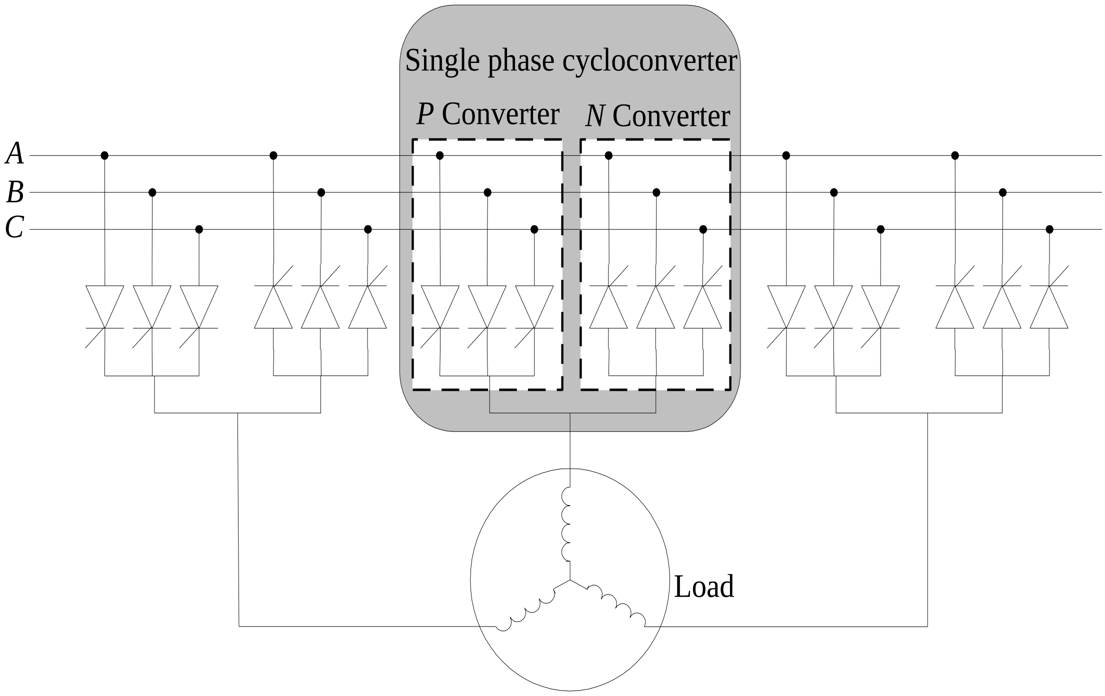


Figure 5.8: The schematic of a three-phase 3-pulse half-wave cycloconverter (Pinto et al., 2016)

We see that the AC harmonic currents generated by a six-pulse converter include all odd harmonics except triplens. Harmonics generated by converters of any pulse number can be expressed as:

$$h = pn \pm 1 \tag{5-1}$$

Where n is any integer and p is the pulse number of the converter. For the ideal case, converter harmonic current magnitudes decrease according to 1/h rule (Abdel-Salam et al., 2011)

5.8. Effect of harmonics in the system

A power system carrying non-linear loads is less efficient and therefore, it is important to find them and take corrective action to reduce their negative impact on the power grid. Power system harmonics comes from a variety of sources, the dominant ones within transmission networks being large power converters such as those used for HVDC links and large industrial processes.

In the real world, the grid is filled with all kind of non-linear equipment/loads, like the power supply of computers, lump dimmers, variable speed drives (VSD), and variable frequency drives (VFD) and new conversion technologies such as renewable generation technologies.

As an electrical power utility, distorted current wave forms are problematic as they can affect the power grid in many ways:

1. Increased TS and DS line losses
2. Equipment damage (transformers, power capacitors and generators), decreased lifespan, and energy waste.
3. Decreases the plant efficiency and increased PQ issues- which means increased power cost
4. The frequency mismatch during grid synchronization

The distorted current that is drawn by the non-linear load is local in nature and flows only into the non-linear loads consuming that current, thus when the distorted current is transported to the non-loads, it causes distorted voltages all along the power system which leads to distorted voltages on the grid.

5.9. Harmonic standards

The importance of standards to limit high emissions is reflected in the creation of working international association and standardization committees, such as the IEEE, IEC 61000-3-2, and the C4.24 (CIGRE /CIRED). The interest in the distortion in the considered frequency range is due to an increasing number of sources of emission, including energy-efficient lighting and generation (such as DERs) and some other electrical equipment within the LV sector of the electricity distribution network (Zavoda et al., 2016).

5.9.1. IEEE 519-1992

The recommendation described in this document attempts to reduce the harmonic effects at any point in the entire system by establishing limits on certain harmonic indices (currents and voltages) at the point of common coupling (PCC), a point of metering, or any point as long as both the utility and the consumer can either access the point for direct measurement of the harmonic indices meaningful to both, or can estimate the harmonic indices at the point of interface (POI) through mutually agreeable methods.

5.9.2. IEEE 519- 2014

The limits in this recommended practice are the intended for application at a point of common coupling (PCC) between the system owner or operator and a user, where the PCC is usually taken as the point in the power system closest to the user where the system owner or operator could offer service to another user.

IEEE 519-1992, known as the “Recommended Practices and Requirements for Harmonic Control in Electric Power Systems”, established limits for harmonic currents and voltages at the point of common coupling (PCC), or point of metering in 1981 as a guide for harmonic control and reactive compensation of static power converters (Franquelo et al., 2007).

The limits of IEEE 519 are intended to:

- Assure that the electric utility can deliver relatively clean power to all of its customers.
- Assure that the electric utility can protect its electrical equipment from overheating, loss of life from excessive harmonic currents, and excessive voltage stress due to excessive harmonic voltage.
- To protect the voltage integrity of the utility grid system

Each table from IEEE 519 lists the limits for harmonic distortion at the point of common coupling (PCC) or metering point with the utility. The voltage distortion limits are 3% for individual harmonics and 5% THD.

Maximum harmonic current distortions limits that can be contained at the PCC as per IEEE-519 requirement (Standard, 2014)

Table 5.1: Maximum harmonic current distortions limits that can be contained at the PCC as per IEEE-519 requirement (Standard, 2014)

I_{SC}/I_L	<11	11≤h<17	17≤h<23	23≤h<35	35≤h≤50	%TDD
<20	4.0	2.0	1.5	0.6	0.3	5.0
20<50	7.0	3.5	2.5	1.0	0.5	8.0
50<100	10.0	4.5	4.0	1.5	0.7	12.0
100<1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

Table 5.2 from IEEE 519-2014 defines the voltage distortion limits that can be reflected back onto the utility distribution system.

Table 5.2: Voltage Distortion limits (Standard, 2014)

PCC Voltage	Individual Harmonic Magnitude (%) HD%	Total harmonic distortion THD%
≤69	3.0	5.0
69-161	1.5	2.5
>161	1.0	1.5

The harmonics in the electric power distribution system combine with the fundamental current (60 Hz) to create distortion. All of the harmonic frequency currents combine with the fundamental current to form the total harmonic distortion. The THD value is expressed as a percentage of the fundamental current and any THD values over 10% are significant enough for concern. Usually if the industrial user controls the overall combined current distortion according to Table 5.1, this will help meet the limitations set forth in the guidelines.

Therefore, IEEE standard 519-1992 is a guidance document for utilities and electric power users which specifies both the maximum distortion levels and recommends correction levels.

The harmonic distortion limit of 5% is proven to be the point where harmonics begin to have a detrimental effect on the electrical distribution system.

5.9.3. IEC 61000-3-2 (1995-03), IEC 61000-3-6, IEC 61000-4-7, & IEC 61000-4-30

The study of renewable generation technologies harmonic emission is an important issue when connecting these power plants to the national grid. Requirements set by power system operators have to be fulfilled and the harmonic emission is part of these requirements. For example, IEC 61400-21, IEC 61000-3-6, IEC 61000-4-7, and IEC 61000-4-30, are the standards that guide the limits, measurement procedures and assessment of power quality related to renewable technologies, in particular wind plants (Schwanz, 2016).

The IEC 61000-3-2 harmonic emissions standards which were first published as IEC 55-2 1982 and applied only to household appliances specified limits for harmonic current emissions applicable to electrical and electronic equipment having an input current up to and including 16A per phase, and intended to be connected to public low-voltage distribution systems (Schwanz, 2016).

The objective of IEC 61000-3-2 (harmonics) is to test the equipment under the conditions that will produce the maximum harmonic amplitudes under normal operating conditions for each harmonic component. For the purpose of this research the IEE 519-1992 harmonic limitation standards are used for the harmonic study analysis presented later in this Chapter (Schwanz, 2016).

5.9.4. CIGRE and CIRED (C4.24) Standard

The- International Council on Large Electric Systems-(in French: Conseil International des Grands Réseaux Électriques and abbreviated as (CIGRÉ) is a global organization in the field of high voltage electricity (Zavoda et al., 2016). It was founded in Paris, France in 1921. The scope of its activities includes the technical and economic aspects of the electrical grid, as well as the environmental and regulatory aspects (Zavoda et al., 2016).

CIGRE and CIRED is a joint working group of C4.24 for “Power Quality and EMC Issues associated with future electricity networks” (Bollen et al., 2015). The mandate Working group

C4.24 obtained its mandate in 2012 and it should, according to its scope, address the following issues:

- The study of new emissions from equipment connected to the low-voltage network which includes integration of renewable generation system to the LV grid network. The emissions (harmonic and unbalance) by new types of devices connected to the distribution network as production (DG) or consumption (load), especially devices with active power-electronics interface including equipment connected to low voltage and installations connected to higher voltage levels (Bollen et al., 2015).

- This might require the evaluation of new measurement techniques, including a closer look at the frequency response of existing instrument transformers and sensors. The main question is whether this will require new ways of considering power quality in the design (Bollen et al., 2015)?

- The positive and negative impact of new smart distribution technologies applications such as Volt &VAR control, as well as feeder reconfiguration on the power quality (voltage unbalance and harmonic flow) in the distribution system (Bollen et al., 2015). The question here is in terms of how these power quality issues at the distribution level may impact the transmission system.

5.10. Harmonic Mitigation Techniques

The emission of harmonics producing loads can increase the risks of tripping and possible damage to the electrical protection of the plants, essential loads, and the equipment connected to the grid. Due to this, studies are needed related to specific ways in which harmonic currents are expected to impact the electrical protection system in order to avoid unnecessary tripping and damage to the equipment. To mitigate or reduce the levels of distorted voltage, it is important to limit the flow of distorted current. Harmonic mitigation methods can be separated into two groups:

- Those that reduce harmonic voltage distortion
- Those that reduce harmonic current distortion

For example, when planning the installation of non-linear plant components the decision has to be made between designing the non-linear devices for **low levels of waveform distortion** and installing **harmonic compensation equipment** at the PCC (Cundeva et al., 2016).

The aim of harmonic mitigation and of all work on power quality is to avoid so-called “electromagnetic interference”, i.e. to make sure that all equipment functions as intended (Cundeva et al., 2016). Interference can be avoided in three distinctively different ways:

- Reducing the emission from devices;
- Increasing the immunity of devices against disturbances;
- Reducing the transfer of disturbances from emitting devices to susceptible devices

In general, the limit for harmonic voltage distortion is the role of the network operator to avoid that these limits are exceeded. The network operator in turn can place limits on the harmonic current emission from installations or from large equipment. The most typical and efficient harmonic mitigation techniques solutions are (Cundeva et al., 2016):

- Line reactors;
- Tuned harmonic filters;
- Low pass harmonic filters;
- Pulse rectifier solutions;
- Phase shifting transformers;
- Transformer Connections;
- Active harmonic filters;
- Hybrid harmonic filters.

In this Chapter, only passive harmonic filter are discussed. The study of power system harmonics in recent years has developed into complex literature that covers various study topics in the field of harmonics.

5.10.1.1. Passive Power Filter

Passive filters are commonly used for harmonic mitigation. In nature, passive filters absorb the harmonic currents in a low-impedance path. These are inductance, capacitance, and resistance elements configured and are tuned to control harmonic distortion. They are classified as shunt, series, hybrid, single- tuned, double- tuned, band-pass, damped and high-pass, as shown in Figure 5.9 (Tareen et al., 2017).

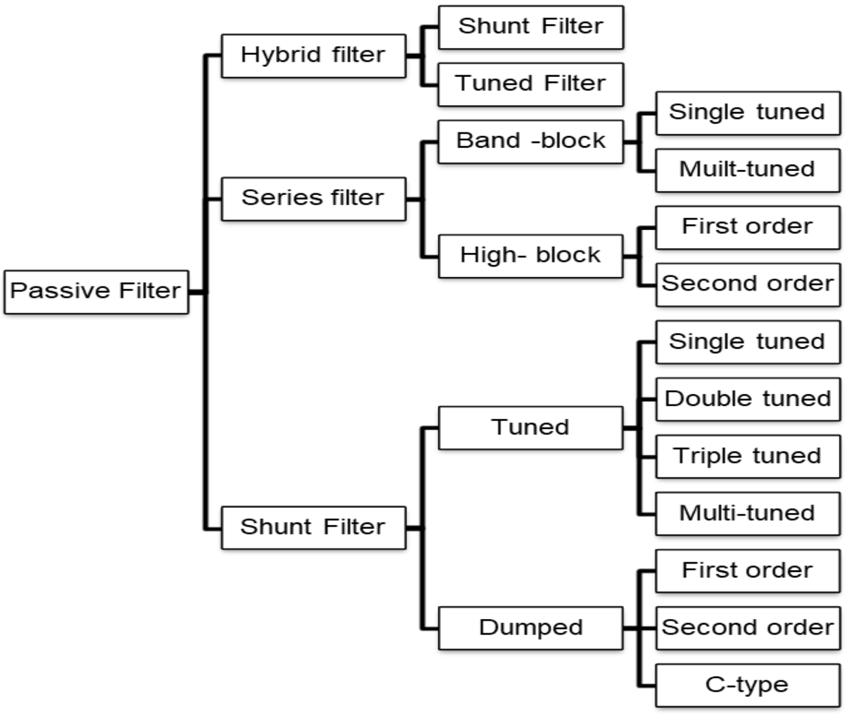


Figure 5.9: Classifications of Passive Harmonic Filters (Moe, 2014)

Shunt, series, and hybrid topology are briefly discussed in this chapter. The hybrid type is discussed in a specific section describing passive and active solutions. Passive filters are widely used to limit harmonic propagation, to improve power quality, to reduce harmonic distortion, and to provide reactive power compensation. These are designed for high-current and high-voltage applications (Moe, 2014).

5.10.2. Series Passive Filter

Series passive filters are passive filters that have a parallel LC filter in series with the supply and the load. The impedance from the non-linear loads is higher in the supply system and the harmonic currents flows in the local passive circuits do not enter the supply system. When multiple harmonic currents need to be eliminated, more filters need to be connected in series. In general they consist of various branches, which are respectively tuned to the predominant harmonics. Figure 5.11 presents various branches (Tareen et al., 2017):

- **Band -block**
    - Single-tuned

    - Multi-tuned
- **High- block**
    - First order
    - Second order

The inductance and capacitance are connected in parallel and are tuned to provide high impedance at a selected harmonic frequency. The high impedance then blocks the flow of harmonic currents at the tuned frequency only. At the fundamental frequency, the filter would be designed to yield low impedance, thereby allowing the fundamental current to follow with only minor additional impedance and losses (Tareen et al., 2017). Figure 5.10 shows a typical passive series filter arrangement.

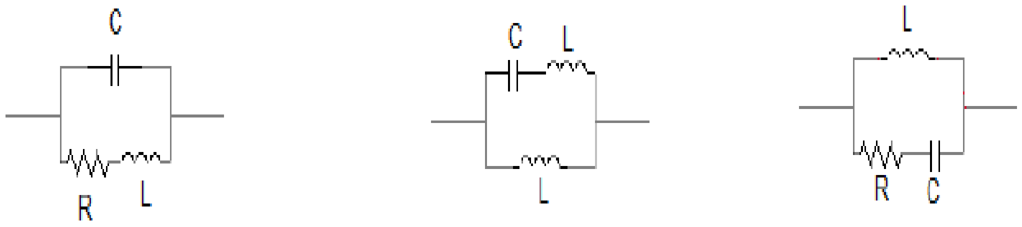


Figure 5.10: Series Passive Filters Configurations (Tareen et al., 2017)

5.10.3. Passive Shunt Filter

Passive shunt filters provide low-impedance paths for harmonic currents, so they do not enter the supply systems and are confined to flow in the local circuits consisting of lossless elements such as inductors and capacitors. These types of filters are therefore based on passive elements and offer good results for filtering out odd harmonics especially the 3rd, 5th and 7th (Sahithullah et al., 2016). Increasing the order of harmonics makes the filter more efficient but it reduces the ease in designing.

Since they are connected in shunt they are designed to carry only harmonic the current (Sher et al., 2013). As shown in Figure 5.11 and below, they can be divided into tuned (single, double, triple and multi-tuned) and damped (first, second, third order and C-type) filters (Sher et al., 2013).

- Tuned
    - Single tuned

    - Double tuned
    - Triple tuned
    - Multi-tuned
- Dumped
    - First order
    - Second order
    - C-type

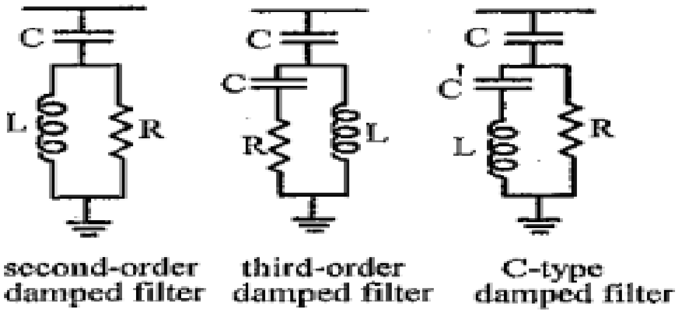


Figure 5.11: Different order types of passive shunt filters (Venkatesh et al., 2014)

Besides the harmonics reduction, passive filters can be used for the optimization of apparent power in a power network. Shunts filters are fixed and once installed they become part of the network and need to be redesigned to get different filtering frequencies. Some of the drawbacks of using shunt configurations are the resonance problems that may occur due to fixed compensation, however, compared to other types, the design cost is lower. Figure 5.11 above indicates typical shunt filter arrangements in practice. Passive shunt filters are also known as parallel filters and offset the harmonic distortions caused by the non-linear load. They work on the same principal of active filters but they are connected in parallel and they act as a current source in parallel with the load.

5.10.4. Hybrid filter

Hybrid filter combine the passive series and passive shunt filters for better solution of harmonic improvement. They are designed to overcome the drawback of shunt filter and series filter. Therefore hybrid harmonic filters are the combination of both active and passive power filters. They have the advantage of both active and passive filters. They contain the advantages of active filters and lack the disadvantages of passive and active filters

(Sahithullah et al., 2015). They use low cost high power passive filters to reduce the cost of power converters in active filters that is why they are now very much popular in industry (Sahithullah et al., 2015). For example, the hybrid filter combination in Figure 5.12 below has the advantage of both series connected APF i.e., elimination of voltage harmonics and that of a shunt connected APF of eliminating current harmonics.

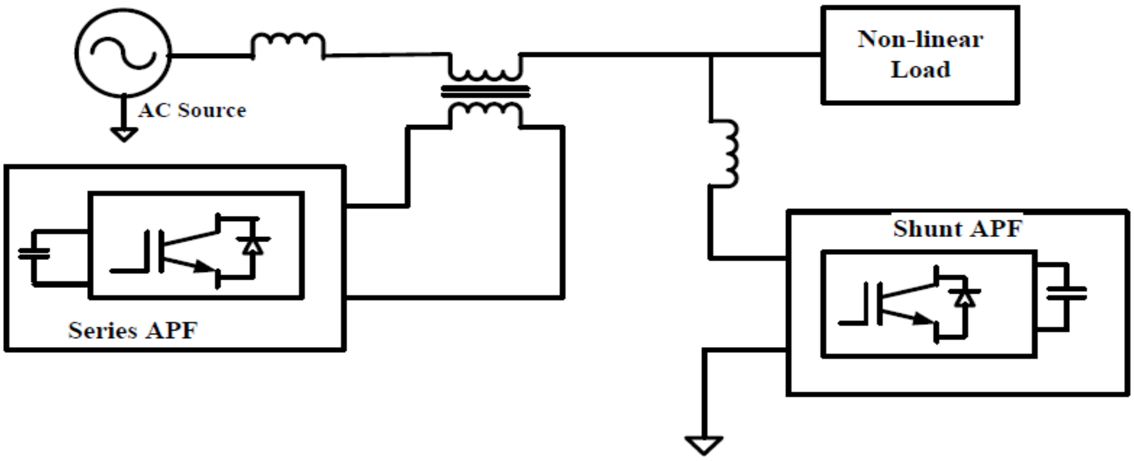


Figure 5.12: Shunt APF and Series APF Combination (Prasad et al., 2012)

There are different hybrid filters based on the circuit combination and arrangement. They are (Venkatesh et al., 2014):

- Shunt Active Power Filter and Series Active Power Filter (SAPF)
- Shunt Active Power Filter (SAPF) and Shunt Passive Filter
- Active Power Filter in series (APFS) with Shunt Passive Filter (SPF)
- Series Active Power Filter (SAPF) with Shunt Passive Filter

Hybrid filters are immune to the system impedance, thus harmonic compensation is done in an efficient manner and they do not produce the resonance with system impedance (Venkatesh et al., 2014). The above combination in Figure 5.14 finds its application in Flexible AC Transmission Systems. By controlling the amplitude of the voltage fundamental component across the coupling transformer, the power factor of the power distribution system can be adjusted (Sahithullah et al., 2016). However, the control of the load power factor imposes a higher voltage across the filter capacitor (Sahithullah et al., 2016). The control of APF is an additional thesis on its own that this Chapter will not discuss.

5.11. Harmonic Analysis

As mentioned in previous pages, distorted currents create heat in the power delivery equipment. Resolving the non-linear wave into its sinusoidal component is called harmonic analysis. Harmonic analysis estimates the heating effect due to the non-linear current flowing through circuit breakers, overhead transmission line conductors, and transformers.

Jean Baptiste Joseph Fourier (21 March 1768-16 May 1830) introduced the notion that even the most complex wave form could be understood and mathematically defined as a composed of a fundamental frequency sine wave with other sine waves in multiples of that frequency. These waves are known as harmonics (Chen et al., 2012). An example of a complex wave consisting of the fundamental frequency, 3rd harmonic, 5th harmonic, and resolved non-linear wave is illustrated in Figure 5.1 above.

Fourier introduced this complex mathematical equation to define harmonics content in the fundamental waveform (Chen et al., 2012):

Where;

- *f(t)* = is the time domain function
- h = is the harmonic number
- A_h=B_h=C_h=h is the amplitude of the hth harmonic component
- T= is the length of one cycle in seconds

$$f(t) = C_o + \sum_{h=1}^{\alpha} C_h(t) \qquad (5\text{-}2)$$

$$f(t) = C_o + \sum_{h=1}^{\infty} \{A_h \cos\left(h\omega t + \theta_h\right) + B_h \sin\left(h\omega t + \theta_h\right)\} \qquad (5\text{-}3)$$

Where average value: (5-4)

$$C_o = \frac{1}{T}\int_o^T f(t)dt,$$

Therefore, the RMS value of all the harmonic components including the fundamental (i.e. *h* = 1) combined is (Chen et al., 2012):

$$C_h = \sqrt{A_h^2 + B_h^2} \tag{5-5}$$

$$A_h = \frac{2}{T}\int_o^T f(t)\cos(h\omega t)dt \tag{5-6}$$

$$B_h = \frac{2}{T}\int_o^T f(t)\sin(h\omega t)dt \tag{5-7}$$

5.11.1. Total Harmonic Distortion

When all harmonic currents are added to the fundamental waveform, a complex waveform is formed. Fourier also introduced a complex mathematical equation (5-8) to define the relationship. The *THD* is used to define the effect of harmonics on the power system voltage or current. It can also be defined as the ratio of the square root of the sum of the square of the *Vrms* value for harmonic component to the *Vrms* value of the fundamental component (Xu &Liu., 2000).

$$THD_v\% = \frac{\sqrt{\sum_{h=2}^{\infty} V_h^2}}{V_1} \times 100 \tag{5-8}$$

The *THD* is expressed in percentage and is defined such that *h* refers to the (integer) harmonic order, *h* = 2, 3, 4 …, V_h is the amplitude of *h* order harmonic, and V_1 is the power frequency component at 60 Hz. THD is expressed as the percentage of the fundamental, the higher the percentage the higher the harmonic content or the percentage. If the waveform under discussion is current, then the THD definition is called current harmonic distortion (Abdel-Salam et al., 2011).

$$THD_I\% = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_1} \times 100 \tag{5-9}$$

where *h* refers to the index number of all harmonics and all non-standard frequency components, I_h is the amplitude of harmonics or non-standard frequency components, and I_1 is the power frequency component.

5.11.2. Voltage Harmonic distortion (VHD)

A voltage harmonic a distortion is distortion caused by harmonic current flowing through the system impedance. The utility power system has relatively low system impendence, and the VHD is very low. VHD on the distribution power system can be significant due to its relatively high system impedance. The primary concern in power system is voltage harmonics since voltage is common to all users, it must therefore be understood that the only way of limiting voltage harmonics is to minimize current harmonic (Xu & Liu., 2000). If current harmonics are under control, voltage harmonics are generally acceptable.

5.11.3. Current Harmonics distortion (CHD)

The asymmetrical power flows from PV systems, wind systems, and the use of power electronic converters inject harmonics into the power system network. This harmonic current flowing through the impedances of electric grid causes voltage distortion (Abdel-Salam et al., 2011). The RMS current contains both the fundamental and harmonics. Note that the value of current at each harmonic as well as that for the RMS current are the same at each measuring point, just as in a system containing only fundamental current (Mantilla.,2015).

Usually, using the harmonic ratio and the total harmonic distortion to measure the total size of the harmonic component and the distortion degree of the waveform is defined as follows: Percentage content of *h* order harmonic current:

$$HD = \frac{I_h}{I_1} \times 100\% \tag{5-10}$$

The term distortion RMS is used to denote the RMS value of harmonic current with the fundamental left out of the summation. The RMS current is basically the total effective load current. The nature of non-linear loads is to generate harmonics in the current waveform (Abdel-Salam et al., 2011). This distortion of the current waveform leads to distortion of the voltage waveform. Under these conditions, the voltage waveform is no longer proportional to the current.

CHAPTER 6: MODELLING AND ANALYSIS OF HARMONIC STABILITY AND VOLTAGE DISTORTION

6.1. Chapter Review

This chapter discusses network design in DigSILENT, filter design for power quality and harmonic mitigation, and the discussion of the simulation's result.

6.2. Network modelling and design

The primary aim of an electricity supply system is to meet the energy demands of its customer's. It must deliver power to all its customers, reaching every customer with a supply of sufficient strength to meet the peak load demand. The electricity supply must also be reliable, providing an uninterrupted flow of power to the customer.

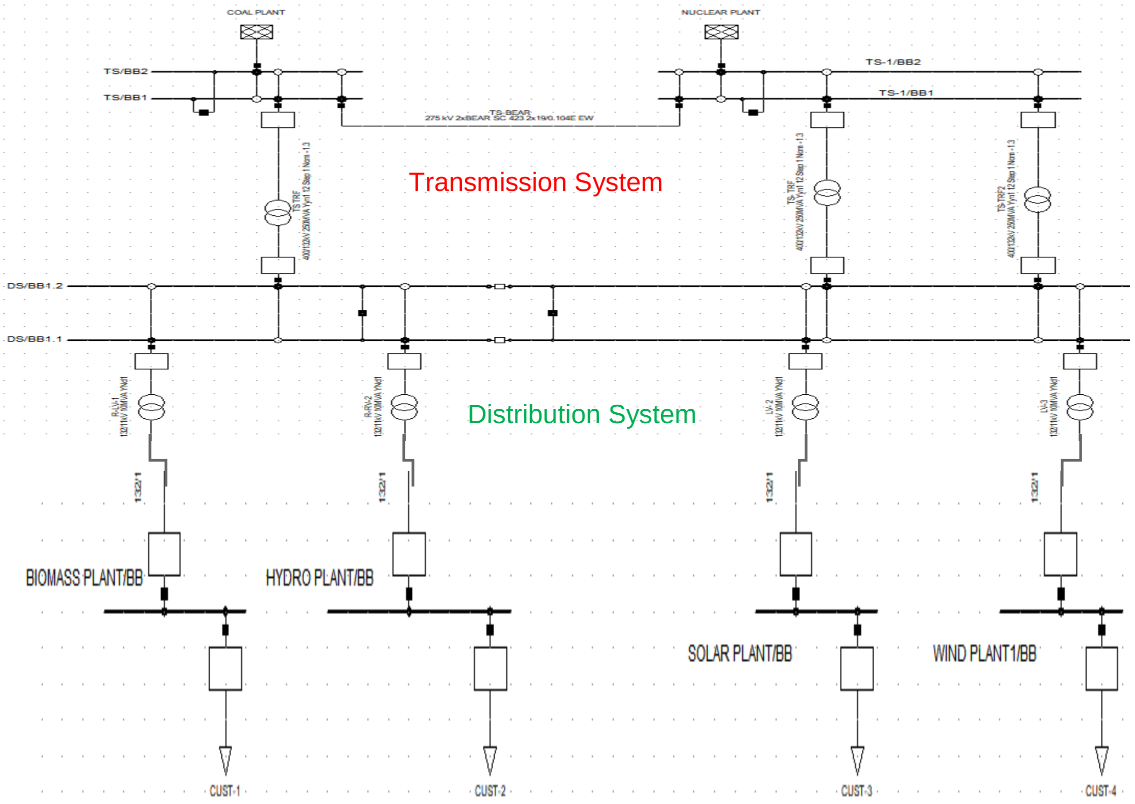


Figure 6.1: Illustrates of typical electrical distribution grid network of MV- LV

In Chapter 4, the detailed study on system stability is discussed as well as all power quality related issues to ensure the design of a reliable power system grid upon the integration of renewable generation technologies on the grid. Electricity networks, like the one shown in Figure 6.1 above, satisfy our daily energy transmission and distribution network. The increase in the integration of DG in the electrical power system network causes network complexity. This section presents a network design model for the analysis of renewable generation technology (RG) and its impact on the power quality of the grid or the impact of energy mix on the power system of the grid. The design of the network and simulation was conducted using DIgSILENT power factory software.

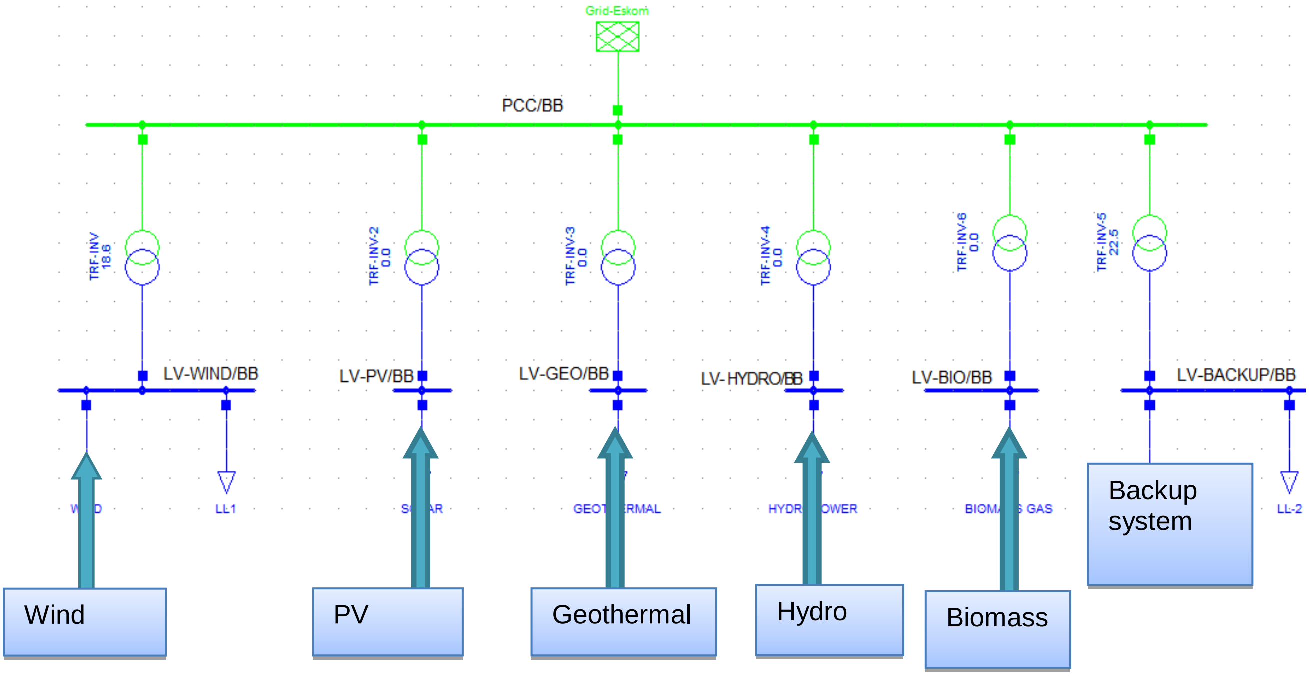


Figure 6.2: An example of a single line diagram of the electric grid model of different renewable generation technologies integrated with the grid.

A technique to evaluate this impact of renewable generation is achieved by the simulation of the network below Figure 6.4 under two case study conditions

- *Analysis of the electrical network behavior without the filter at PCC*
- *Analysis of the electrical network behavior with the filter at PCC*

The point of connection for the filter and harmonic source was chosen to be at the harmonic Load-Bus (see figure 6.4 below) because it was found that, although this is not the point-of-common-coupling (PCC) of the low voltage system, it was effective in the mitigation of harmonic voltage distortion and interventions to improve stability and achieve results. The inverter (voltage source) connected to the grid via another filter module provides both circuit isolation and the filtering operation to reduce harmonic disturbances and connected to the grid via the distribution transformer. Single-tuned harmonic filters in Figure 6.3 below, was implemented to remove sufficient harmonic current to achieve harmonic limits at PCC on grid.

The harmonic source is located at the busbar (PCC) in the power system network where non-linear loads interconnect. In this thesis, mitigation of power quality as well as the analysis of voltage distortion and harmonic distortion is analysed by using DIgSILENT power factory load flow analysis function.

6.3. Simulation design and harmonic analysis using DIgSILENT

The modeling concepts presented below has been incorporated into the DIgSILENT power system analysis package, starting with the basic power stage shown in Figure 6.2. The RES modelling is based on the voltage source inverter representing the source of harmonic injection at the PCC. The intention is that the model complies with the appropriate standard. On this basis, a filtering mechanism was implemented to limit the magnitudes of harmonic current (Ih) and ITHD by the recommended limits of harmonic emissions (Duffey & Stratford, 1989).

IEEE standard 519-1992 is the international standard set up to evaluated harmonic current and voltage. All the work done during harmonic analysis will comply with the standards below. According to the voltage harmonic limits in Table 5.1, the harmonics voltage distortion on power systems 69kV and below is limited to 5.0% total harmonic distortion (THD) with each individual harmonic distortion.

6.3.1. Filter design

A notch filter is an example of a single-tuned filter sees Figure 6.3 and it consists of a series RLC circuit. It is the most economical type and is commonly used for harmonic mitigation (Desmet & Baggini, 2003). This particular topology is tuned to suppress a single frequency and is designed based on three quantities:

- The harmonic current order that requires blocking
- The capacitive reactive power that it is going to provide
- The quality factor

The following formulae were used for the filter design calculation, labelled as equation 6.1- 6.6 (Desmet & Baggini, 2003): In summary, the values used to define the input parameters are:

- h Tuning point of the filter (Harmonic order)
- Q_C Reactive power of the filter (MVAr)
- Q Quality factor
- f System Frequency (f)
- V System voltage (kV)

$$P = 3 \times V_{phaseBus} \times I^{*}{}_{phase} \times Cos\varphi_1 \quad (6\text{-}1)$$

$$Q_C = P\left[\tan\varphi_1 - \tan\varphi_2\right] \quad (6\text{-}2)$$

$$X_C = \frac{V_{line}^2}{Q_C} \quad (6\text{-}3)$$

$$h_N = \sqrt{\frac{X_C}{X_L}} \quad (6\text{-}4)$$

$$X_L = \frac{X_C}{h_N^2} \quad (6\text{-}5)$$

$$X_N = \sqrt{X_L \times X_C} \quad (6\text{-}6)$$

Single-tuned filter. The voltage level and the fundamental frequency, which are given by the system, must also be considered during the design process.

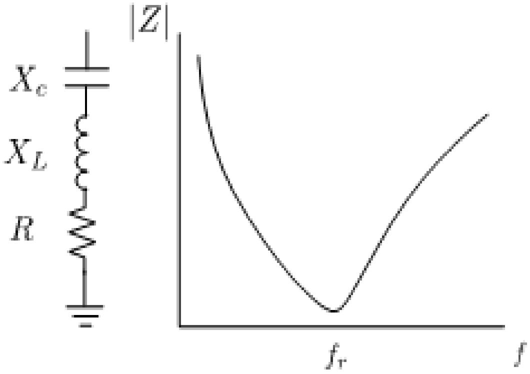


Figure 6.3: Circuit schematic and a typical impedance characteristic for the series tuned filter (Desmet & Baggini, 2003)

6.3.2. Network Parameters

The following data in Tables 6.1 to 6.5 were used to simulate a one line diagram, three phase four wire network using DIgSILENT.

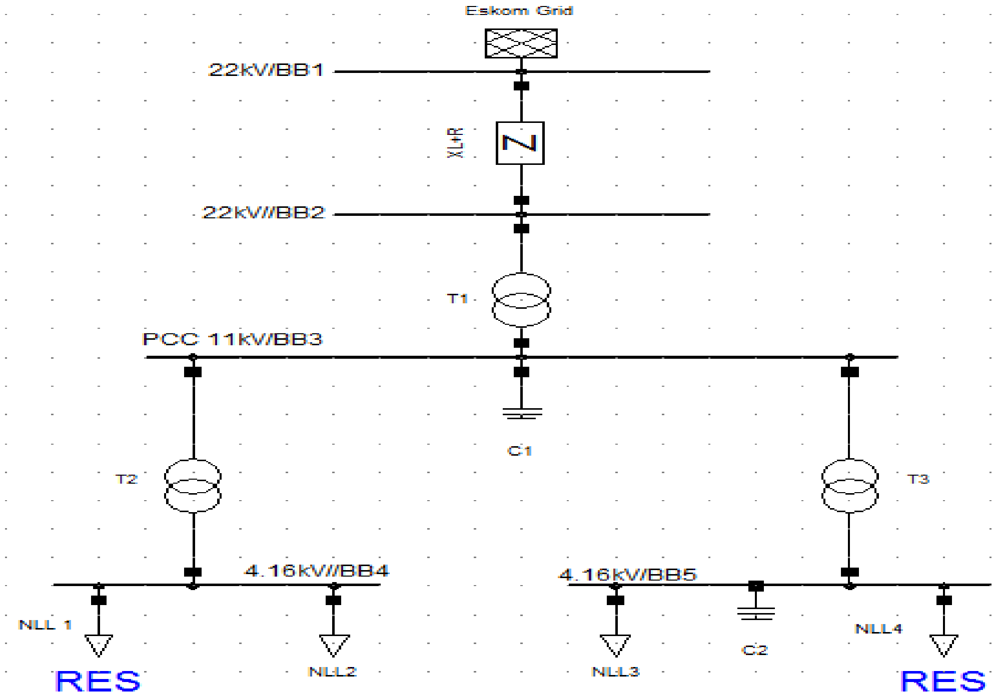


Figure 6.4: 22kV Single-line-diagram of load flow simulation

The network consists of a 22kV grid in-feed. The magnetizing losses for the transformers were ignored and the X/R constant for transformer T1 is kept constant. For effective harmonic mitigation C2 was connected on B5, C2 improved the voltage on B5 before connection of C1 on PCC. All loads (Grid-tied inverter) are simulated as non-linear or harmonic current source loads and two power factor correction capacitor banks, C1 and C2 are connected to Bus3 and Bus5 load buses for the harmonic analysis study.

Table 6.1: Sinusoidal voltage source parameter

Name	Bus	Type	KV	θ	MV
	1	Swing	22KV	0	-

Table 6.2: 4-winding transformers parameters

Name	Bus	MVA	KV (HS)	KV (LS)	Z (%)	X/R
T1	2-3	20	22	11	61.18	5
T2	3-4	0.8	11	4.16	4.99	7.5
T3	3-5	0.8	11	3.3	3.99	7

Table 6.3: Linear loads parameter

Name	Bus	MW	PF	R(Ω)	X(Ω)
LL1	3	0.04499	0.75	6.534	3.164
LL2	4	1.75	0.699	2.4044	4.164
LL3	5	75	0.8	0.673	0.687
LL4	6	2.48	0.78	3.337	2.854

Table 6.4: Non-linear load (RES)

Name	Bus	MW	PF	R(Ω)	X(Ω)
Inverter	4	1.35	0.9	6.534	3.16456

Table 6.5: Published harmonic spectrum

H/O	Harmonic Factor K_h(%)	SPA(°)
5th	17.25	-82.11
7th	13.85	110.51
11th	8.75	-65.22
13th	6.50	-35.75

6.3.3. Simulation Results

The first step in solving harmonics or power quality related problems is to perform an analysis to determine the specific needs of your electrical distribution system. To determine the capacitor and filter requirements, it is necessary to establish the impedance of the supply network and the value of each harmonic current. Capacitor and filter bank equipment are then specified under very detailed and stringent computer analysis to meet the quality desired needs (Mantilla, 2015). The following results were obtained using DIgSILENT power factory software used by power system operator for the analysis of electrical networks.

6.3.3.1. Analysis of the grid network behavior without the filter at PCC

Table 6.6. Load flow voltage results before filter design at PCC

Bus	V_{L-L} (KV)	Angle (°)
3	10.3923	-5.8585

Table 6.7: Load flow current results before filter design at PCC

Name	I (A)	Angle (°)
$I_{T1(HV)}$	90.811	-20.9394
$I_{T1(LV)}$	181.832	159.0605

Table 6.8. Harmonic current results before power factor correction

H/O	V_{L-L} (kV)	Angle (°)	%IEEE Limit	%HD	IEEE Comp.
Fundamental	10.3423	-5.8585	N/A	N/A	N/A
5	0.23681	-152.1089	3	3.22	exceed
7	0.3569	-3.2787	3	3.5977	exceed
11	0.13328	164.6479	3	0.1273	Fine
13	0.04578	161.89569	3	0.2144	Fine
%THD	N/A	N/A	5	7.1594	Fine

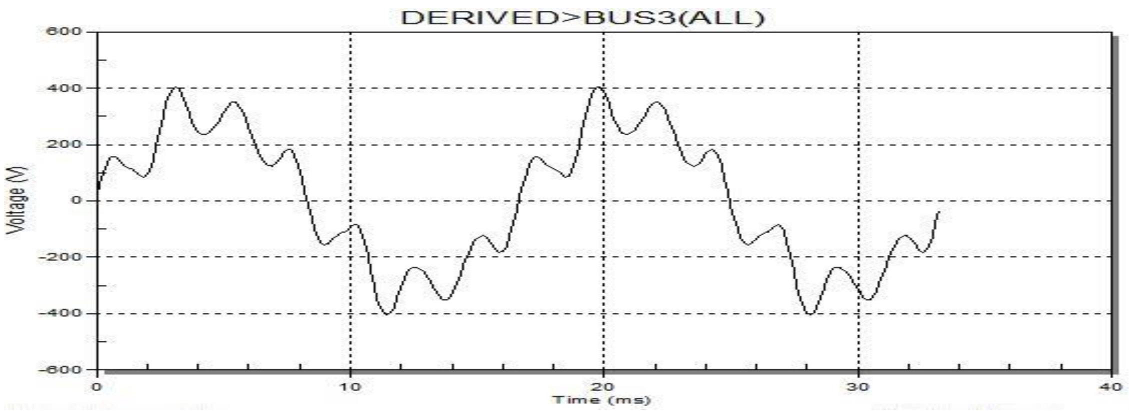


Figure 6.5: Non-linear voltage waveform at PCC without filters being installed

6.3.3.2. Analysis of the electrical network behavior with filter at PCC

For this case study a series tuned filter was introduced in the network. The impedance of the filter at the tuned harmonic frequency is purely resistive due to equal capacitive and inductive reactance.

Table 6.9. Load flow voltage results after filter design

Bus	V_{L-L} (KV)	Angle (°)
3	10.802	-6.5444

Table 6.10. Load flow current results after filter design

Name	I (A)	Angle (°)
$I_{T1(HV)}$	90.991	-3.7387
$I_{T1(LV)}$	**181.932**	**176.2612**

Table 6.11. Harmonic current distortion results after filter design

H/O	I (A)	Angle (°)	%IEEE Limit	%HD	IEEE Comp.
Fundamental	186.55	153.71	N/A	N/A	N/A
5	4.316	64.616	4	2.313	Fine
7	4.86	93.959	4	2.605	Fine
1 1	0.278	-74.730	2	0.149	Fine
1 3	0.167	9.491	2	0.089	Fine

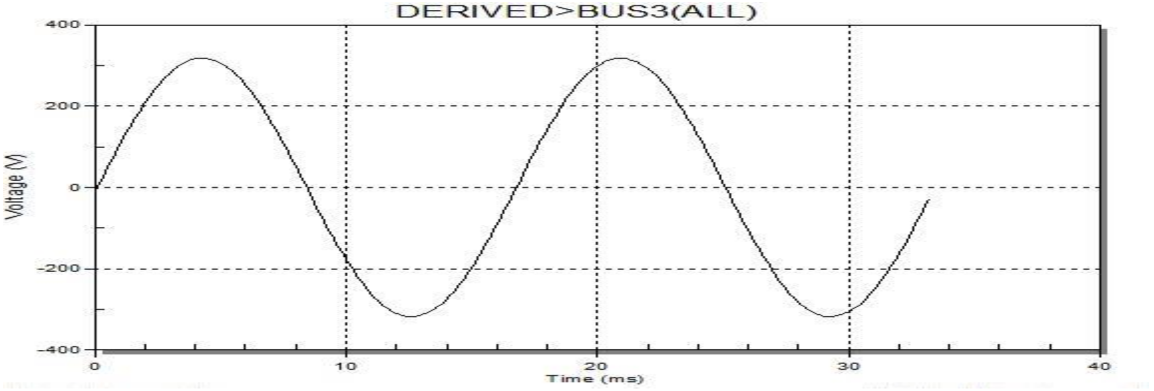


Figure 6.6: Voltage waveform at PCC with filter being installed

6.3.4. Final Analysis of Simulation Results

The results in Tables 6.6-6.8 and Figure 6.4 show the voltage load flow results before the implementation of the filter at the PCC and Tables 6.9- 6.11 and Figure 6.5 show the simulation results after the filter implementation at the PCC. Table 6.11 also shows a Total Voltage Distortion (THDV) level of 69.389% at Bus3 and a total current distortion surpassed to the 5% limit. The total harmonic voltage distortion at bus 3 surpassed the 5% limit of the IEEE. The analysis of results in Table 6.11 shows that the 7th harmonic is the most offender harmonic in the network at the point of common coupling (PCC). This was the major reason for the filter design. Both distortion of the voltage and current were above the limits set by IEEE Std. 519, which allows a distortion of up to 5% or less (Duffey & Stratford, 1989).

The generated harmonics due to the grid-tied inverter resulted in the voltage distortion levels at the PCC which exceeded the IEEE standard 519-1992 voltage and current distortion limits. The tuned filter was designed effectively to reduce the voltage distortion levels at the PCC below the IEEE standard 519-1992 voltage distortion limits. This effectively diminished the harmonic level to the IEEE required limits and established **power system stability** by restricting the voltage harmonics distortion. Filter installation demonstrated the capability of voltage restoration to normal line voltage at the PCC, stabilizing the system to the required distortion. Most of the voltage and current distortion is caused by the 7th harmonic current injected by the non-linear load (grid-tied inverter) as can be seen from Table 6.11.

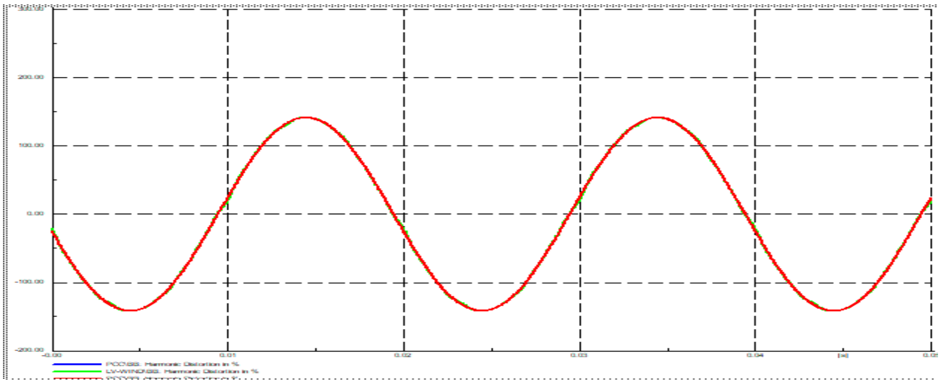


Figure 6.7: Voltage waveform at harmonic order 150Hz, 350Hz and 550Hz

The voltage harmonic distortion after the installation of the filter is so insignificant that 5th, 7th and 11th harmonic order wave forms are identical. Figure 6.6 above illustrates a simulation of harmonic and the effectiveness of filter implantation at the PCC. The filter design introduced voltage stability at the PCC and improved the load current. Figure 6.7 is the result of a high harmonic order at PC before the filter installation.

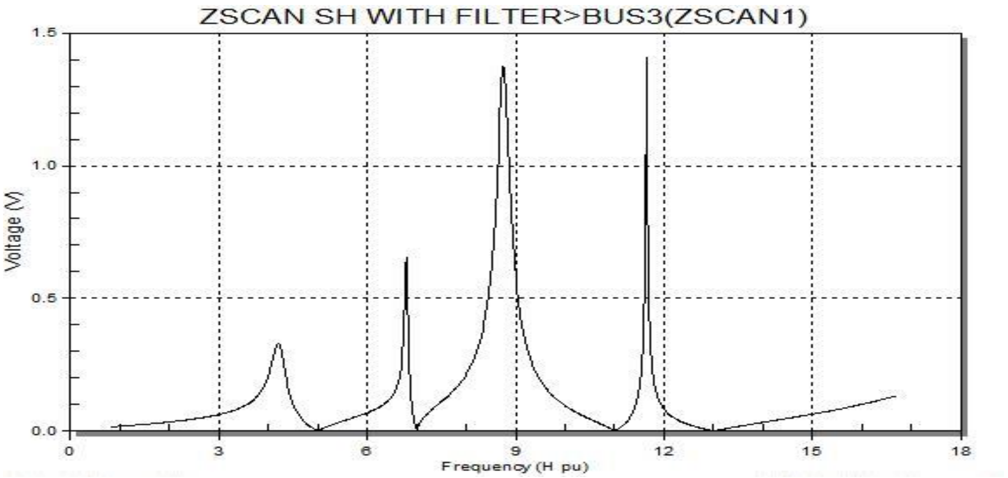


Figure 6.8: Harmonic impedance scan at PCC

Network resonances have been identified in systems during the simulation. Issues due to the integration of renewable energy production are highlighted in that the inverter introduces harmonic currents and on the other hand, this inverter could induce resonances in the network impedance. For effective results, it was very necessary to connect harmonic filters at the point of harmonic producing device. The effectiveness of the filter implementation on the scan impedance is demonstrated in Figure 6.9 below.

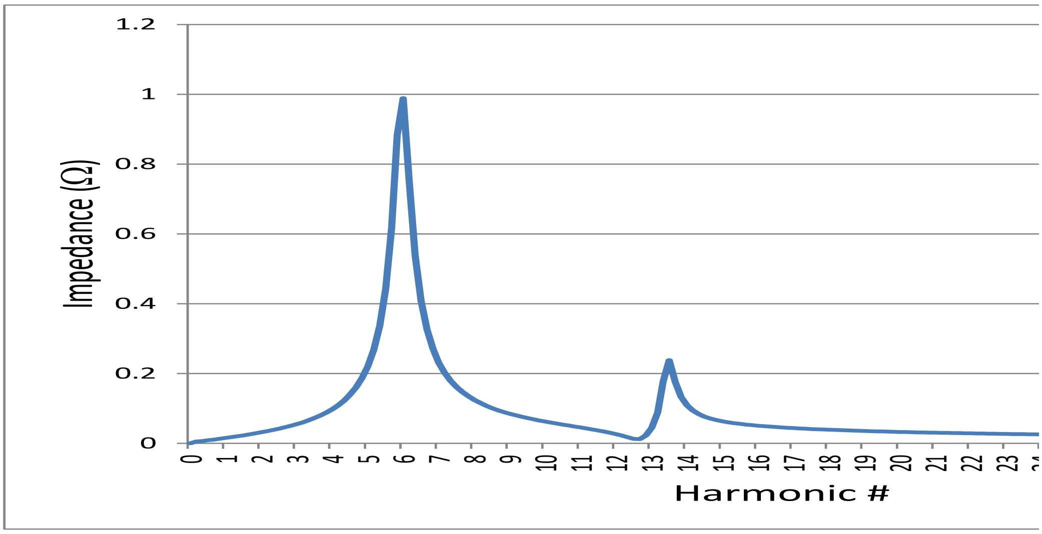


Figure 6.9: The harmonic filter designed shifted the resonance point to less harmful frequencies

The impedance variations are similar to a series and parallel resonating circuit. Figure 6.3 shows the calculated impedance. Figure 6.8 shows that, the harmonic filter designed shifted the resonance point to less harmful frequencies. Since the filter passive used is a series circuit, the current flowing through the filter will be the same current at the PCC where harmonic mitigation takes place.

CHAPTER 7: CONCLUSION AND RECOMMENDATION

7.1. Chapter Review

This chapter discusses conclusion and suggested recommendations

Conclusion

After the analysis of the above harmonic current model for renewable generation technology, the negative influence on the power quality of the grid electric is apparent, however, this is within limits and controllable measure. Eliminating completely from the system can be an impossible task, but putting mitigation measure in place can improve power quality while simultaneously bringing certain economic benefits. This research was carried out to mitigate the impact of grid-connected renewable generation technologies on the power quality of the grid and harmonic stability. In conclusion, it is evident that electrical power quality reliability and the normal operation of electrical equipment rely heavily upon a clean free distortion from the power operator.

Electrical engineers wishing to reduce the level of power quality related issues, particularly harmonic pollution on a power distribution network where harmonic generating loads are connected; have to understand harmonics, their negative effect, and what causes them. With this understanding we would be able to mitigate them.

The main aim of integrating renewable generation energy on the grid is to improve the operation of the transmission and distribution systems and generate active power.

This thesis has shown that the increase of renewable generation technologies have negative impact on the power quality of grid. However, several mitigation techniques have been discussed in Chapter 4 and 5 to improve the voltage at the PCC.

Lastly, simulations done in DIgSILENT have shown that distorted current waveform injected into the grid by renewable generation technologies can influence power quality negatively by causing voltage instability and voltage distortion.

The analysis and design was done in accordance with the IEEE-519 standards. The result obtained showed that the harmonic distortion limits at the PCC exceeded when no filter is connected. Thus, a filter was recommended as a remedial action to mitigate the harmonic load current. The non-linear harmonic current source design model was observed to significantly contribute negatively to the power quality of the grid.

Another important observation was that the voltage harmonic is caused by current harmonic which distorts the voltage. It is evident that integration of renewable generation plants in the DS and TS requires more impactful studies on the power quality of the grid.

Recommendation

On recommendations, to enhance control measures of power quality of the grid, adequate evaluation of grid-tied renewable system has to be introduced. The purpose of adequate evaluation of renewable generation technologies is to monitor their accumulation connection on the grid to effectively address power quality concerns through a controlled system.

For example, all grid-tied systems and mini-grids system have to be registered through a utility center that registers and monitors all small scale embedded generations wishing to connect on the grid.

Lastly, the field trip with the Germany expert to two major solar plants in the Northern Cape (DeAar and Droogfontein Solar plants) for PV inspection, revealed concerning technical issues which influence the power quality generated and of the grid. Several faults and factor can potentially lead to early degradation of the solar module.

The effect of these factors can results in distribution and transmission losses which influence the power quality of the grid. The factors are categorized as follow;

External factors on the modules;

- Chipped solar module
- Scratched solar module
- Bird poo which cause shedding on the modules

Manufacturer defects include;

- Delamination of the solar panel cell
- Discoloring of the solar module

- Hot spots
- Snail trial on panel

The above mentioned factors contributed to the degradation and consequently failure of PV models. PV modules are designed with warranty of 20years but based on the assessment carried out, 10% of the inspected module had developed the above concerns before 5years of the warranty. This concern raised up the following question;

1. The warranty of the solar panel is 25years; will the module supplier be around in next 25year when the problems are encountered?
2. IEC is the body that regulates the suppliers of PV modules, does the supplier reply on IEC test? Likewise who qualifies the supplier how they ensure long- term durability test is enforced by the supplier?

The recommendations for PV utility operator is to ensure quality control mechanisms are developed on site to safeguard the best grade modules are installed. The finding of the inspection of the solar PV plants found no quality control measure to ensure that the above factors and fault are prevented to ensure stable supply and reliable power grid.

References

Ackermann, T. and Knyazkin, V., 2002, October. Interaction between distributed generation and the distribution network: operation aspects. In *Transmission and Distribution Conference and Exhibition 2002: Asia Pacific. IEEE/PES* Vol. 2, pp. 1357-1362, IEEE.

Ackermann, T., Andersson, G. and Söder, L., 2001. Distributed generation: a definition. *Electric power systems research*, *57*(3), pp.195-204.

Adefarati, T. and Bansal, R.C., 2016. Integration of renewable distributed generators into the distribution system: a review. *IET Renewable Power Generation*, *10*(7), pp.873-884.

Adil, A.M. and Ko, Y., 2016. Socio-technical evolution of Decentralized Energy Systems: A critical review and implications for urban planning and policy. *Renewable and Sustainable Energy Reviews*, *57*, pp.1025-1037.

Africa, G., 2016. Solar Maps. *Stellenbosch, South Africa. [OnlineGeosolar model]. Available: http://geosun. co. za/solar-maps/.*

Ahmadi, H., Ellis, A. and Marti, J.R., 2016, May. Voltage management challenges in feeders with high penetration of distributed generation. In *Electrical and Computer Engineering (CCECE), 2016 IEEE Canadian Conference on* (pp. 1-6). IEEE.

Ainah, P.K. and Folly, K.A., 2015. Development of Micro-Grid in Sub-Saharan Africa: An Overview. International Review of Electrical Engineering (I.R.E.E.), Volume. 10, N. 5 pp.827- 6660.

Aïssa, M.S.B., Jebli, M.B. and Youssef, S.B., 2014. Output, renewable energy consumption and trade in Africa. *Energy Policy*, *66*, pp.11-18.

Aliyu, A.K., Modu, B. and Tan, C.W., 2017. A review of renewable energy development in Africa: A focus in South Africa, Egypt and Nigeria. *Renewable and Sustainable Energy Reviews*.

Amusa, H., Amusa, K. and Mabugu, R., 2009. Aggregate demand for electricity in South Africa: An analysis using the bounds testing approach to cointegration. *Energy policy*, *37*(10), pp.4167-4175.

Angelopoulos, K., 2004. Integration of distributed generation in low voltage networks: Power quality and economics. *University of Strathclyde in Glasgow Departement of Mechanical Engineering Glasgow*.

Anto, E.K., Frimpong, E.A. and Okyere, P.Y., Impact Assessment of Increasing Solar PV Penetrations on Voltage and Total Harmonic Distortion of a Distribution Network.

Anyamba, A. and Tucker, C.J., 2005. Analysis of Sahelian vegetation dynamics using NOAA-AVHRR NDVI data from 1981–2003. *Journal of Arid Environments, 63*(3), pp.596-614.

Archer, C.L., Simão, H.P., Kempton, W., Powell, W.B. and Dvorak, M.J., 2017. The challenge of integrating offshore wind power in the US electric grid. Part I: Wind forecast error. *Renewable Energy*, *103*, pp.346-360.Barbier, E., 2002. Geothermal energy technology and current status: an overview. *Renewable and Sustainable Energy Reviews, 6*(1), pp.3-65.

Arghandeh, R., Onen, A., Jung, J., Cheng, D., Broadwater, R.P. and Centeno, V., 2014. Phasor-based assessment for harmonic sources in distribution networks. *Electric Power Systems Research*, *116*, pp.94-105.

Arias-Guzman, S., Ruiz-Guzman, O., Garcia-Arias, L., Jaramillo-Gonzales, M., Cardona-Orozco, P., Ustariz-Farfan, A., Cano-Plata, E. and Salazar-Jimenez, A., 2016. Analysis of voltage sag severity case study in an industrial circuit. *IEEE Transactions on Industry Applications*.

Barbier, E., 2002. Geothermal energy technology and current status: an overview. *Renewable and Sustainable Energy Reviews*, *6*(1), pp.3-65.

Bertani, R., 2012. Geothermal power generation in the world 2005–2010 update report. *Geothermics*, *41*, pp.1-29.

Blaabjerg, F. and Ionel, D.M., 2015. Renewable energy devices and systems–state-of-the-art technology, research and development, challenges and future trends. *Electric Power Components and Systems*, *43*(12), pp.1319-1328.

Bollen, M.H. and Gu, I., 2006. *Signal processing of power quality disturbances* (Vol. 30).

Bollen, M.H., 2000. *Understanding power quality problems* (Vol. 3). New York: IEEE press.

Braun, M. and Strauss, P., 2008. A review on aggregation approaches of controllable distributed energy units in electrical power systems. *International Journal of Distributed Energy Resources*, *4*(4), pp.297-319.

Brent, A.C., 2013. *Development of a Renewable Energy Power Supply Outlook 2015 for the Republic of South Africa* (Doctoral dissertation, University of Stellenbosch).

Burton, J.E.S.S.E. and Winkler, H.A.R.A.L.D., 2014. South Africa’s planned coal infrastructure expansion: drivers, dynamics and impacts on greenhouse gas emissions. *Energy Research Centre, University of Cape Town. Available: http://www. erc. uct. ac. za/Research/publications/14-Burton-Winkler-Coal_expansion. pdf*.

Calvin, K., Pachauri, S., De Cian, E. and Mouratiadou, I., 2016. The effect of African growth on future global energy, emissions, and regional development. *Climatic Change*, *136*(1), pp.109-125.

Carrasco, J.M., Franquelo, L.G., Bialasiewicz, J.T., Galván, E., PortilloGuisado, R.C., Prats, M.M., León, J.I. and Moreno-Alfonso, N., 2006. Power-electronic systems for the grid integration of renewable energy sources: A survey. *IEEE Transactions on industrial electronics*, *53*(4), pp.1002-1016

Chandorkar, M., Guerrero, J.M., Lee, T.L. and Loh, P.C., 2013. Advanced control architectures for intelligent microgrids—Part I: Decentralized and hierarchical control. *IEEE Transactions on Industrial Electronics*, *60*(4), pp.1254-1262.

Chauhan, A. and Saini, R.P., 2014. A review on integrated renewable energy system based power generation for stand-alone applications: configurations, storage options, sizing methodologies and control. *Renewable and Sustainable Energy Reviews*, *38, pp.99-120.*

Chauhan, A. and Saini, R.P., 2016. Techno-economic feasibility study on Integrated Renewable Energy System for an isolated community of India. *Renewable and Sustainable Energy Reviews*, *59*, pp.388-405.

Chen, J., Song, S. and Wang, Z., 2006, October. Analysis and implement of thyristor-based STATCOM. In *2006 International Conference on Power System Technology* (pp. 1-5). IEEE.

Chevallier, R., 2010. South Africa’s dilemma: Reconciling energy-climate challenges with global climate responsibilities. *Climate Change & Trade: The Challenges for Southern Africa. Auckland Park: Fanele*.

Chevallier, R., 2012. Political barriers to climate change adaptation implementation in SADC. *Overcoming Barriers to Climate Change Adaptation Implementation in Southern Africa*, pp.1-19.

Claire, G., 2016. “Energy pick n’ mix: are hybrid systems the next big thing?”, *CSIRO blog*, https://blog.csiro.au/energy/, 8th , September, 2016.

Cochran, J., Bird, L., Heeter, J. and Arent, D.J., 2012. *Integrating Variable Renewable Energy in Electric Power Markets. Best Practices from International Experience* (No. NREL/TP--6A00-53732). National Renewable Energy Lab.(NREL), Golden, CO (United States).

Cossent, R., Gómez, T. and Frías, P., 2009. Towards a future with large penetration of distributed generation: Is the current regulation of electricity distribution ready? Regulatory recommendations under a European perspective. *Energy Policy*, *37*(3), pp.1145-1155.

Cuamba, B., Cipriano, A. and Jaime Turatsinze, R., 2013. Investment incentives for renewable energy in Southern Africa: the case of Mozambique. *IISD Trade Knowledge Network (TKN). See: https://www. iisd. org/tkn/research/pub. aspx*.

Deepa, S. and Rajapandian, S., 2010. Voltage Sag Mitigation Using Dynamic Voltage Restorer System. *International Journal of Computer and Electrical Engineering*, *2*(5), p.821.

Demirbas, A., 2005. Potential applications of renewable energy sources, biomass combustion problems in boiler power systems and combustion related environmental issues. *Progress in energy and combustion science*, *31*(2), pp.171-192.

Desmet, J. and Baggini, A., 2003. Harmonics–neutral sizing in harmonic rich installations. *Leonardo Power Quality Application Guide–Part 3.5*, *1*.

Duffey, C.K. and Stratford, R.P., 1989. Update of harmonic standard IEEE-519: IEEE recommended practices and requirements for harmonic control in electric power systems. *IEEE Transactions on Industry Applications*, *25*(6), pp.1025-1034.

Dugan, R.C., McGranaghan, M.F. and Beaty, H.W., 1996. Electrical power systems quality. *New York, NY: McGraw-Hill,| c1996*.

Duku, M.H., Gu, S. and Hagan, E.B., 2011. A comprehensive review of biomass resources and biofuels potential in Ghana. *Renewable and sustainable energy reviews*, *15*(1), pp.404-415.

Dzobo, O., Gaunt, T. and Herman, R., 2012. Reliability worth assessment of electricity consumers: a South African case study. *Journal of Energy in Southern Africa*, *23*(3), pp.31-39.

Eberhard, A. and Gratwick, K.N., 2011. IPPs in Sub-Saharan Africa: determinants of success. *Energy policy*, *39*(9), pp.5541-5549.

Eberhard, A., 2015. Powering Africa: Facing the Financing and Reform Challenges. *Revue d'économie du développement*, *23*(HS), pp.39-48.

Eberhard, A., Gratwick, K., Morella, E. and Antmann, P., 2016. *Independent power projects in Sub-Saharan Africa: Lessons from five key countries*. World Bank Publications.

Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Seyboth, K., Kadner, S., Zwickel, T., Eickemeier, P., Hansen, G., Schlömer, S., von Stechow, C. and Matschoss, P. eds., 2011. *Renewable energy sources and climate change mitigation: Special report of the intergovernmental panel on climate change*. Cambridge University Press.

Ellabban, O., Abu-Rub, H. and Blaabjerg, F., 2014. Renewable energy resources: Current status, future prospects and their enabling technology. *Renewable and Sustainable Energy Reviews*, *39*, pp.748-764.

Emanuel, A., Janczak, J., Pileggi, D., Gulachenski, E., Root, C., Breen, M., & Gentile, T. (1994). Voltage distortion in distribution feeders with non-linear loads.IEEE Transactions on Power Delivery. 9, 79-87.

Emanuel, A.E., 2004. Summary of IEEE standard 1459: definitions for the measurement of electric power quantities under sinusoidal, nonsinusoidal, balanced, or unbalanced conditions. *IEEE transactions on industry applications*, *40*(3), pp.869-876.

Enslin, J.H. and Heskes, P.J., 2004. Harmonic interaction between a large number of distributed power inverters and the distribution network. *IEEE transactions on power electronics*, *19*(6), pp.1586-1593.

Fadaeenejad, M., Saberian, A.M., Fadaee, M., Radzi, M.A.M., Hizam, H. and AbKadir, M.Z.A., 2014. The present and future of smart power grid in developing countries. *Renewable and Sustainable Energy Reviews*, *29*, pp.828-834.

Fagan, E., Grimes, S., McArdle, J., Smith, P. and Stronge, M., 2005, June. Grid code provisions for wind generators in Ireland. In *Power Engineering Society General Meeting, 2005. IEEE* (pp. 1241-1247).

Farghal, S.A. and Aziz, M.A., 1988. Generation expansion planning including the renewable energy sources. *IEEE transactions on power systems*, *3*(3), pp.816-822.

Farhoodnea, M., Mohamed, A., Shareef, H. and Zayandehroodi, H., 2012. An enhanced method for contribution assessment of utility and customer harmonic distortions in radial and weakly meshed distribution systems. *International Journal of Electrical Power & Energy Systems*, *43*(1), pp.222-229.

Favalli, M., Chirico, G.D., Papale, P., Pareschi, M.T. and Boschi, E., 2009. Lava flow hazard at Nyiragongo volcano, DRC. *Bulletin of Volcanology*, *71*(4), pp.363-374.

Favuzza, S., Graditi, G.I.O.R.G.I.O., Spertino, F. and Vitale, G., 2004, December. Comparison of power quality impact of different photovoltaic inverters: the viewpoint of the grid. In *Industrial Technology, 2004. IEEE ICIT'04. 2004 IEEE International Conference on* (Vol. 1, pp. 542-547). IEEE.

Field, C.B., Campbell, J.E. and Lobell, D.B., 2008. Biomass energy: the scale of the potential resource. *Trends in ecology & evolution*, *23*(2), pp.65-72.

Fitzer, C., Barnes, M., Green, P., Voltage sag detection technique for a dynamic voltage restorer.

Fluri, T.P., 2009. The potential of concentrating solar power in South Africa. *Energy Policy*, *37*(12), pp.5075-5080.

Foley, A., & Olabi, A. G. 2017. Renewable energy technology developments, trends and policy implications that can underpin the drive for global climate change.

Fritz, W.L.O., 2012, August. Renewable energy feed in tariffs, REBID, SASGI and the smart grid. In *Industrial and Commercial Use of Energy Conference (ICUE), 2012 Proceedings of the 9th* (pp. 1-5). IEEE.

Gabriel, C.A., 2016. What is challenging renewable energy entrepreneurs in developing countries? *Renewable and Sustainable Energy Reviews*, *64*, pp.362-371.

Gautam, D., Vittal, V. and Harbour, T., 2009. Impact of increased penetration of DFIG-based wind turbine generators on transient and small signal stability of power systems. *IEEE Transactions on Power Systems*, *24*(3), pp.1426-1434.

Global Energy Network Institute (GENI), 2000, wind energy potential in Africa, http://www.geni.org/globalenergy/library/renewable-energy-resources/world/africa/wind-africa/index.shtml, California, USA.

Golkar, M.A., 2002, July. Power Quality in Electric Networks: Monitoring and Standards. In *the second world engineering conference* (pp. 137-141).

Golovanov, N., Lazaroiu, G.C., Roscia, M. and Zaninelli, D., 2013. Power quality assessment in small scale renewable energy sources supplying distribution systems. *Energies*, *6*(2), pp.634-645.

Gratwick, K.N. and Eberhard, A., 2008. An analysis of independent power projects in Africa: understanding development and investment outcomes. *Development Policy Review*, *26*(3), pp.309-338.

Gratwick, K.N., 2007. *Independent power projects in Africa: balancing development and investment outcomes* (Doctoral dissertation, University of Cape Town).

Grunau, S., Reese, J., Jessen, L. and Fuchs, F.W., 2013, November. Aspects of grid integration of renewable energy sources in weak power systems. In *Security in Critical Infrastructures Today, Proceedings of International ETG-Congress 2013; Symposium 1:* (pp. 1-7). VDE.

Guerine, A., El Hami, A., Walha, L., Fakhfakh, T. and Haddar, M., 2017. Dynamic response of wind turbine gear system with uncertain-but-bounded parameters using interval analysis method. *Renewable Energy*.

Gungor, V.C., Sahin, D., Kocak, T., Ergut, S., Buccella, C., Cecati, C. and Hancke, G.P., 2013. A survey on smart grid potential applications and communication requirements. *IEEE Transactions on Industrial Informatics*, *9*(1), pp.28-42.

Hand, M.M., Baldwin, S., Demeo, E., Reilly, J.M., Mai, T., Arent, D., Porro, G., Meshek, M. and Sandor, D., 2012. *Renewable Electricity Futures Study. Volume 1. Exploration of High-Penetration Renewable Electricity Futures* (No. NREL/TP--6A20-52409-1). National Renewable Energy Lab.(NREL), Golden, CO (United States).

Harris, H.C. and Krueger, D.L.W., 2017. Implementing energy efficiency policy in housing in South Africa. *Journal of Energy in Southern Africa*, *16*(3), pp.38-44.

Heydt, GT 2005, Electric Power Quality. in *The Electrical Engineering Handbook.* Elsevier Inc., pp. 805-810. DOI: 10.1016/B978-012170960-0/50059-1.

Hoogwijk, M., Faaij, A., Eickhout, B., de Vries, B. and Turkenburg, W., 2005. Potential of biomass energy out to 2100, for four IPCC SRES land-use scenarios. *Biomass and Bioenergy*, *29*(4), pp.225-257.

Hou, G., Sun, H., Jiang, Z., Pan, Z., Wang, Y., Zhang, X., Zhao, Y. and Yao, Q., 2016. Life cycle assessment of grid-connected photovoltaic power generation from crystalline silicon solar modules in China. *Applied Energy*, *164*, pp.882-890.

Huda, A.S.N. and Zivanovic, R., 2017. Large-scale integration of distributed generation into distribution networks: Study objectives, review of models and computational tools. *Renewable and Sustainable Energy Reviews*, *76*, pp.974-988

Hulme, M., 1992. Rainfall changes in Africa: 1931–1960 to 1961–1990. *International Journal of Climatology*, *12*(7), pp.685-699.

Hung, D.Q., Shah, M.R. and Mithulananthan, N., 2016. Technical challenges, security and risk in grid integration of renewable energy. In *Smart Power Systems and Renewable Energy System Integration* (pp. 99-118). Springer International Publishing.

Intergovernmental Panel on Climate Change, 2015. *Climate change 2014: mitigation of climate change* (Vol. 3). Cambridge University Press.

Jackson, T.M., Walker, G.R. and Mithulananthan, N., 2014, September. Integrating PV systems into distribution networks with battery energy storage systems. In *Power Engineering Conference (AUPEC), 2014 Australasian Universities* (pp. 1-7). IEEE.

Jacobsson, S. and Lauber, V., 2006. The politics and policy of energy system transformation—explaining the German diffusion of renewable energy technology. *Energy policy*, *34*(3), pp.256-276.

Javadi, A., Hamadi, A., Ndtoungou, A. and Al-Haddad, K., 2017. Power quality enhancement of smart households using a multilevel-thseaf with a PR controller. *IEEE Transactions on Smart Grid*, *8*(1), pp.465-474.

Jay, F. and Goetz, J.A., 1988. IEEE standard dictionary of electrical and electronics terms. Institute of Electrical and Electronics Engineers.

Jenkins, N. and Ekanayake, J., 2017. *Renewable Energy Engineering*. Cambridge University Press.

Jonker Klunne, W.E., 2009. Small hydropower for rural electrification in South Africa-using experiences from other African countries.

Jordehi, A.R., 2016. Parameter estimation of solar photovoltaic (PV) cells: a review. *Renewable and Sustainable Energy Reviews*, *61*, pp.354-371.

Junior, O.H.A., Macan, R., Neto, J.M., Oliveira, M.O., Horacio, J. and Reversat, R.C.L., 2013. Study to Distributed Generation Deployment Using Photovoltaic System Connected in a Grid Residencial Consumer. *International Journal of Automation and Power Engineering*, *2*(5), pp.312-320.

Junyent-Ferr, A., Pipelzadeh, Y. and Green, T.C., 2015. Blending HVDC-link energy storage and offshore wind turbine inertia for fast frequency response. *IEEE Transactions on Sustainable Energy*, *6*(3), pp.1059-1066.

Justo, J.J., Mwasilu, F., Lee, J. and Jung, J.W., 2013. AC-microgrids versus DC-microgrids with distributed energy resources: A review. *Renewable and Sustainable Energy Reviews*, *24*, pp.387-405.

Justus Rabi, B., and Arumugam, R., 2005, Harmonics Study and Comparison of Z-Source Inverter with Traditional Inverters, American Journal of Applied Sciences 2 (10): 1418-1426.

Karekezi, S. and Kithyoma, W., 2002. Renewable energy strategies for rural Africa: is a PV-led renewable energy strategy the right approach for providing modern energy to the rural poor of sub-Saharan Africa?. *Energy policy*, *30*(11), pp.1071-1086.

Karimi, M., Mokhlis, H., Naidu, K., Uddin, S. and Bakar, A.H.A., 2016. Photovoltaic penetration issues and impacts in distribution network–a review. *Renewable and Sustainable Energy Reviews*, *53*, pp.594-605.

Katiraei, F. and Aguero, J.R., 2011. Solar PV integration challenges. *IEEE Power and Energy Magazine*, *9*(3), pp.62-71.

Kaunda, C.S., Kimambo, C.Z. and Nielsen, T.K., 2012. Potential of small-scale hydropower for electricity generation in Sub-Saharan Africa. *ISRN Renewable Energy*, *2012*.

Kenneth, A.P. and Folly, K., 2014. Voltage rise issue with high penetration of grid connected PV. *IFAC Proceedings Volumes*, *47*(3), pp.4959-4966.

Kenneth, A.P. and Folly, K., 2014. Voltage rise issue with high penetration of grid connected PV. *IFAC Proceedings Volumes*, *47*(3), pp.4959-4966.

Kerekes, T., Koutroulis, E., Séra, D., Teodorescu, R. and Katsanevakis, M., 2013. An optimization method for designing large PV plants. *IEEE Journal of Photovoltaics*, *3*(2), pp.814-822.

Key, T.S., 1979. Diagnosing power quality-related computer problems. *IEEE Transactions on Industry Applications*, (4), pp.381-393.

Khalid, S. and Dwivedi, B., 2011. Power quality issues, problems, standards & their effects in industry with corrective means. *International Journal of Advances in Engineering & Technology*, *1*(2), pp.1-11

Kim, H.S. and Lu, D.D.C., Review on wind turbine generators and power electronic converters with the grid-connection issues. In *2010 20th Australasian Universities Power Engineering Conference*.

Kirby, N.M., Luckett, M.J., Xu, L. and Siepmann, W., 2001, November. HVDC transmission for large offshore windfarms. In *AC-DC Power Transmission, 2001. Seventh International Conference on (Conf. Publ. No. 485)* (pp. 162-168).

Kishore, R.A., Coudron, T. and Priya, S., 2013. Small-scale wind energy portable turbine (SWEPT). *Journal of Wind Engineering and Industrial Aerodynamics*, *116*, pp.21-31.

Kjaer, S.B., Pedersen, J.K. and Blaabjerg, F., 2005. A review of single-phase grid-connected inverters for photovoltaic modules. *IEEE transactions on industry applications*, VOL. 41, NO. 5, pp.1292-1306.

Kochtcheeva, L.V., 2016. Renewable Energy: Global Challenges. *Environment, Climate Change and International Relations*, p.175.

Kouro, S., Leon, J.I., Vinnikov, D. and Franquelo, L.G., 2015. Grid-connected photovoltaic systems: An overview of recent research and emerging PV converter technology. *IEEE Industrial Electronics Magazine*, *9*(1), pp.47-61.

Kumar, C. and Alwarsamy, T., 2012. Solution of economic dispatch problem using differential evolution algorithm. *International Journal of Soft Computing and Engineering (IJSCE) ISSN*, pp.2231-2307.

Kusakana, K., 2014. A survey of innovative technologies increasing the viability of micro-hydropower as a cost effective rural electrification option in South Africa. *Renewable and Sustainable Energy Reviews*, *37*, pp.370-379.

Kusre, B.C., Baruah, D.C., Bordoloi, P.K. and Patra, S.C., 2010. Assessment of hydropower potential using GIS and hydrological modeling technique in Kopili River basin in Assam (India). *Applied Energy*, *87*(1), pp.298-309.

Kwon, J., Wang, X., Blaabjerg, F., Bak, C.L., Sularea, V.S. and Busca, C., 2017. Harmonic Interaction Analysis in a Grid-Connected Converter Using Harmonic State-Space (HSS) Modeling. *IEEE Transactions on Power Electronics*, *32*(9), pp.6823-6835.

Laghari, J.A., Mokhlis, H., Bakar, A.H.A. and Mohammad, H., 2013. A comprehensive overview of new designs in the hydraulic, electrical equipments and controllers of mini hydro power plants making it cost effective technology. *Renewable and sustainable Energy reviews*, *20*, pp.279-293.

Larsson, A., 2000. *The power qualities of wind turbines*. Chalmers University of Technology, Sweden, pp.50-70.

Lasseter, R.H., 2007. Microgrids and distributed generation. *Journal of Energy Engineering*, *133*(3), pp.144-149.

Latran, M.B., Teke, A. and Yoldaş, Y., 2015. Mitigation of power quality problems using distribution static synchronous compensator: a comprehensive review. *IET Power Electronics*, *8*(7), pp.1312-1328. (Latran et al. 2015)

Lee, D., Habetler, T., 2007, A voltage sag supporter utilizing a pwm-switched autotransformer. IEEE Transactions on Power Electronics, 22(2): 626–635.

Libo, W., Zhengming, Z. and Jianzheng, L., 2007. A single-stage three-phase grid-connected photovoltaic system with modified MPPT method and reactive power compensation. *IEEE Transactions on Energy Conversion*, *22*(4), pp.881-886.

Liu, K.H. and Wang, L., 2007, June. Analysis of measured harmonic currents and voltages contributed by a commercial wind power system. In *Power Engineering Society General Meeting, 2007. IEEE* (pp. 1-6). IEEE.

Lopes, J.P., Hatziargyriou, N., Mutale, J., Djapic, P. and Jenkins, N., 2007. Integrating distributed generation into electric power systems: A review of drivers, challenges and opportunities. *Electric power systems research*, *77*(9), pp.1189-1203.

Lovins, A.B., Datta, K., Feiler, T., Rábago, K., Swisher, J.N., Lehmann, A. and Wicker, K., 2002. Small is profitable: The hidden economic benefits of making electrical resources the right size. Snowmass, CO: Rocky Mountain Institute.

Luderer, G., Krey, V., Calvin, K., Merrick, J., Mima, S., Pietzcker, R., Van Vliet, J. and Wada, K., 2014. The role of renewable energy in climate stabilization: results from the EMF27 scenarios. *Climatic change*, *123*(3-4), pp.427-441.

Lund, H. and Mathiesen, B.V., 2009. Energy system analysis of 100% renewable energy systems—the case of Denmark in years 2030 and 2050.*Energy*, *34*(5), pp.524-531.

Lund, J.W. and Boyd, T.L., 2016. Direct utilization of geothermal energy 2015 worldwide review. *Geothermics*, *60*, pp.66-93.

Lund, P.D., Lindgren, J., Mikkola, J. and Salpakari, J., 2015. Review of energy system flexibility measures to enable high levels of variable renewable electricity. *Renewable and Sustainable Energy Reviews*, *45*, pp.785-807.

Magoro, B. and Khoza, T., 2012. Grid Connection code for renewable power plants (RPPs) connected to the electricity Transmission System (TS) or the Distribution System (DS) in South Africa. *National Energy Regulator of South Africa (NERSA), Version*, *2*.

Mai, T., Hand, M.M., Baldwin, S.F., Wiser, R.H., Brinkman, G.L., Denholm, P., Arent, D.J., Porro, G., Sandor, D., Hostick, D.J. and Milligan, M., 2014. Renewable electricity futures for the United States. *IEEE Transactions on Sustainable Energy*, *5*(2), pp.372-378.

Maity, A.K., Pratihar, R. and Dalai, S., 2015, February. Design of a dynamic model of the unified power quality conditioner and its operation control. In *Computer, Communication, Control and Information Technology (C3IT), 2015 Third International Conference on* (pp. 1-4). IEEE.

Maity, A.K., Pratihar, R. and Dalai, S., 2015, February. Design of a dynamic model of the unified power quality conditioner and its operation control. In *Computer, Communication, Control and Information Technology (C3IT), 2015 Third International Conference on* (pp. 1-4). IEEE.

Malengret, M. and Gaunt, C.T., 2011. General theory of instantaneous power for multi-phase systems with distortion, unbalMasebinu, S.O., Akinlabi, E.T., Muzenda, E. and Aboyade, A.O., 2016. Renewable energy: deployment and the roles of energy storage.

Marrison, C.I. and Larson, E.D., 1996. A preliminary analysis of the biomass energy production potential in Africa in 2025 considering projected land needs for food production. *Biomass and Bioenergy*, *10*(5-6), pp.337-351.

Masdi, H., Mariun, N., Mahmud, S., Mohamed, A. and Yusuf, S., 2004, November. Design of a prototype D-STATCOM for voltage sag mitigation. In*Power and Energy Conference, 2004. PECon 2004. Proceedings. National*(pp. 61-66). IEEE.

Mentis, D., 2013. Wind Energy Assessment in Africa; A GIS-based approach. KTH School of Industrial Engineering and Management Energy Technology.

Mentis, D., Hermann, S., Howells, M., Welsch, M. and Siyal, S.H., 2015. Assessing the technical wind energy potential in Africa a GIS-based approach. *Renewable Energy*, *83*, pp.110-125.

Merven, B., Moyo, A., Stone, A., Dane, A. and Winkler, H., 2014. Socio-economic implications of mitigation in the power sector including carbon taxes in South Africa.

Mithulananthan N., Than Oo, Phu L.V., 2004, Distributed Generator Placement in Power System using Genetic Algorithm to Reduce Losses, Thammasat Int. J. Sc. Tech , 55–62.

MMcGranaghan, M., Mueller, D., Samotyj, M., 1993, Voltage sags in industrial systems. IEEE Transactions on Industry Applications, 29(2), 397–403.

Mohammed, Y.S., Mustafa, M.W. and Bashir, N., 2013. Status of renewable energy consumption and developmental challenges in Sub-Sahara Africa. *Renewable and Sustainable Energy Reviews*, *27*, pp.453-463.

Mohd, A., Ortjohann, E., Schmelter, A., Hamsic, N. and Morton, D., 2008, June. Challenges in integrating distributed energy storage systems into future smart grid. In *Industrial Electronics, 2008. ISIE 2008. IEEE International Symposium on* (pp. 1627-1632). IEEE.

Molina, M.G. and Espejo, E.J., 2014. Modeling and simulation of grid-connected photovoltaic energy conversion systems. *International Journal of Hydrogen Energy*, *39*(16), pp.8702-8707.

Mukasa, A.D., Mutambatsere, E., Arvanitis, Y. and Triki, T., 2015. Wind energy in sub-Saharan Africa: Financial and political causes for the sector's under-development. *Energy Research & Social Science*, *5*, pp.90-104.

Muruganantham, B., Gnanadass, R. and Padhy, N.P., 2017. Challenges with renewable energy sources and storage in practical distribution systems. *Renewable and Sustainable Energy Reviews*, *73*, pp.125-134.

Musango, J.K., Amigun, B. and Brent, A.C., 2011. Sustainable electricity generation technologies in South Africa: initiatives, challenges and policy implications. *Energy and Environment Research*, *1*(1), p.124

Music, M., Bosovic, A., Hasanspahic, N., Avdakovic, S. and Becirovic, E., 2012, September. Integrated power quality monitoring systems in smart distribution grids. In *Energy Conference and Exhibition (ENERGYCON), 2012 IEEE International* (pp. 501-506). IEEE.

Nakumuryango, A. and Inglesi-Lotz, R., 2016. South Africa’s performance on renewable energy and its relative position against the OECD countries and the rest of Africa. *Renewable and Sustainable Energy Reviews*, *56*, pp.999-1007.

Newton, I., 1729. In experimental philosophy particular propositions are inferred from the phenomena and afterwards rendered general by induction.

Nguyen, P.T. and Saha, T.K., 2004, June. Dynamic voltage restorer against balanced and unbalanced voltage sags: modelling and simulation. In *Power Engineering Society General Meeting, 2004. IEEE* (pp. 639-644).

Nikolaev, P., Zhang, J., McClure, S.M. and Colbert, D.T., 1994. Growth and sintering of fullerene nanotubes. *Science*, *266*(5188), p.1218.

Niyimbona, P., 2005, June. The challenges of operationalizing power pools in Africa. In *United Nations Commission for Africa, UNDESA Seminar on Electricity Interconnection*.

Noraini, M.R. and Geraghty, J., 2011. Genetic algorithm performance with different selection strategies in solving TSP.

Ohunakin, O.S., Adaramola, M.S., Oyewola, O.M. and Fagbenle, R.O., 2014. Solar energy applications and development in Nigeria: drivers and barriers. *Renewable and Sustainable Energy Reviews*, *32*, pp.294-301.

Onwunta, O.E.K. and Kahn, M.T.E., 2014. Smart Grid Concept and Developments: The Relevance to South Africa. *Journal of Energy and Power Engineering*, *8*(11).

Onyeji, I., 2014. Harnessing and Integrating Africa's Renewable Energy Resources. *Renewable Energy Integration*, Elsevier, United Kingdom, pp.27-38, p.022.

Outlook, S.A.E., 2013. World energy outlook special report. *France International Energy Agency (IEA)*.

Owusu, P.A. and Asumadu-Sarkodie, S., 2016. A review of renewable energy sources, sustainability issues and climate change mitigation. *Cogent Engineering*, *3*(1), p.1167990.

Parikka, M., 2004. Global biomass fuel resources. *Biomass and Bioenergy*, *27*(6), pp.613-620.

Passey, R., Spooner, T., MacGill, I., Watt, M. and Syngellakis, K., 2011. The potential impacts of grid-connected distributed generation and how to address them: A review of technical and non-technical factors. *Energy Policy*, *39*(10), pp.6280-6290.

Pegels, A., 2010. Renewable energy in South Africa: Potentials, barriers and options for support. *Energy policy, 38*(9), pp.4945-4954.

Perlack, R.D., Wright, L.L., Turhollow, A.F., Graham, R.L., Stokes, B.J. and Erbach, D.C., 2005. *Biomass as feedstock for a bioenergy and bioproducts industry: the technical feasibility of a billion-ton annual supply*. Oak Ridge National Lab TN.

Peskett, L., 2011. The history of mini-grid development in developing countries. *Policy brief. Global Village Energy Partnership, London, UK.*

Pfenninger, S., Hawkes, A. and Keirstead, J., 2014. Energy systems modeling for twenty-first century energy challenges. *Renewable and Sustainable Energy Reviews*, *33*, pp.74-86.

Phiri, D., 2013. *Biomass modelling of selected drought tolerant Eucalypt species in South Africa* (Doctoral dissertation, Stellenbosch: Stellenbosch University).

Pimentel, D., Herz, M., Glickstein, M., Zimmerman, M., Allen, R., Becker, K., Evans, J., Hussain, B., Sarsfeld, R., Grosfeld, A. and Seidel, T., 2002. Renewable Energy: Current and Potential Issues Renewable energy technologies could, if developed and implemented, provide nearly 50% of US energy needs; this would require about 17% of US land resources. *Bioscience*, *52*(12), pp.1111-1120.

Pinto, R., Mariano, S., Calado, M.D.R. and de Souza, J.F., 2016. Impact of rural grid-connected photovoltaic generation systems on power quality. *Energies*, *9*(9), p.739.

Prakash, P. and Khatod, D.K., 2016. Optimal sizing and siting techniques for distributed generation in distribution systems: A review. *Renewable and Sustainable Energy Reviews*, *57*, pp.111-130.

Preece, R. and Milanović, J.V., 2015. Risk-based small-disturbance security assessment of power systems. *IEEE Transactions on Power Delivery*, *30*(2), pp.590-598.

Price, T. and Probert, D., 1997. Harnessing hydropower: A practical guide. *Applied energy*, *57*(2), pp.175-251.

Radousky, H.B. and Liang, H., 2012. Energy harvesting: an integrated view of materials, devices and applications. *Nanotechnology*, *23*(50), p.502001.

Rahimi, M. and Parniani, M., 2009. Dynamic behavior and transient stability analysis of fixed speed wind turbines. *Renewable energy*, *34*(12), pp.2613-2624.

Reddi, K.R., Weilin Li, W. Wang, B., & Moon, YB. 2013. Energy Systems and Combined Heating and Power Generator. *Syracuse University, New York. USA, Mechanical and Aerospace Engineering.*

Reddy, M.V. and Sodhi, R., 2016. A rule-based S-Transform and AdaBoost based approach for power quality assessment. *Electric Power Systems Research*, *134*, pp.66-79.

Reed, G.F., Takeda, M. and Iyoda, I., 1999, January. Improved power quality solutions using advanced solid-state switching and static compensation technologies. In *Power Engineering Society 1999 Winter Meeting, IEEE* (Vol. 2, pp. 1132-1137).

Reid, W.E., 1996. Power quality issues-standards and guidelines. *IEEE Transactions on Industry Applications*, *32*(3), pp.625-632.

Revana, G. and Kota, V.R., 2017. Modeling and Fuzzy Logic Control of PV Based Cascaded Boost Converter Three Phase Five-level Inverter System. *International Journal of Power Electronics and Drive Systems (IJPEDS)*, *8*(3), pp.1389-1400.

Romero-Cadaval, E., Francois, B., Malinowski, M. and Zhong, Q.C., 2015. Grid-connected photovoltaic plants: An alternative energy source, replacing conventional sources. *IEEE Industrial Electronics Magazine*, *9*(1), pp.18-32.

Roopnarain, A. and Adeleke, R., 2017. Current status, hurdles and future prospects of biogas digestion technology in Africa. *Renewable and Sustainable Energy Reviews*, *67*, pp.1162-1179.

Samalca, I.K., 2007. Estimation of forest biomass and its error: A case in Kalimantan, Indonesia. *Unpublished MSc. Thesis, ITC the Netherlands, Enschede*.

Sangwongwanich, A., Yang, Y., Sera, D. and Blaabjerg, F., 2017, June. Interharmonics from grid-connected PV systems: Mechanism and mitigation. In *Future Energy Electronics Conference and ECCE Asia (IFEEC 2017-ECCE Asia), 2017 IEEE 3rd International* (pp. 722-727). IEEE.

Schmidt, T.S., Matsuo, T. and Michaelowa, A., 2017. Renewable energy policy as an enabler of fossil fuel subsidy reform? Applying a socio-technical perspective to the cases of South Africa and Tunisia. *Global Environmental Change*, *45*, pp.99-110.

Schwerhoff, G. and Sy, M., 2016. Financing renewable energy in Africa–Key challenge of the sustainable development goals. *Renewable and Sustainable Energy Reviews*.

Setati, M., Adler, J., Reed, Y. and Bapoo, A., 2002. Incomplete journeys: Code-switching and other language practices in mathematics, science and English language classrooms in South Africa. *Language and education*, *16*(2), pp.128-149.

Sewchurran, S. and Davidson, I.E., 2016, January. Guiding Principles for Grid Code Compliance of Medium-High Voltage Renewable Power Plant Distributed Generation Integration onto South Africa's

Transmission and Distribution Networks. In *Proceedings of the 24th South African Universities Power Engineering Conference* (pp. 26-28).

Shaaban, M. and Petinrin, J.O., 2014. Renewable energy potentials in Nigeria: meeting rural energy needs. *Renewable and Sustainable Energy Reviews*, *29*, pp.72-84.

Shah, R., Mithulananthan, N., Bansal, R., Lee, K.Y. and Lomi, A., 2012. Influence of large-scale PV on voltage stability of sub-transmission system. *International Journal on Electrical Engineering and Informatics*, *4*(1), pp.148-161.

Short, J.A., Infield, D.G. and Freris, L.L., 2007. Stabilization of grid frequency through dynamic demand control. *IEEE Transactions on power systems*, *22*(3), pp.1284-1293.

Simonyan, K. J., and O. Fasina. 2013, March. "Biomass resources and bioenergy potentials in Nigeria." *African Journal of Agricultural Research* 8.40 (2013): 4975-4989.

Singh, B., Adhya, A., Mittal, A.P. and Guptha, J.R.P., 2006, January. Analysis and implement of thyristor-based statcom for small isolated alternator feeding distribution system. In *International Conference on Power Electronics and Drive Systems* (Vol. 1, pp. 274-279).

Sipahutar, R., Bernas, S.M. and Imanuddin, M.S., 2013. Renewable energy and hydropower utilization tendency worldwide. *Renewable and Sustainable Energy Reviews*, *17*, pp.213-215.

Solangi, K.H., Islam, M.R., Saidur, R., Rahim, N.A. and Fayaz, H., 2011. A review on global solar energy policy. *Renewable and sustainable energy reviews*, *15*(4), pp.2149-2163.

Solar, G., 2010. Solar radiation maps: Global Horizontal Irradiation (GHI). *Solar GIS*, *2014*.

Sotkiewicz, P.M. and Vignolo, J.M., 2007. Towards a cost causation-based tariff for distribution networks with DG. *IEEE Transactions on Power Systems*, *22*(3), pp.1051-1060.

Spiess, T. and De Sousa, C., 2016. Barriers to Renewable Energy Development on Brownfields. *Journal of Environmental Policy & Planning*, *18*(4), pp.507-534.

Standard, South Africa, Power Quality., 1996. National Revised Standard (NRS) NRS 048-2: 1996.

Su, H.I. and El Gamal, A., 2013. Modeling and analysis of the role of energy storage for renewable integration: Power balancing. *IEEE Transactions on Power Systems*, *28*(4), pp.4109-4117.

Suri, M., Cebecauer, T., Skoczek, A., Marais, R., Mushwana, C., Reinecke, J. and Meyer, R., 2014. Cloud cover impact on photovoltaic power production in South Africa. *Proceedings of SASEC*.

Svendsen, T.M., 2013. *Hydroelectric Power in Present and Future Energy Systems* (Master's thesis, The University of Bergen).

Swider, D.J., Beurskens, L., Davidson, S., Twidell, J., Pyrko, J., Prüggler, W., Auer, H., Vertin, K. and Skema, R., 2008. Conditions and costs for renewables electricity grid connection: examples in Europe. *Renewable Energy*, *33*(8), pp.1832-1842.

Tareen, W.U., Mekhilef, S., Seyedmahmoudian, M. and Horan, B., 2017. Active power filter (APF) for mitigation of power quality issues in grid integration of wind and photovoltaic energy conversion system. *Renewable and Sustainable Energy Reviews*, *70*, pp.635-655.

Taylor, L., Rezai, A. and Foley, D.K., 2016. An integrated approach to climate change, income distribution, employment, and economic growth. *Ecological Economics*, *121*, pp.196-205.

Tech central, (2015), Africa’s biggest renewable energy projects,https://techcentral.co.za/africas-biggest-renewable-energy-projects/58752.

Tekiner-Mogulkoc, H., Coit, D.W. and Felder, F.A., 2012. Electric power system generation expansion plans considering the impact of Smart Grid technologies. *International Journal of Electrical Power & Energy Systems*, *42*(1), pp.229-239.

Turconi, R., Boldrin, A. and Astrup, T., 2013. Life cycle assessment (LCA) of electricity generation technologies: overview, comparability and limitations. *Renewable and sustainable energy reviews*, *28*, pp.555-565.

Tyagi, V.V., Rahim, N.A., Rahim, N.A., Jeyraj, A. and Selvaraj, L., 2013. Progress in solar PV technology: research and achievement. *Renewable and sustainable energy reviews*, *20*, pp.443-461.

Ujile, A. and Ding, Z., 2016. A dynamic approach to identification of multiple harmonic sources in power distribution systems. *International Journal of Electrical Power & Energy Systems*, *81*, pp.175-183.

Valois, P.S., Tahan, C.V., Kagan, N. and Arango, H., 2001, June. Voltage unbalance in low voltage distribution networks. In *Electricity Distribution, 2001. Part 1: Contributions. CIRED. 16th International Conference and Exhibition on (IEE Conf. Publ No. 482)* (Vol. 2, pp. 5-pp). IET.

Venkatesh, C., Reddy, V.P. and Sarma, D.S., 2008, September. Mitigation of voltage sags/swells using PWM switched autotransformer. In *Harmonics and Quality of Power, 2008. ICHQP 2008. 13th International Conference on* (pp. 1-6). IEEE

Wahab, S.W. and Yusof, A.M., 2006. Voltage sag and mitigation using dynamic voltage restorer (DVR) system. *Elektrika*, *8*(2), pp.32-37.

Walwyn, D.R. and Brent, A.C., 2015. Renewable energy gathers steam in South Africa. *Renewable and Sustainable energy reviews*, *41*, pp.390-401.

Wan, Y.H. and Parsons, B.K., 1993. *Factors relevant to utility integration of intermittent renewable technologies* (No. NREL/TP--463-4953). National Renewable Energy Lab., Golden, CO (United States).

Ward, S. and Walsh, V., 2010. Cape Town energy case study. *Energy for Large Cities, World Energy Council Study. Disponible à l'adresse http://www. worldenergy. org/documents/annex_1_cape_town_1. pdf [consulté le 16 septembre 2011]. (Ward & Walsh, 2012)*.

Weedy, B.M., Cory, B.J., Jenkins, N., Ekanayake, J.B. and Strbac, G., 2012. *Electric power systems*. John Wiley & Sons.

Welsch, M., Bazilian, M., Howells, M., Divan, D., Elzinga, D., Strbac, G., Jones, L., Keane, A., Gielen, D., Balijepalli, V.M. and Brew-Hammond, A., 2013. Smart and just grids for sub-Saharan Africa: exploring options. *Renewable and Sustainable Energy Reviews*, *20*, pp.336-352.

Wikipedia, (2010): "hydro power or water waves", 10 August 2010, https://en.wikipedia.org/wiki/Hydropower

Winkler, B., Lemke, S., Ritter, J. and Lewandowski, I., 2016. Integrated assessment of renewable energy potential: Approach and application in rural South Africa. *Environmental Innovation and Societal Transitions*.

Winkler, H., 2005. Renewable energy policy in South Africa: policy options for renewable electricity. *Energy Policy*, *33*(1), pp.27-38.

Wolfram, C., Shelef, O. and Gertler, P., 2012. How will energy demand develop in the developing world?. *The Journal of Economic Perspectives*, *26*(1), pp.119-137.

Xu, Y. and Singh, C., 2012. Adequacy and economy analysis of distribution systems integrated with electric energy storage and renewable energy resources. *IEEE Transactions on power systems*, *27*(4), pp.2332-2341.

Yaghoobi, J., Mithulananthan, N. and Saha, T.K., 2015, July. Dynamic voltage stability of distribution system with a high penetration of rooftop PV units. In *Power & Energy Society General Meeting, 2015 IEEE* (pp. 1-5). IEEE.

Zhao, W., Ruan, X., Yang, D., Chen, X. and Jia, L., 2016. Neutral Point Voltage Ripple Suppression for Three-Phase Four-Wire Inverter with Independently-Controlled Neutral Module. *IEEE Transactions on Industrial Electronics*.

Zhong, Q.C and Hornik, T., 2013. Parallel PI voltage-H∞ current controller for the neutral point of a three-phase inverter. *IEEE Transactions on Industrial Electronics*, *60*(4), pp.1335-1343.

Zhu, F., Zhao, H.G., Liu, Z.H. and Kou, H.Z., 2007. The influence of large power grid interconnected on power system dynamic stability. *Proceedings of the CSEE, 1*, pp.1-7.

Zin, A.A.B.M., HA, M.P., Khairuddin, A.B., Jahanshaloo, L. and Shariati, O., 2013. An overview on doubly fed induction generators′ controls and contributions to wind based electricity generation. *Renewable and Sustainable Energy Reviews*, *27*, pp.692-708.

Zweifel, P., Praktiknjo, A. and Erdmann, G., 2017. Economics of Electrical Grids. In *Energy Economics* (pp. 297-313). Springer Berlin Heidelberg.

Appendices of picture

Load Profile

The load profile of electricity usage is important to the efficiency and load reliability of the grid. A load profile will vary according to customer load type (typical examples is shown figure 7.1 below), temperature and holiday seasons. Power producers use this information to plan how much electricity they will need to make available at any given time. For energy efficiency planning and mitigation of all power quality related problems, proper measurements of load profile is required for analysis

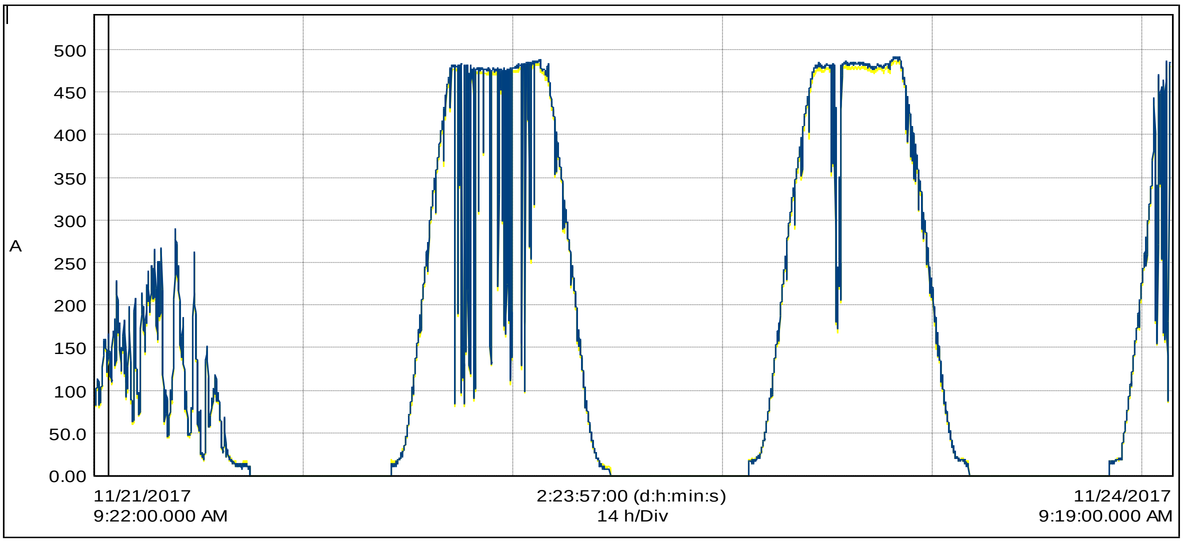


Figure 7.1: The load profile of Langerberg mall in Mosselbay with 1.5MW PV

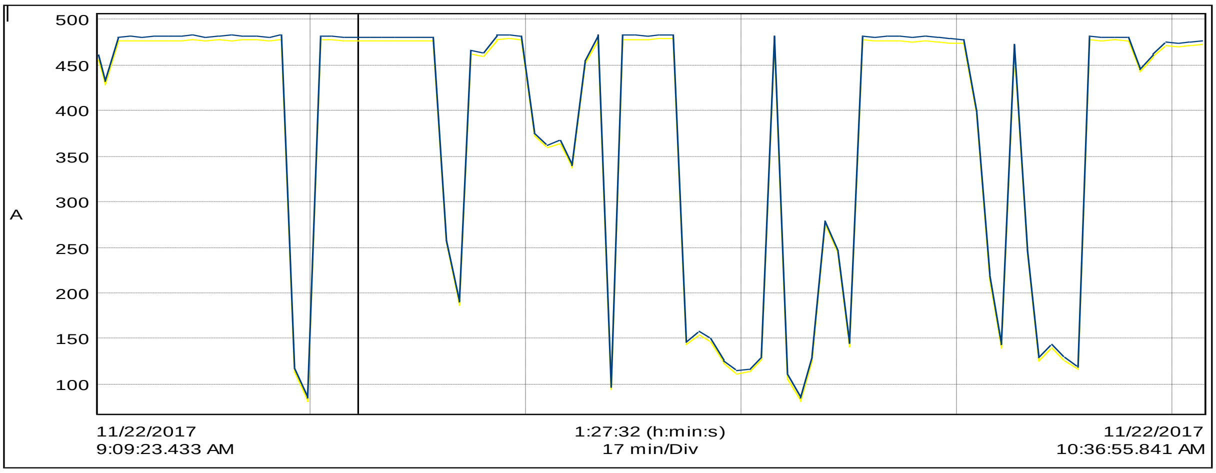


Figure 7.2: Analysis of the load profile of Langerberg mall in Mosselbay with 1.5MW rooftop PV

A modern harmonic measurement instrument is shown in Figure 7.3. Load profile waveform measurements are obtained from the meters setup to measure harmonics at 1.5MW solar PV plant mini-substation at Langerberg mall in Mosselbay. This digital data is processed and stored for further analysis of possible harmonic injection in the grid.

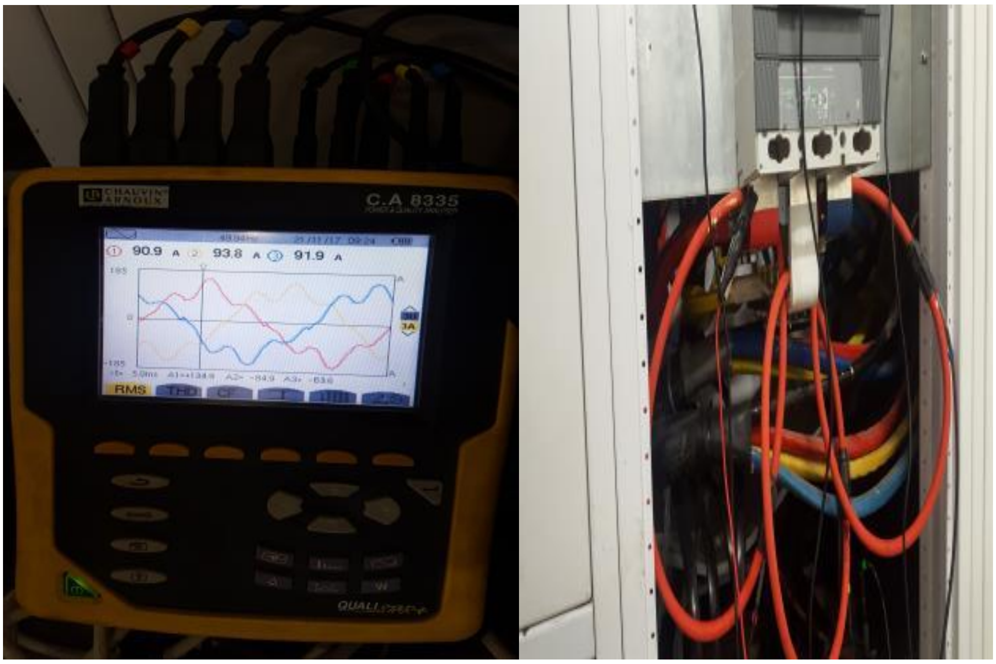


Figure 7.3: Illustrates PQ measurement instrument at langergberg mall 1.5MW gried-tied system

This instrumentation for harmonic analysis is sophisticated and costly but more accurate than ordinary measurements. Intelligent software and algorithms are required to store, process, and display the huge amount of data acquired through measurements. From Figure 7.3 to 7.7

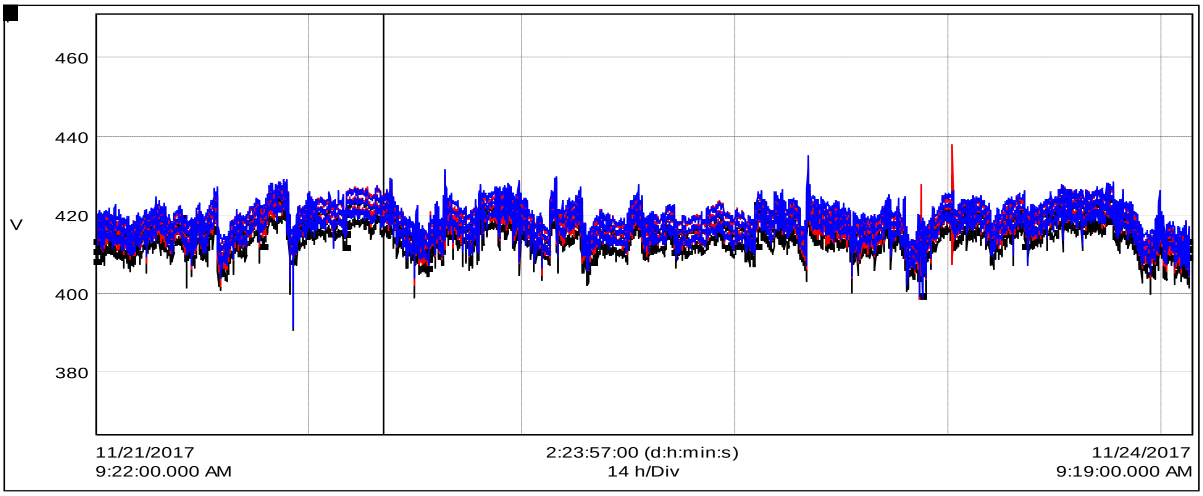


Figure 7.4: Voltage profile at Langerberg mall load with 1.5MW Solar PV rooftop

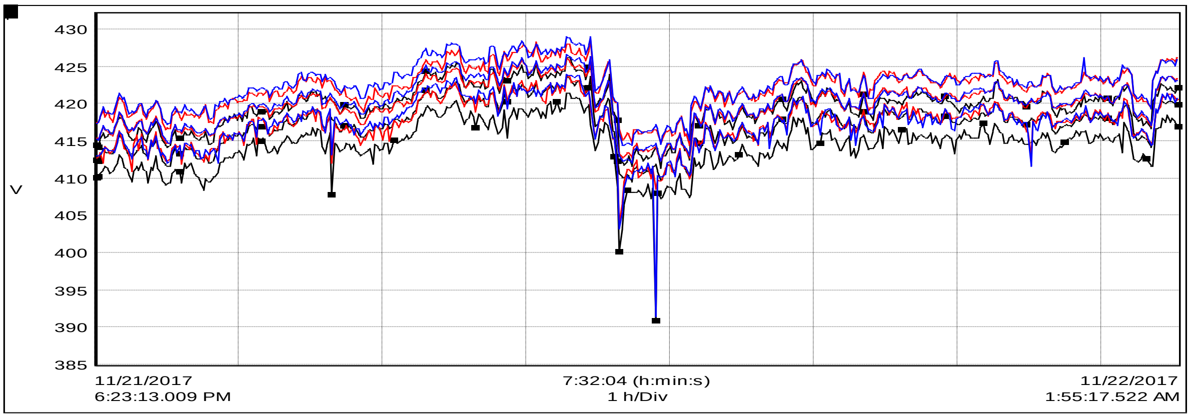


Figure 7.5: Illustrates close-in analysis of the voltage profile

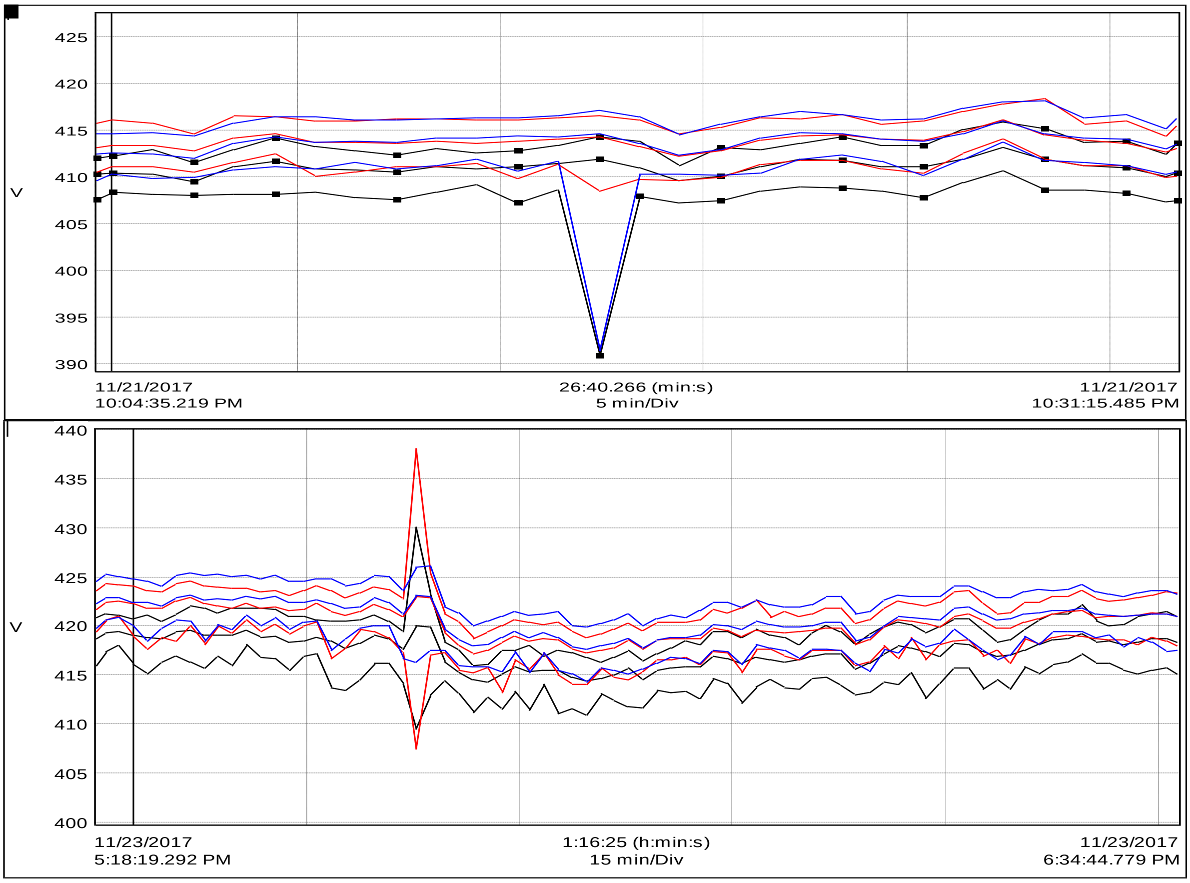


Figure 7.6: Illustrates close analysis of the voltage profile (showing voltage spikes)

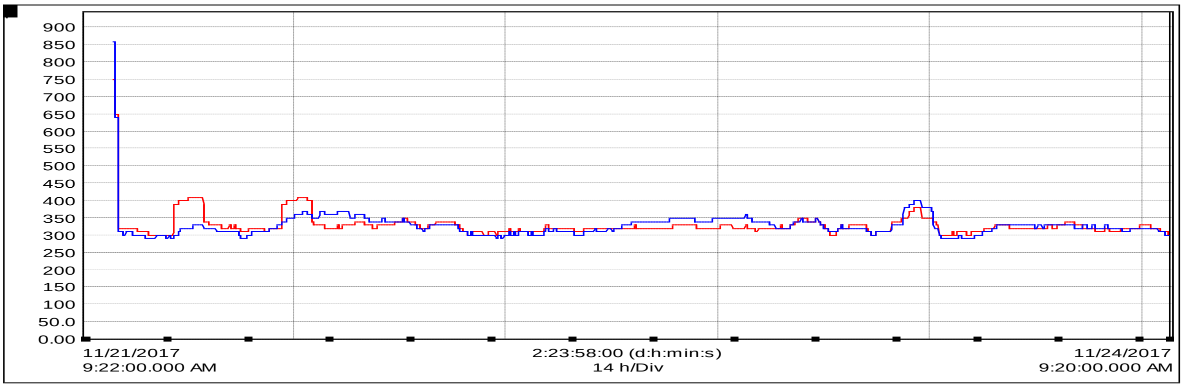


Figure 7.7: Illustrates long term voltage spikes on Langerberg mall load

The figure illustrates long term voltage spike but still within the regulation ranges. The flickers are attributed to a number of reasons. Voltage flicker has been discussed in detail in Chapter 5. Figure 7.8 illustrates close-in analysis of Figure 7.9

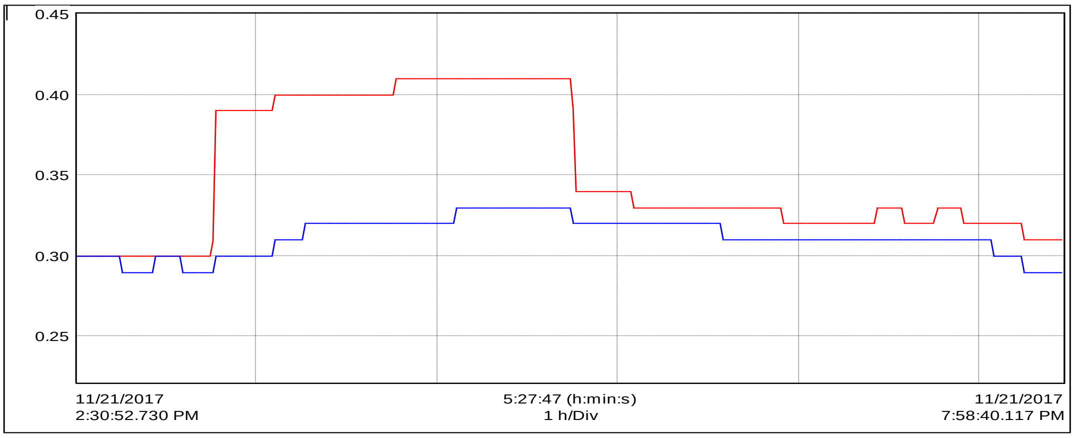


Figure 7.8: Illustrates measurement of long term voltage spikes (PLT) at Langerberg mall load

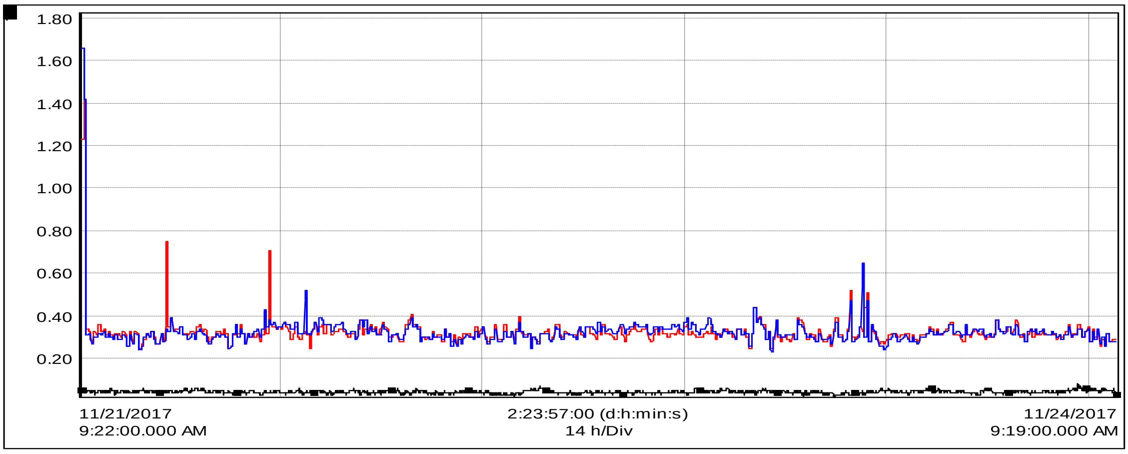


Figure 7.9: Illustrates measurement of short term of voltage spikes (PST) profile at Langerberg mall load

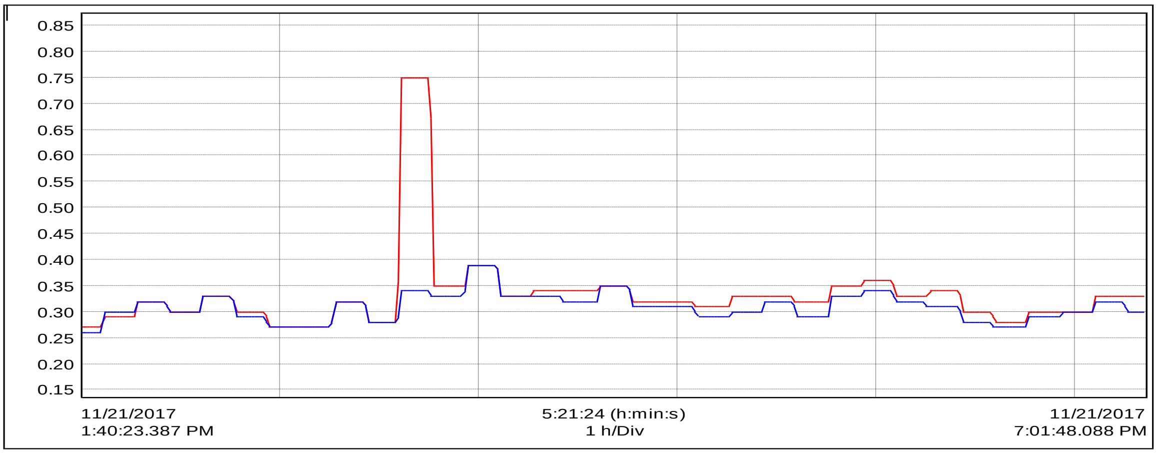


Figure 7.10: Illustrates close analysis of short term voltage spikes (PST) profile at Langerberg mall load

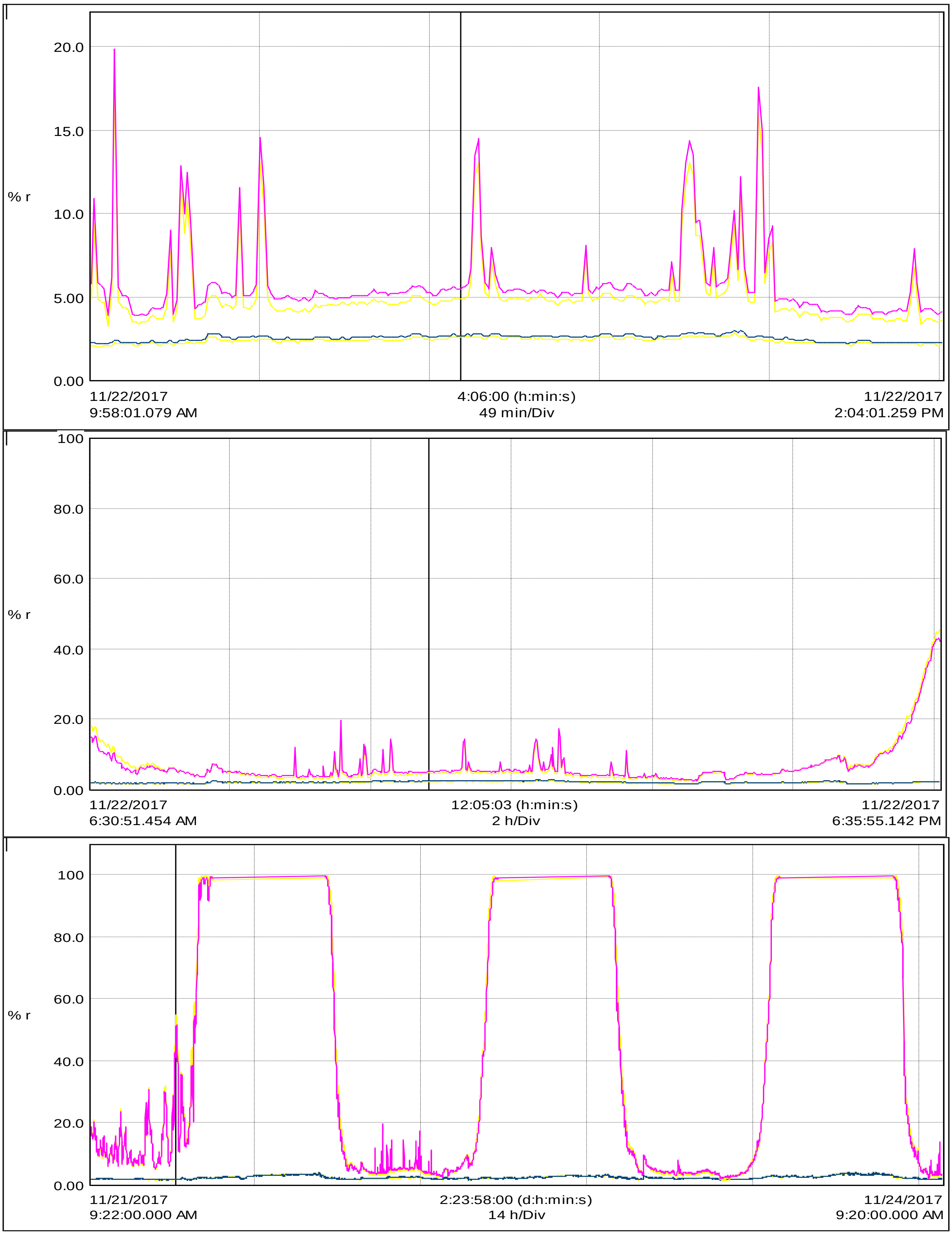


Figure 7.33: Measurement of the total harmonic distortion with respect to the RMS AC value (THD in % r) for the current

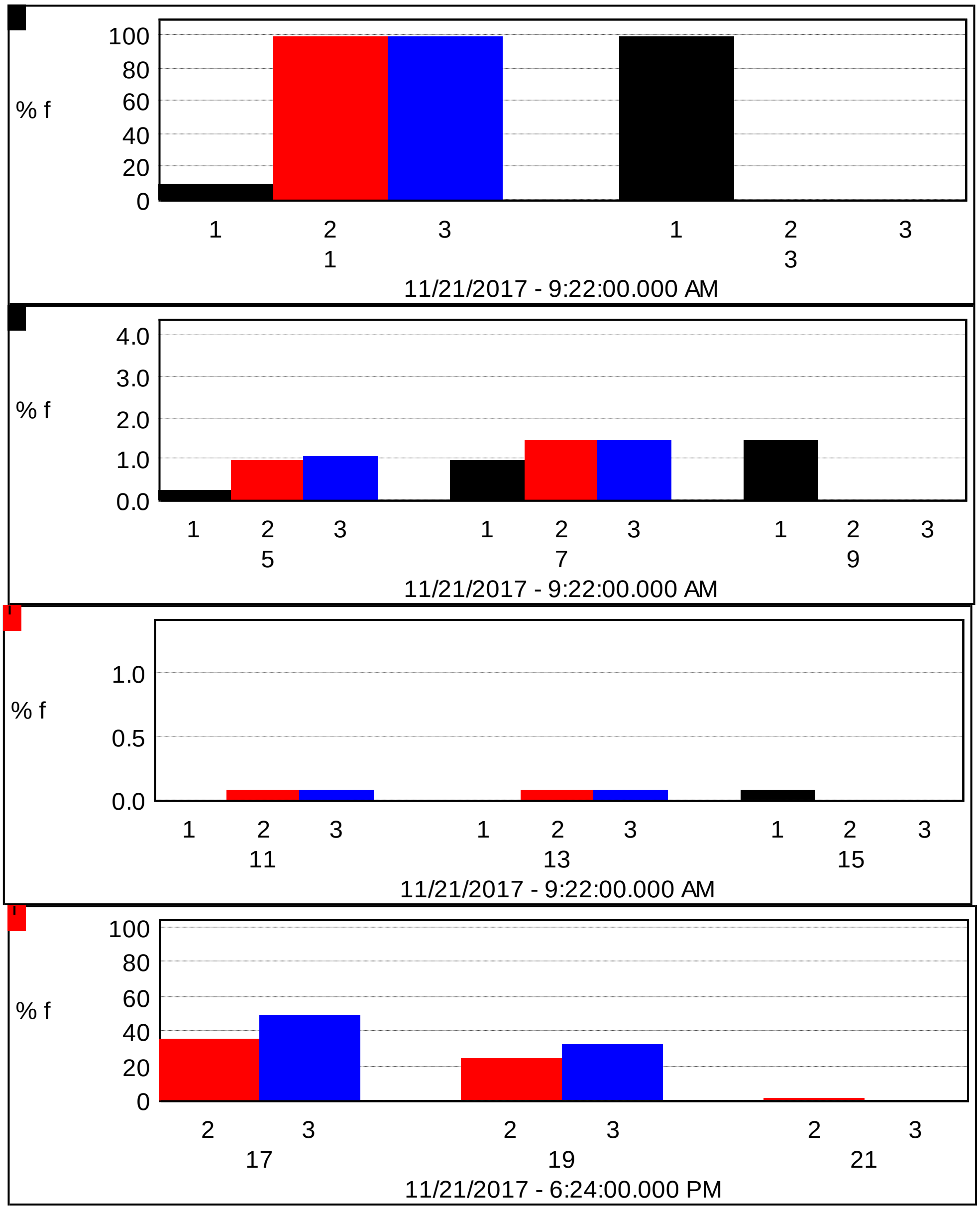


Figure 7. 34: Measurement of total harmonic distortion with respect to the fundamental (THD in % f) of the current and of the voltages

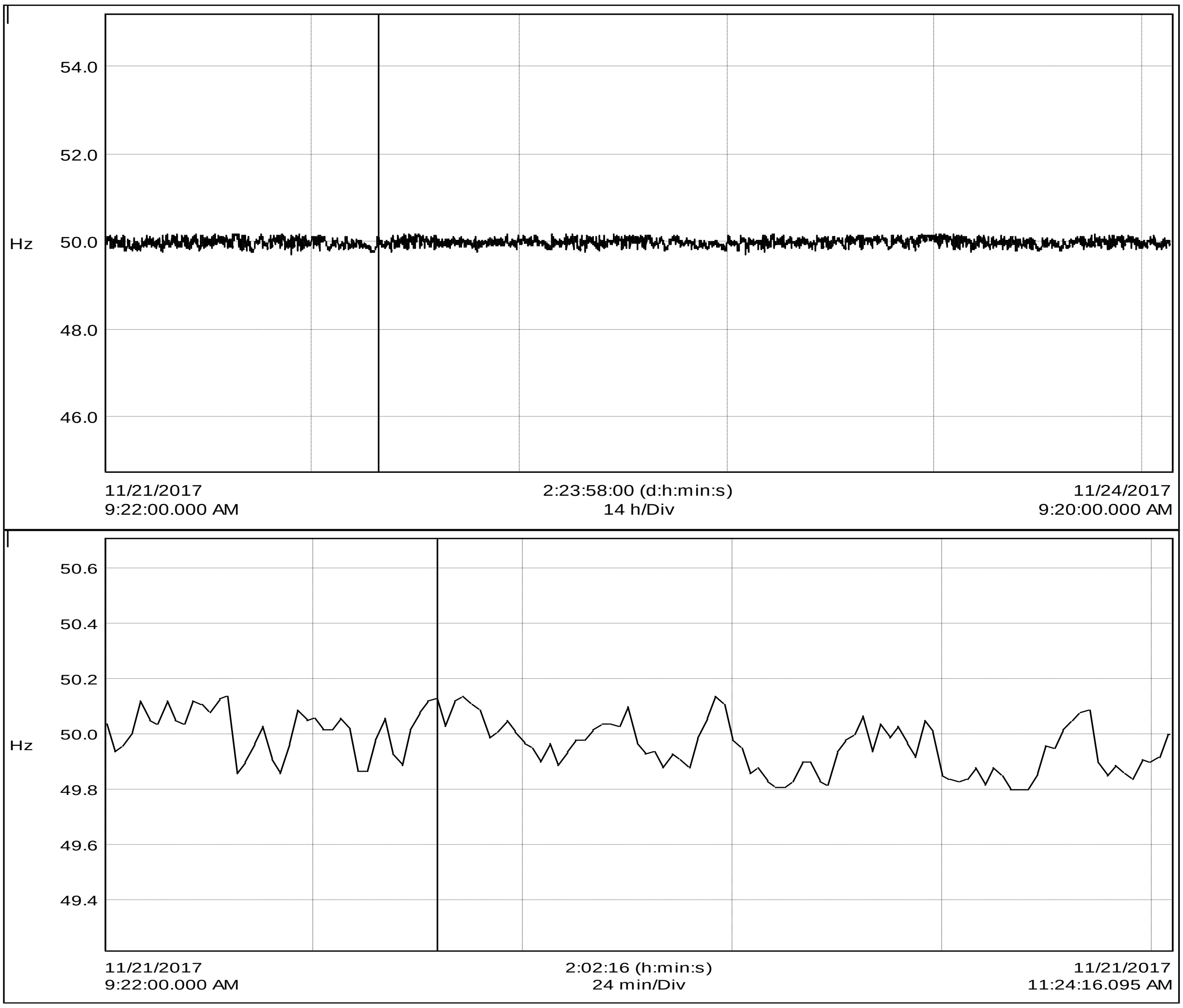


Figure 7.35: Measurement of Frequency of the network studied