Cape Peninsula University of Technology

Impact of Distributed Generation on the electric protection system

by

RUFARO MAVIS MUTAMBUDZI

Thesis submitted in partial fulfilment of the requirements for the Cape Peninsula University of Technology Master of Technology Degree

Master of Technology: ELECTRICAL ENGINEERING

in the Faculty of Engineering

at the Cape Peninsula University of Technology

Supervisor: Dr Raji

Bellville Campus
July 2019

DECLARATION

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

08/07/2019

Signed **Date**

ABSTRACT

This document provides a study of the impact of distributed generation (particularly Solar and wind energy) on the electric protection system. Due to energy poverty, most countries globally have been opened up to use of DG such as wind and solar powered generators, South Africa being one of them. There has been a prediction of the exhaustion of fossil fuels in the past decades, leaving economies with the need to find sustainable energy options. The contribution of fossil fuels to greenhouse gases has also been a global concern. This has increased the use of DG for sustainable energy systems as well as to curb the level of carbon emissions. While DG may increase energy sustainability, they have various impacts on the electric grid. It is uncertain how DG may affect the protection system of the power grid henceforth the thesis analyses the impact of DG on the electric protection. A comprehensive literature review is carried out on distributed generation and electrical protection. DigSilent PowerFactory software is used to simulate a network pre-and post-connection of the DG according to the South African grid code requirements to reflect the power flow and fault levels. Furthermore, the software is used to populate protection devices for the system. The results include a DigSilent network diagram with simulation results, fault levels pre-and post-connection of the distributed generators and protection coordination of the Distance and Overcurrent Relays.

ACKNOWLEDGEMENTS

I would like to extend my greatest appreciation to my supervisor Dr Raji for taking me under supervision and for the advice throughout my research. To the Department of Electrical, Electronic and Computer Engineering at CPUT for providing the facilities to carry out the project, Mr Sikelela Mkhabela and rest of the Eskom team for helping me gather information and providing me the facilities to design my network diagram. I would also like to thank my supervisor from Smart Energy SA, Mr John Chirwa for his technical guidance and moral support.

To my friends and family, Tariro Mudarikwa, Eunice Jani, Linda Tekere and my father, Dr Mutambudzi, thank you for the constant encouragement throughout the project, love and infinite support.

DEDICATION

To my father, Dr A. Mutambudzi thank you for your unconditional love and support throughout my whole life.

Table of Contents

List of Figures

List of Tables

List of Appendices

List of Abbreviations

AC	Alternating Current
DC	Direct Current
CB	Circuit Breaker
CT	Current Transformer
CTI	Coordination Time Interval
DFIG	Double-Fed Induction Generator
DG	Distributed Generation
DOE	Department of Energy
FC	Fuel Cell
FCL	Fault Current Limiter
GDP	Gross Domestic Product
HV	High Voltage
IDMT	Inverse Definite Minimum Time
IEC	International Electrotechnical Commission
IPP	Independent Power Plant
IRP	Integrated Resource Plan
LV	Low Voltage
LVRT	Low Voltage Ride Through
MV	Medium Voltage
MW	Mega-Watt
NECR	Neutral Electromagnetic Coupler with neutral earthing Resistor
NERSA	National Energy Regulator of South Africa
PCC	Point of Common Coupling

POC	Point of Connection
PV	Photo-Voltaic
RE	Renewable Energy
REFIT	Renewable Energy Feed-In Tariff
RPP	Renewable Power Plant
TW	Terra-Watt
WT	Wind Turbine
WTS	Wind Turbine System

Definition of Terms

Alternating Current	This is bi-directional electrical current, which reverses its direction many times in regular time intervals typically in power supplies.
Auto Transformer	This is an electrical transformer with one winding used to step-up or step-down voltages in a power system. The primary and secondary share a common winding.
Busbar	defined as a conductor or a set of conductors used for assembling electric power from the incoming feeders and distributes them to the outgoing feeders.
Current Transformer	An instrument transformer typically used for measuring alternating current by producing current in its secondary proportional to the primary
DC/DC Converter	Power electronics devices used to convert direct current from one voltage level to another
DigSilent	A power systems software used in different application in analysing generation, transmission, distribution and industrial systems.
Direct Current	Current which flows in one direction only.
Distance Protection	It is a name given to the type of protection which the action depends on the distance of the feeding point to the fault normally in transmission lines.

Distributed Generation	This is decentralized energy generating electricity close to the loads and is usually in small scale.
Electrical Faults	Abnormal electrical current flowing in a power system due to overload, short circuits or open circuits.
Electrical Load	A section of an electrical circuit that consumes active power or energy.
Generation source	The process of generating primary energy source such as coal, wind, natural gas into electrical power.
Grid Code	Technical specifications outlining the requirements of plants connected to a utility grid in terms of operation to ensure safety, security and economic operation of the electric system.
Grid-Tie	Normally referred to in Solar Photovoltaic systems. A generation source linked to the mains of the supply which typically feeds its excess power back into the grid.
IDMT Relay	Inverse Definite Minimum Time relays normally used for overcurrent protection in a power system
Inverter	A device which converts direct current to alternating current.
IRP2010	Integrated Resource Plan 2010,
Islanding	A condition in which distributed generation continues to power a section of a network regardless of the electric grid being disconnected.
Loadability	The extent of load which can flow through the line without exceeding its limitations.
Load Flow	Also known as power flow, is a steady-state analysis of a power network. The objective is to determine the voltages, currents, and power (real & reactive) flows in a network under load conditions.
Microgrid	Is a local energy grid which may or may not be connected to the utility grid with its own generation sources and energy storage.
Micro-turbine	Are small combustion turbines which produce both electricity and heat in a small scale.

Overcurrent Protection	This is defence against extreme current which is over the rated current of equipment for example short-circuit protection.
Photovoltaic	The production of electricity from light mostly relating to the sun.
Protection system	Defence against undesirable conditions in a power system such as electrical faults.
Relay	Electrically operated switches that open and close circuits electromechanically or electronically
Renewable Source	Refers to energy from sources that are naturally replenishing or virtually inexhaustible in duration for example wind, solar etc.
Short Circuit	This is a low resistance connection between two conductors allowing current to flow through an unintended path.
Solar array	A linked collection of solar panels.
Three-winding Transformer	This is a transformer with three windings, the primary, secondary and third winding called the "tertiary winding."
Two-winding Transformer	A static machine consisting of two windings (primary and secondary) which steps up or steps down voltages in a power system.

CHAPTER ONE
INTRODUCTION

1.1 Background of the study

The exhaustion of fossil fuels such as coal, oil and natural gas has been predicted in the past decades; hence global attention is being paid into making the energy systems sustainable. After the oil shocks of the 1970s, most of Organization for Economic Co-operation and Development (OECD) started focusing in developing alternative sources of energy. As Renewable Energy Sources (RES's) considered a low–carbon solution for electricity generation, they become popular in last decade. Such sources are more important in countries with abundance of Solar Irradiance and Wind such as South Africa. Furthermore, exploitation of the conventional fossil fuels for electricity generation has been resulting in pollution of the environment through carbon dioxide emissions which contributes to Greenhouse Gases (GHG) causing climate change. There have been many efforts to reduce the carbon emissions which have resulted in the move towards clean energy such as solar, wind, hydropower, and bioenergy. Normally, RES are incorporated into the energy system in the form of distributed power generation systems (Frede Blaabjerg, Yongheng Yang, 2017).

The study on the impact of distributed generation (DG) on the electric protection arose from most governments in the world opening to the exploitation and use of DG. Taking South Africa for instance, it is intensely dependent on fossil fuels and are currently implementing ways to diversify its energy generating capacity by using RE which involves independent power producers (IPPs). The South African Integrated Resource plan of 2010 projects an amount of 17 800MW from renewables by 2030, which will represent 21% of the countries' total energy output (Department of Energy, 2011). Wind and Solar will dominate the renewable energy mix with these energy sources projected to grow at an anticipated rate of 800MW per annum. The advent of these generators into the traditional power system brings about several important subjects which include reliability, stability and power quality which makes it important to provide proper protection to the power system.

According (P Manditereza, 2015), studies have discovered sites viable for the installation of wind and solar energy in SA. These studies have placed the massive potential of wind and solar capacity in the country. Wind potential is approximated to be 76.6GW, while solar energy is vast in the country and having a potential of about 886GW. The traditional power system is vertically integrated consisting of large generating power stations with steady power outputs. The penetration of DG is usually at the LV to MV networks with large windfarms integrated at sub-transmission and transmission level (HV). There is need to investigate the impact of these generators on the protection scheme in a power system considering their variable nature.

The study which will be presented in this project, will use DigSilent (PowerFactory) Software to simulate a network to reflect the impact of distributed generators (particularly solar and wind) on the electric protection.

1.2 Statement of the research problem

Distributed generation (DG) has become popular over the years globally. South Africa is one of the major players in DG systems in Africa particularly with the connection of wind and solar technologies in the energy mix. The decision to include distributed generation in the energy mix was triggered by the increase in power demand in the nation which resulted in power shortages in (Times Media, 2015). In 2010 the country issued an IRP2010 which opened-up to the use of DG such as wind and solar powered generators to solve power problems. These generators are known to be variable in nature hence may have an impact on the power grid. It is fundamental to analyse the impact of these generators on the electric protection of the grid. With the advent of DG into the conventional power system particularly in SA, it is uncertain how these generators may impact the electric protection particularly in the long run. The thesis will analyse the impact of DG on the electric protection system in SA by using DigSilent software.

1.3 Aim of the Research

The main aim of the research is to determine the impact of DG on the electric protection system by using Digsilent software to simulate a network showing pre- and post- connections of DG particularly wind and solar Photovoltaic (PV) to clearly show power flow, fault levels and any change in the relay settings/protection system.

1.4 Research Objectives

i. Conduct a literature review on distributed generation and their impact on the electric protection system.

ii. Use DigSilent PowerFactory software to model and simulate a network diagram with and without DG connected to the grid.

iii. Use of DigSilent to populate HV, MV and LV protection systems;
    - Overcurrent Protection LV & part of the MV Networks and
    - Distance Protection in MV and HV Networks

iv. Perform short-circuit calculations on DigSilent with and without the connection of DG.

v. Provide results and a conclusion on the impact of DG on the electric protection system.

1.4 Hypothesis

There is no question that DG will play a large role in most electric grids globally and for some countries like Germany, DG is already playing a vital role. The question then becomes what the high penetration degree of distributed generation can do to the grid particularly the electric protection system. Nowadays the ability to create a sustainable and resilient power system has become very important and it is highly crucial to integrate DG.

Solar and wind already play a vital role in the modern power system, but how much work needs to be put into the connection of these generation sources to create a reliable and effective protection scheme? They most likely affect the load flow, but is there any need to change protection equipment? How much does DG affect the electric protection system? Can modern simulation tools like DigSilent Powerfactory be used to model different scenarios in order to determine the impact?

It becomes important to discuss strategies for enhancing the connection and protection of the DG. By simulating a network diagram, performing load flow calculations through DigSilent one can be able to conclude how much DG can impact the electric protections system of a grid.

1.5 Research Design and Methodology

The research was carried out by firstly collecting data which mainly involved requesting a network diagram of a part of the West Coast, South Africa from Eskom, the main electricity supplier in the country. While they could not provide most of their information, they were very helpful in the data they provided. DigSilent Powerfactory was used to model a part of the West Coast network in South Africa before and after the connection of Sere Windfarm and Bulte Solar PV Farm.

Case study 1- The first scenario to be analysed will be the variation in fault current levels before and after connection of DG. The main types of faults to be analysed are the three-phase faults on Busbars and single-phase to ground faults on transmission lines. A comparison will be done to determine the percentage change in fault levels pre and post connection of DG. The results will be outlined in form of tables and discussed.

Case study 2- This study considers the impact of DG on Overcurrent relays and their protection coordination/settings. The investigation of the behaviour of the Overcurrent relays before and after connection of DG particularly on Time Grading.

Case study 3- This study reflects the impact of DG on Distance relays including how the relay coordination is affected in a power network.

1.6 Outcome of the Research

The main outcome of the research is to provide a simulated model that will highlights the effects of Distributed Generation on the electric protection system in High, Medium and Low Voltage networks.

1.7 Delimitations of the Research

While there are other types of DG like hydro, Gas and Biomass, the study mostly focuses on the impact of two types of DG, namely solar and wind power generation as they are the main types currently dominating in the South African electric grid. The research is narrowed down to Grid-connected Solar PV and Double-Fed Induction Generators (DFIG) in the case of wind generators. Two types of protection systems are covered, distance protection in HV networks and overcurrent protection in MV and LV networks. The assumption is that both types of DG are static for modelling purposes.

1.8 Outline of the Research

Chapter One- This chapter introduces the research topic by first outlining the background of the research. It also covers the statement of the research problem, clearly stating the aim of research, the research objectives and hypothesis. Further to this, the research design and methodology is summarised, the outcomes of the research and delimitations provided as well.

Chapter Two- This chapter covers an in-depth Literature review on Distributed Generation starting with a comparison between the traditional power system versus the new concept of power systems which include DG. A summary of South Africa’s energy mix is given including their future projections outlined in the Integrated Resource Plan of 2010. In addition to this, the chapter covers the South African Grid code, clearly indicating the requirements of any external Generation source when connected to the grid. Different types of DG sources are explained, a brief study of electrical faults is outlined and summary of DigSilent software provided.

Chapter Three- A discussion on the impact of DG on the electric protection system is carried out, mostly based on previous studies. It begins by clearly defining the requirements of a protection system. Distance protection and the behaviour of distance relays is analysed. The chapter further highlights the impact of DG on overcurrent protection. Other power system protection problems associated with the connection of DG to the grid are also discussed and ends with solutions that can be adopted to curb these problems. The study is mostly based on previously published research.

Chapter Four- This chapter explains how the modelling was done in DigSilent software including the modelling of the protection relays.

Chapter Five- Results obtained from the modelled network are outlined.

Chapter six- This chapter provides a brief discussion on the research and the results obtained. A conclusion is drawn, and some recommendations provided at the end of the chapter.

CHAPTER TWO
LITERATURE REVIEW

2.1 Introduction

Increasing concerns about energy costs, security, and greenhouse gas emissions are inspiring the power industries to integrate more Distributed Generation (DG) and flexible AC transmission system (FACTS) elements into their traditional power systems.The continued depletion of traditional energy sources and the continued emphasis on climate change has left the world resorting to the move towards DG, which are cleaner, vast and seem to be the solution to solving the global energy problems. These sources promise to generate high efficiency and low pollution electricity over the years. Their ranges going from as small as 5kW to 100MW. These energy sources like solar PV and fuel cells are advantageous as they require low maintenance.

Some utilities have introduced the idea of DG for competition purposes to rule out utilities acting as monopolies and exploiting consumers. Some of the need for these energy sources has come from customers demanding customized power supplies to better suit their needs (Chiradeja, 2005). The Department of Energy (DOE) and Eskom, South Africa's major energy supplier embarked on changing the energy policy which included financial metrics of energy performance in the country, by slowly lessening coal's contribution in the energy mix and combining less carbon-intensive conventional sources together with other DG sources (Krupa & Burch, 2011).

According to (Zhang et al., 2009), the introduction of DG can have an impact on the structure as well as the operation of networks, reliability, power flow and short circuit current. Much emphasis is now being put on DG research and their integration with the traditional power system. This chapter outlines a thorough literature review on what distributed generation is, the electric protection system, electric faults and the basic integration of DG into the electric grid. It also defines the South African Grid code requirements for DG sources like solar photovoltaic and wind.

2.2 The Traditional Power System

Traditional Power systems have been known to be vertically integrated with one utility responsible for handling of all functions of the power system. Electricity is produced from large generation plants typically situated far from consumers. Electricity is then delivered to consumers through High Voltage (HV), Medium Voltage (MV) and Low Voltage (LV) networks (Fernnandez Sarabia, 2011). Coal continues to dominate the South African energy mix with most of its mines and power stations located in Gauteng and Free State provinces. Eskom is responsible for operation and coordination of the system particularly in the generation and transmission levels, with the municipality taking part in the distribution of electricity (Bohlmann et al., 2019).

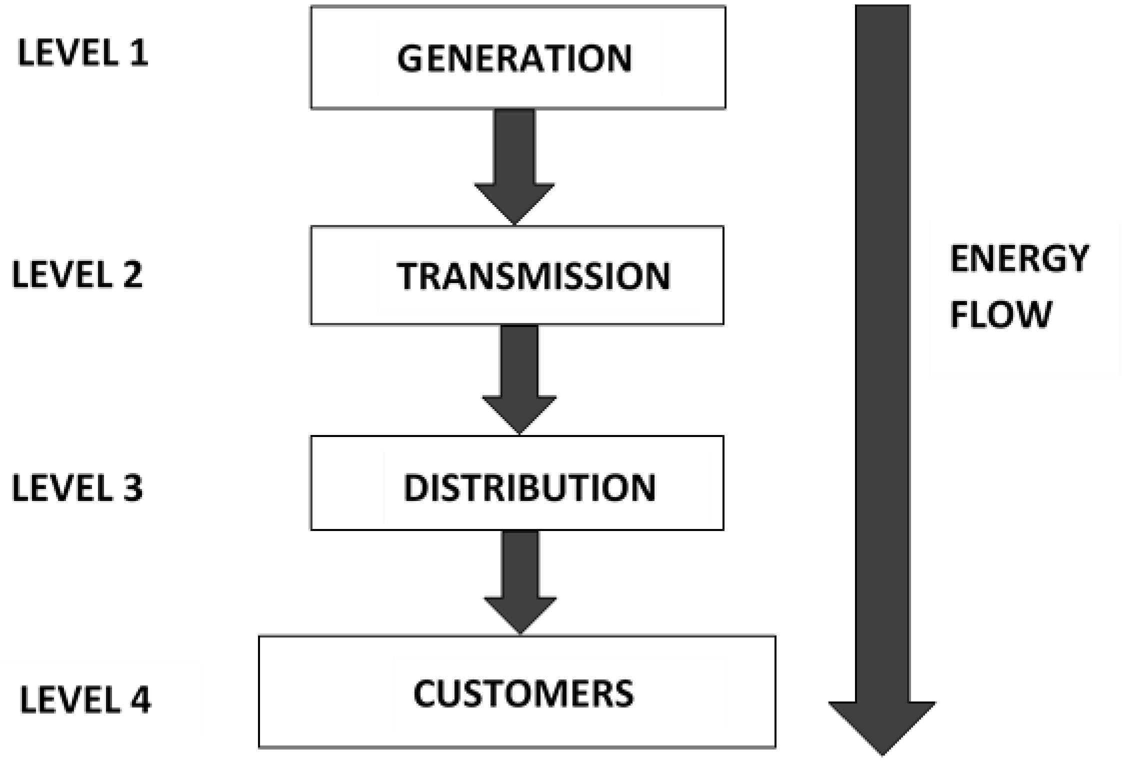


Figure 2.1:The Traditional Power System (Fernnandez Sarabia, 2011)

In figure 2.1, at level 1 there is generation of electricity in large plants located far away from consumers. The voltage is stepped up by transformers from 24kV (generation voltage) to transmission level voltages of 132 kV, 400 kV or 765 kV. At level 2, the voltage is transmitted using overhead lines and underground cables to distribution level. At level 3, the voltage is stepped down into lower voltages using transformers and distributed to the consumers (Fernnandez Sarabia, 2011)

2.3 The new concept of power systems

Presently, with advancement in technology, climate change, environmental concerns as well as the improvement in the electrical and financial market, there has been a move towards a green future promoting the use of Renewable Energy (RE) sources. Electricity can now be produced from small-sized plants to supply loads and feed excess back into the grid. The global crisis of climate change has resulted in the increased deployment of RE sources such as wind energy, solar, hydropower and bioenergy amongst others.

Hydropower is less popular compared to solar and wind due to the complexity and access to rivers and lakes, slowing its utilisation and development. Contrary to this, wind and Solar PV continue to dominate due to their easy access and less dependency on physical location particularly Solar PV.

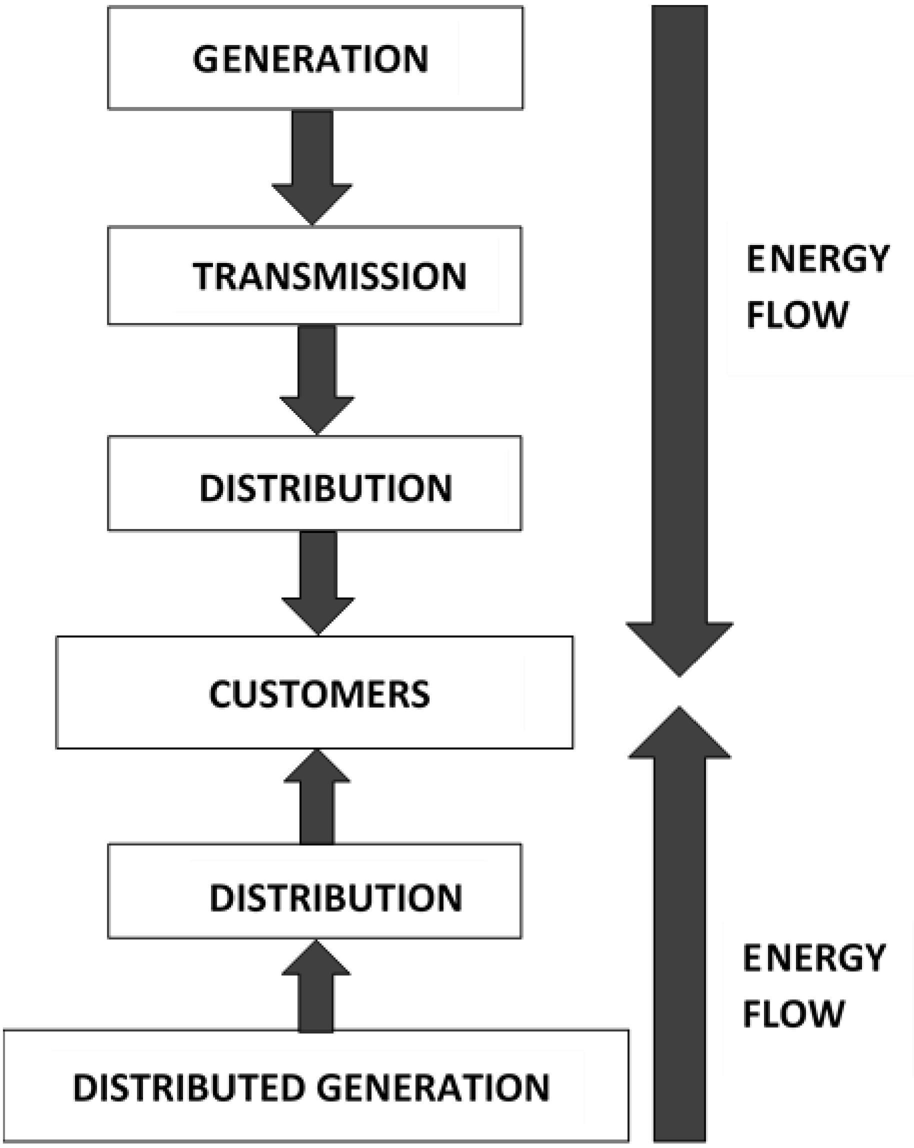


Figure 2.2: The modern concept of Power Systems (Fernnandez Sarabia, 2011)

Figure 2.2 illustrates the modern concept of electricity generation. Part of the energy is supplied by centralized generation usually far from consumers and a part of it supplied by distributed generation usually close to the consumers.

2.4 Distributed Generation (DG)

DG is described in many different ways but basically is small scale electricity generation (Pepermans et al., 2005). These generation sources are usually smaller in capacity than the centralized power sources and typically integrated at LV and MV networks (Fernnandez Sarabia, 2011). Due to the improvement in technology, DG sources now range from as small as 1kW to 1000MW. The definition of DG is very diverse.

A high penetration of these units under the same power system infrastructure may impact the network stability. Most of these generation sources are variable with high dependency on climate and can pose a threat to the national grid. Most economies have written interconnection codes highlighting the requirements for these generators in case of abnormal interruptions (Frede Blaabjerg, Yongheng Yang, 2017).

The most popular DG Technologies are listed in Table 2.1

Table 2.1: DG Technologies and their typical sizes (Niwas et al., 2009)

No.	Technology	Typical size
1	Combined Cycle Gas Turbine	35 - 400MW
2	Internal Combustion Engines	5kW - 10MW
3	Combustion Turbine	1 - 250MW
4	Micro-Turbines	35kW – 1MW
5	Fuel Cells, Phos.Acid	200kW – 2MW
6	Fuel Cells, Molten Carbonate	250kW- 2MW
7	Fuel Cells, Proton Exchange	1 -250kW
8	Fuel Cells, Solid Oxide	250kW – 5MW
9	Battery Storage	0.5 – 5MW
10	Small Hydro	1 – 100MW
11	Micro Hydro	25kW – 1MW
12	Wind Turbine	200W - 100MW
13	Solar Photovoltaic Arrays	20W – 10 MW
14	Solar Thermal, Central Receiver	1 -10MW
15	Solar Thermal, Lutz system	10 - 80MW
16	Biomass Gasification	100kW – 20MW
17	Geothermal	5 – 100MW
18	Ocean Energy	0.1 -1MW

Technologies 10-18 are renewable DG sources while other can only be considered renewable if operated with biofuels (Niwas et al., 2009).

2.4.1 The role of DG in the power system

DG technologies are becoming increasingly more popular due to their merits they bring into the power network such as energy security and voltage stability. Most of these technologies are cleaner providing more benefits in the modern world where the world is fighting pollution and Co2 emissions.

Currently, power systems are becoming very complex in the operation, structure, management and ownership. DG plays a significant role in the mix to solve some of the problems that exists in power networks and are also useful in proving ancillary services, aggregation technology (Niwas et al., 2009).

2.4.2 Benefits and drawbacks of DG

Table 2.2: Benefits and Drawbacks of DG (Pepermans et al., 2005)**,** (Fernnandez Sarabia, 2011)

Benefits	**Drawbacks**
Grid support, DG can contribute power to the grid to maintain a sustainable system. Increases reliability to consumers.	**High financial costs,** these have high capital costs hence they are still expensive to deploy.
Environmental concerns, provides clean energy considering that the reduction of carbon emissions is a global objective presently.	**Grid Instability** some of the DG use converters which inject harmonics into the grid. System frequency may deviate from rated value of 50Hz
Collective generation of heat and electricity, use of CHP systems.	May result in **over-voltage and unbalanced system,** if there is no proper coordination with the grid supply.
DG have **shorter installation time** and **payback period**	May alter the **short circuit levels**, hence need to change relay settings.
Improves voltage profiles, power quality and supports voltage stability. Ability of the power system to withstand high loading conditions.	**Connection issues,** changes the power flow, can reduce the effectiveness of protection equipment

2.4.3 South Africa’s energy mix

There are seven geographical operating units that separate South Africa’s electric power network, each comprising of its own transmission and the distribution network. Thermal generation from mainly coal continuously dominates the base generation with most of these units located in the northern and north-east regions of the country (Bello et al., 2013). This is mainly because South Africa has large coal reserves which are anticipated to last them for more than 50 years according to the Department of Energy in SA. Eskom however anticipates they have up to 200 years of coal reserves, 53 billion in numbers (Eskom Holdings SOC Ltd, 2019)

The energy sector is mostly controlled by Eskom, a state-run enterprise which not only produces 95% of South Africa’s electricity, but also operates and owns the country’s transmission system. Private entities only produce about 2% of the country’s electricity (Pegels, 2010).

Energy Source	Existing Generation & 20 year plan		
	Capacity MW	*Energy GWh*	*2011 Integrated Resource Plan MW*
Coal fired	37 715	218 212	6 250
Hydro-electric	661	1 904	2 609
Pump storage	1400	2 962	
Gas turbines	2 426	709	6 280
Nuclear	1910	23 502	9600
Renewable energy	3.15	2	*17 800*
Availale Capacity	44 115	237 291	
Foreign imports		13 038	
Local IPP & co-gen		4 107	

Figure 2.3: South Africa's Energy Mix (Bello et al., 2013)

As seen on Figure 2.3, DG currently contributes a small portion of the total generating capacity in the country. The government introduced the Integrated Resource plan in 2010 with the aim of increasing the Renewable energy contribution to 17 800MW by 2030. The economy is open to the idea of going green and saving the environment. It is one of the leading economies in Africa in terms of Renewable energy generation and contribution to the grid. The idea is to mitigate the country’s energy crisis, isolation of electricity in the rural and remote areas of SA and to curb the environmental problems arising from over dependence on coal.

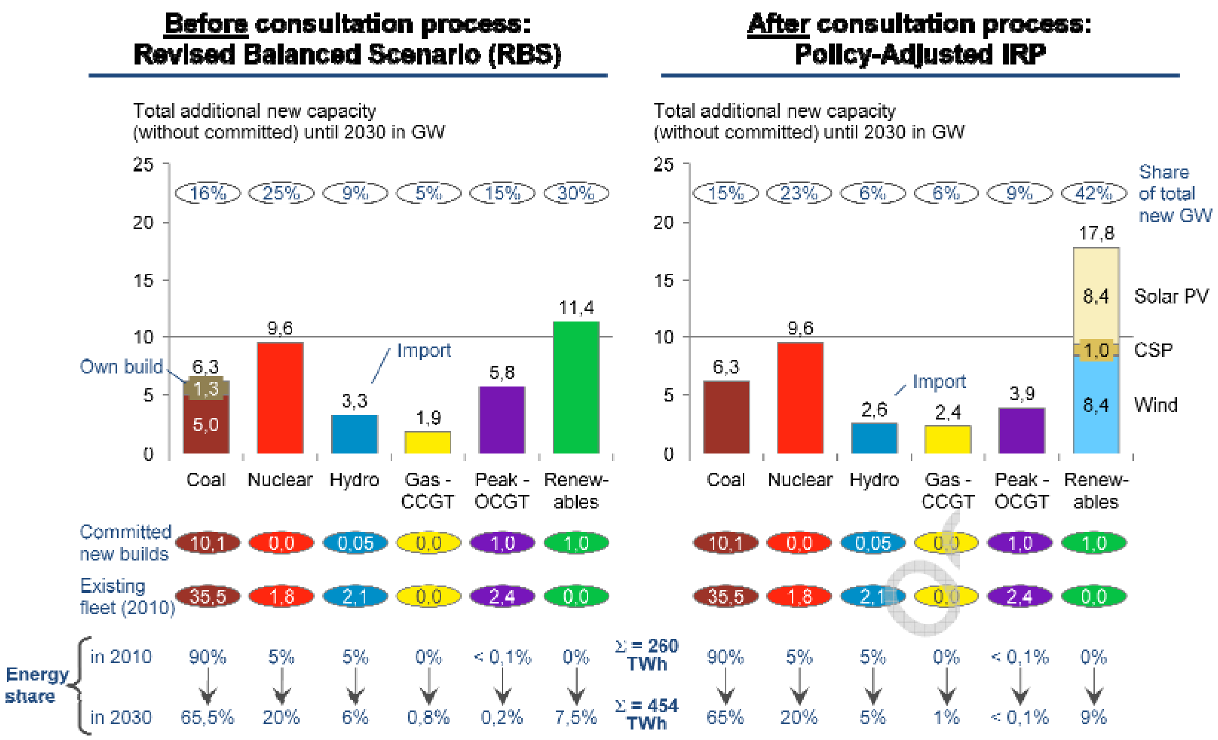


Figure 2.4: Policy adjusted IRP (Department of Energy, 2011)

Figure 2.4 shows South Africa’s plan to have a shared contribution of 17 800MW from Renewable Energy. The Integrated Resource Plan 2010 (IRP2010), is a living plan by the government which is continuously adjusted as necessitated. Every two years, the plan is updated (Department of Energy, 2011).

The nation's pledge to promote RE technologies was derived back from the post-apartheid period in 1996 when most of the policies emerged from the Constitution. In 1998, South African government published a White Paper on Energy Policy and following that, other policy documents were published like the 2003 White Paper on Renewable Energy (WPRE) and the 2011 White Paper on National Climate Change Response Policy (WPNCCRP). The National Development Plan (NDP) was also published in 2011 reflecting on the Government's pledge to promoting RE technologies for sustainable growth (Jain & Jain, 2017).

In terms of GDP, in the year 2012 SA was the fourth major investor in RE. In that year, 16.9% of total energy consumption was from Renewables. Back in 2009, the National Energy Regulator of South Africa (NERSA) had announced renewable energy feed-in-tariffs (REFIT) (Jain & Jain, 2017). REFIT policy was aimed at reducing prices of RE electricity by setting up definite prices for a predetermined period that would cover the cost of supplying electricity as well as a reasonable profit in order to allow investment from RE developers. The idea of REFIT policy was implemented and adopted due to the positive experience of other countries like Germany, Spain and USA (Nakumuryango & Inglesi-lotz, 2016).

2.4.4 South African Grid-Code requirements for RE sources

The Grid Code is an outline of operational rules and requirements given by the power system operators to connect to the grid. The National Energy Regulator of South Africa (NERSA) developed the South African Grid code, and it stipulates the minimum grid connection requirements for RPP who are connected or wish to connect to the SA grid. It applies to all the RE sources or Distributed Generation including solar, wind, small hydropower and bioenergy (NERSA, 2014).

Abnormal Operating conditions

According to (NERSA, 2014) the Renewable Power Plant (RPP) should be designed to endure abrupt phase fluctuations of up to 20° at the Point of Connection (POC) without decreasing their output. Immediately after a settling period, the RPP should recommence operation within five seconds. Plants of the size ranging from 0 to 100kVA should be designed to withstand voltage ride through conditions (NERSA, 2014).

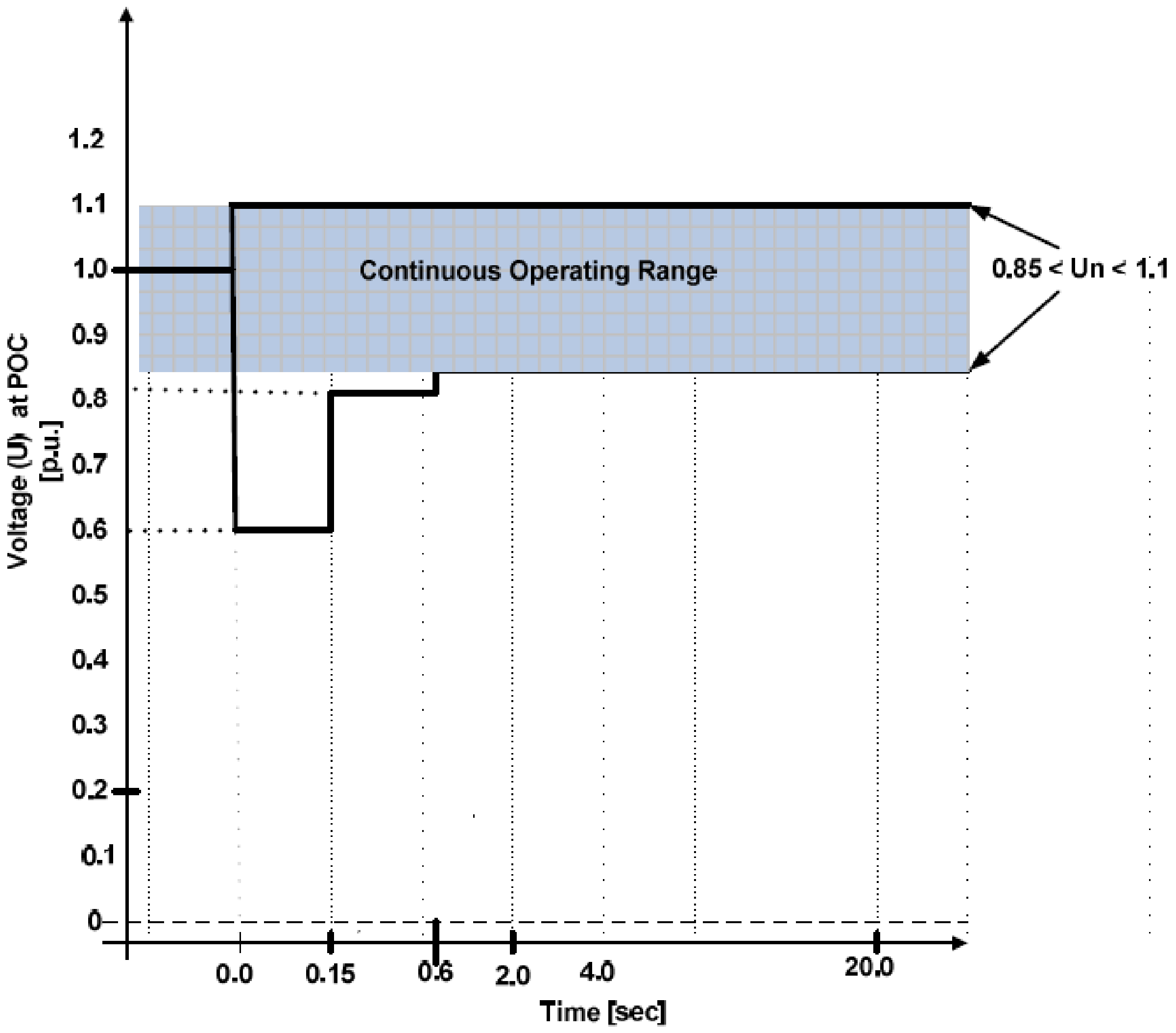


Figure 2.5: : Voltage Ride Through Capability for the RPPs of size 0-100kVA (NERSA, 2014)

Figure 2.5 shows the voltage ride through capability of RPPs with the capacity of 0-100kVA. The shaded region shows the region in which the RPP is expected to continue normal operation. The table below shows the maximum disconnection times of the RPP of the size 0-100kVA (NERSA, 2014).

Table 2.3: Maximum disconnection times for RPPs of size 0-100kVA (NERSA, 2014).

Voltage range (at the POC)	**Maximum trip time** [Seconds]
V < 50 %	0,2 s
50 % ≤ V < 85 %	2 s
85 % ≤ V ≤ 110 %	Continuous operation
110 % < V < 120 %	2 s
120 % ≤ V	0,16 s

RPP of the capacity 100kVA or higher should be designed to be able to endure voltage drops to zero for a minimum of 0.150 seconds as well as withstanding voltage peaks of up to 120% of nominal voltage for a minimu time of 2 seconds without disconnecting. Figure 2.6 shows the conditions that the RPPs should comply with and applies to both symmetrical and asymmetrical faults. It shows the voltage ride through capability of RPPs with capacity higher than 100kVA (NERSA, 2014)

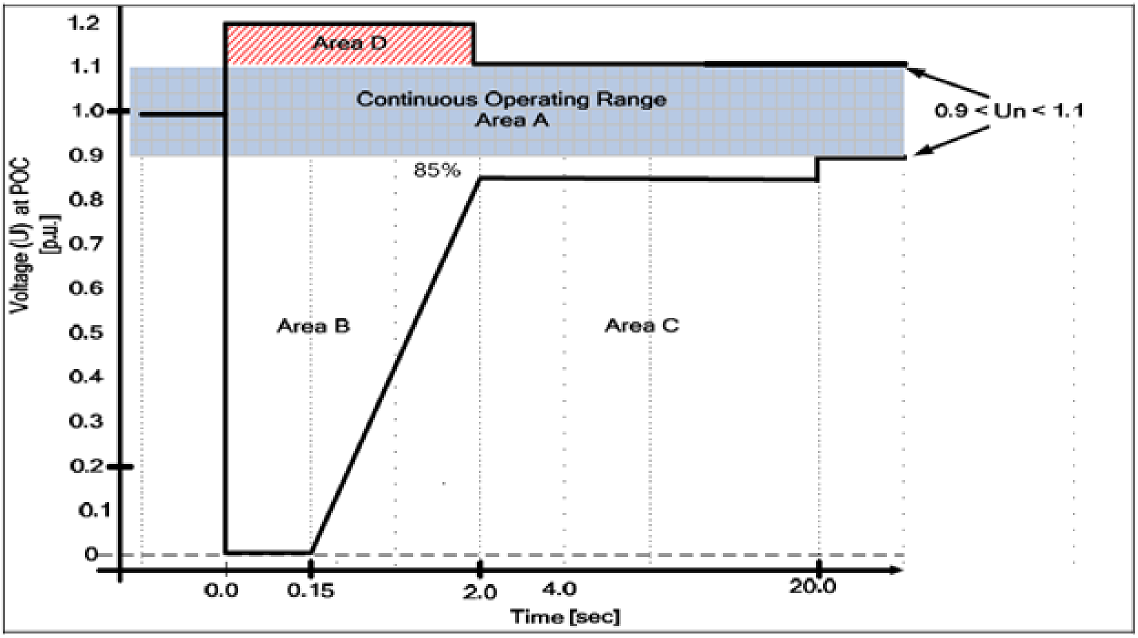


Figure 2.6: Voltage Ride Through Capability for the RPPs of the size greater than 100kVA (NERSA, 2014)

In summary, during a fault if voltage relapses to Area A and Area B, the RPP may not disconnect. Disconnection of the RPP is only allowed in Area C. In area B and D, the RPP should be able to control the reactive current. In Area D, the plant should remain connected and have the capability to deliver maximum voltage support.

In Area B, the plant should prioritize supply of reactive power while the secondary priority is supply of active power. It should be able to maintain the active power when there is voltage drops however a decrease in the active power inside the Plant's design specifications must be proportional to the voltage drop for all voltages below 85%. When the fault has cleared, the RPP can restore its active power production to 90% of the level accessible instantly preceding to what the active power was before the fault. This action should be done within 1 second (NERSA, 2014).

2.4.5 Wind Energy Generation

Wind energy generation uses large turbines to transform wind energy into electricity (Fernnandez Sarabia, 2011). There has been a massive growth in the installation of wind turbines over the past few decades. Presently, the installed generation is over 440GW and is anticipated to surpass 760 GW by 2020, therefore making wind energy generation important for the modern and future energy mix (Blaabjerg, 2014).

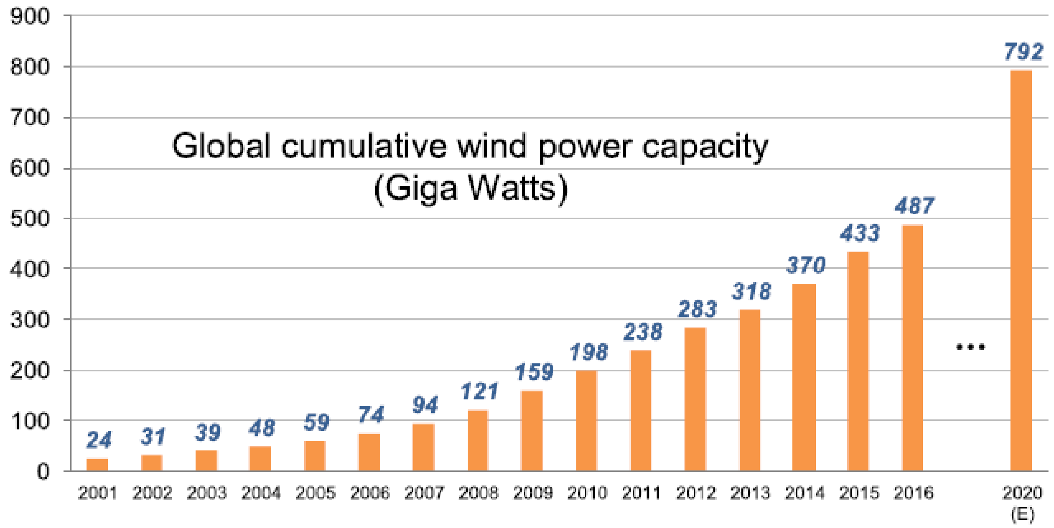


Figure 2.7: Global Cumulative wind power capacity 2001-2020 (Blaabjerg, 2014)

The figure shows how wind power has increased over the years globally from 2001 -2016 and the anticipated capacity by 2020. South Africa is one of the major wind power generation players in Africa. By the end of 2015, wind generation accounted for approximately 55% of the RE capacity worldwide excluding hydropower. In terms of global electricity production, wind accounted for 3.7%. The South African Wind Energy Association (SAWEA) predicts that wind energy alone could potentially generate 62% of SA's present energy needs (MUSONI, 2018).

Wind Turbines configuration

Four main categories of Wind Turbines (WT) can be used to define them namely

a. Fixed speed WTs, abbreviated FSWTs and these operate in the narrow range of rotor speed.
b. Double-fed Induction Generator Wind Turbines (DFIGWT), work on a variable speed with partial frequency converter concept.
c. Partial variable speed WTs (PVSWTs) which work with variable rotor resistance.
d. Voltage Source Converter (VSC) based WTs , these work on variable speed with full rating power converter (Brady, 2014).

The power electronics configuration of the turbines has changed over the years. Squirrel-cage induction generators (SCIG) were the type of wind turbines used in the 1980s which were basically configured as soft starters. Thyristors were used in the power electronics of the turbines. In the 1990s, the technology used rotor resistance control of WRIGs (wound-rotor induction generators). Since the millennium year 2000, more advanced power electronics converters have been introduced (Blaabjerg, 2014). They can now handle continuous wind turbine power generated. DFIGs (Double-Fed induction generators) are now being used.

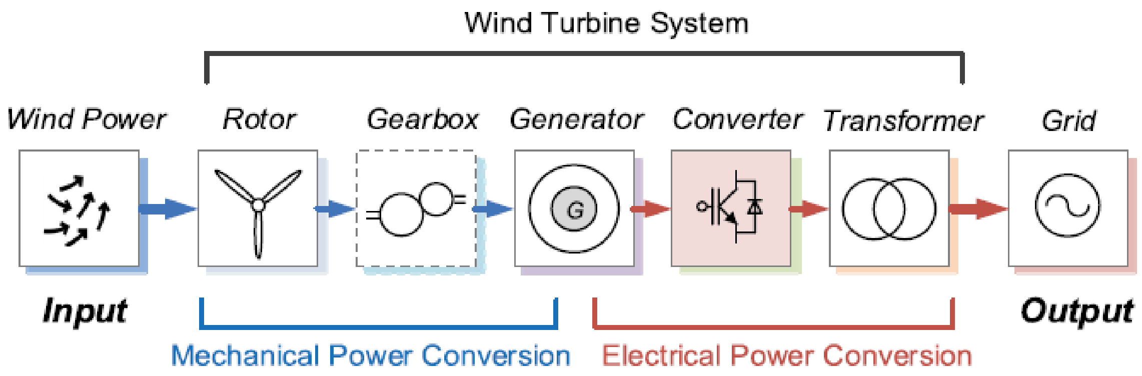


Figure 2.8: A typical Wind Turbine System (Some systems avoid gear box) (Blaabjerg, 2014)**.**

As shown in the above figure, a typical WTS has a rotor, gearbox in certain applications, an electric generator, power electronics converter and a transformer (Herbert et al., 2007). There are different categories in wind turbine designing which normally depend on speed controllability, generator and aerodynamic power limiting. Power electronics also plays a crucial role in the WT concepts. The Doubly Fed Induction Generator (DFIG) has become widely common over the past decade (Blaabjerg, 2014).

Doubly Fed Induction Generator (DFIG)

The DFIG models are used to control the reactive and active power in wind generation. This is done by providing flexible speed operation within wide ranges. The term double-fed is derived from the configuration of the generator as both the stator and rotor are connected to an electrical source. The controls of the generator are very fast due to their "solid state" nature normally taking less than two to three cycles to achieve full response. DFIG has increasingly become popular in the modern wind turbine configuration due to its advantages over other wind turbine models (Jauch et al., 2007).

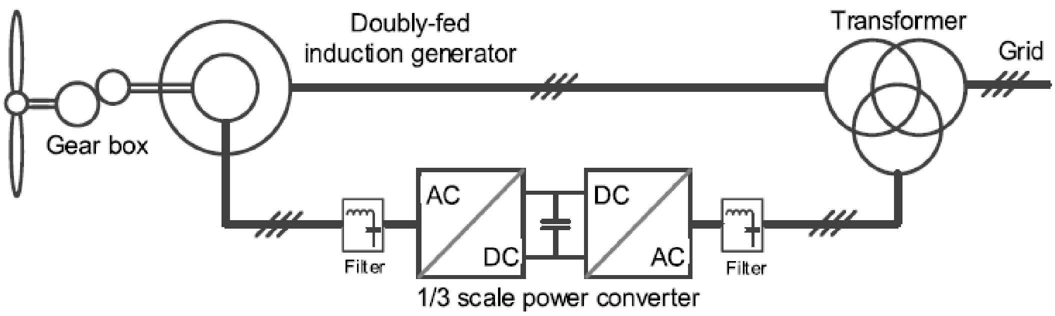


Figure 2.9: Wind Turbine system with DFIG control (Blaabjerg, 2014)

The figure shows a wind turbine using the DFIG configuration. The stator is connected to the grid through a transformer while the rotor connects to the grid through power converters and normally have about 30% power capacity of the wind generator. The rotational speed of the rotor blades maximises the energy yield of the system. The rotor frequency and current are controlled by the power electronics in the DFIG configuration controls. The main drawback of DFIG systems are their use of slip rings which have inadequate power controllability in the event of grid or generator disturbances (Blaabjerg, 2014).

Fault Current Contributions from DFIG configurations

DFIG configurations get extreme voltages induced onto the rotor when there are severe faults in the power network. These voltages are in turn fed onto the power converter. The main problem with this configuration is that it is very costly to design the converter in such a way that it can resist the voltages and currents induced by faults in the network. Hence why DFIGs use a crowbar function intended to divert the imposed rotor current. Various approaches are used to attain the crowbar functionality, which include:

- Connecting a thyristor as a shorting device in parallel with the machine’s rotor and the power converter (rotor side).
- Switching the power converter on the rotor side as a means of shorting of the rotor.
- The most common crowbar functionality is the use of a chopper circuit. This circuit is connected to the converter’s dc bus intended to reduce the dc bus voltage and divert the current coming from the rotor in the event of a fault.

Within certain limits, DFIG control has the capability to keep the electrical power constant despite the unstable wind. However, in this control, there are problems associated with the stator’s direct connection to the grid such as huge disturbances leading to excessive fault currents in the stator. There are advantages with high stator currents particularly for the protection relay coordination in the power system. The high current allows for the circuit breakers to trip the faulty section of the network while isolating the wind turbine from the fault.

The main aim of the protection system is to protect the wind turbine in the event of a fault. This also includes anti-islanding protection. The desired variable speed ratio is one of the factors used to determine the stator-rotor ratio on designing of DFIG controls. This however might make it impossible to achieve desired rotor voltage when trying to control the excessive currents in the rotor when there is a fault. Hence only partial control is given onto the converter during grid faults (Jauch et al., 2007).

2.4.6 Solar Energy Generation

Although solar energy presently represents a small percentage in the global energy mix, there has been an overall increase in the use of the technology particularly solar PV for distributed power generation. There has been a reduction in their costs in the past decade due to technological advancement, economies of scale and innovations in the financing of the technology. The cost is likely to continue decreasing sand hence provide opportunities for developing countries to explore the technologies as well. Solar energy has an installed capacity greater than 137GW globally and has annual additions of about 40GW every year (International Finance Corporation, 2015)

The most common solar energy generation are PV (Photovoltaic) systems. A PV system converts direct sunlight into electrical energy. The electricity produced is normally in the form of direct current (DC). It uses solar cells which are semi conductive materials that convert the self-contained energy of photons into DC when exposed to sunlight. Solar PV systems are environmentally friendly and have simple designs. They however require large spaces of land and have high capital costs (Fernnandez Sarabia, 2011)

Global Renewable Energy Resource potential

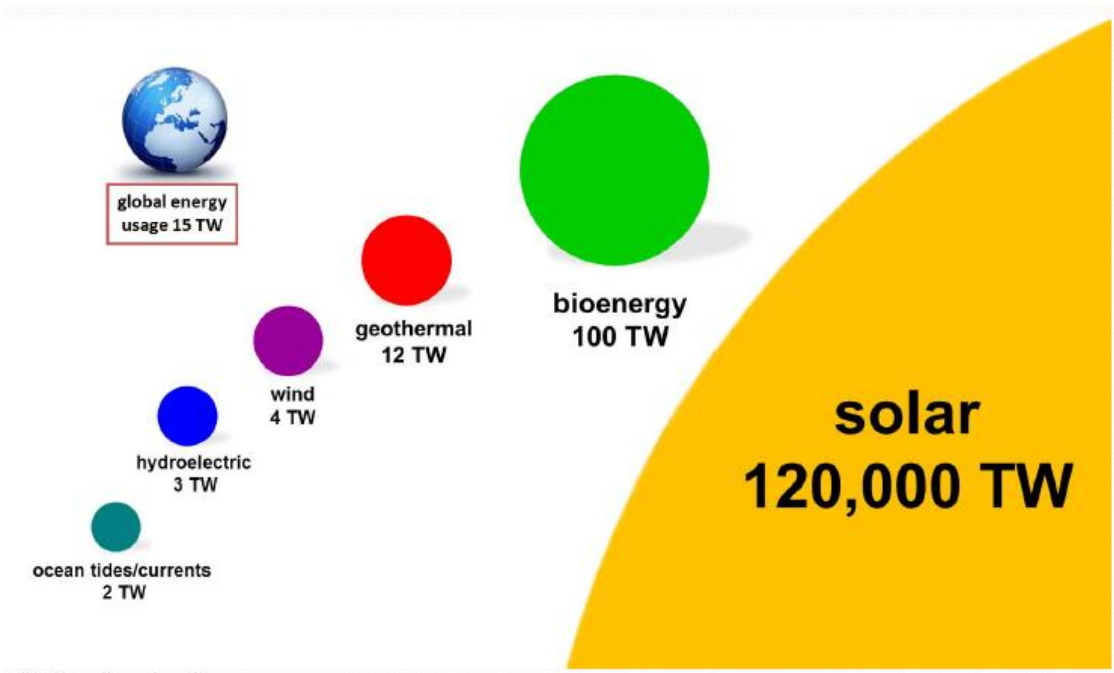


Figure 2.10: RE sources potential (The University of Edinburgh, 2017)

The figure shows the maximum potentials for most DG Resources however it is impossible to harness all the energy. Solar Energy has the most potential due to the sun being powerful. in If humans could harness all the energy from the sun, then it would provide 10 000 times what the world needs. Currently, the Global average energy consumption is about 18TW and it is predicted that by 2050 the consumption will be 30TW and 46TW by 2100. The maximum power that can be supplied by fossil power by 2050 is estimated to be about 18TW. This leaves about 12TW needed supply from Carbon-free sources (Tao, 2014). In SA, most areas average over 2 500 sun hours per year. There is great potential in the generation of electricity through Solar in the country.

Components of a PV system

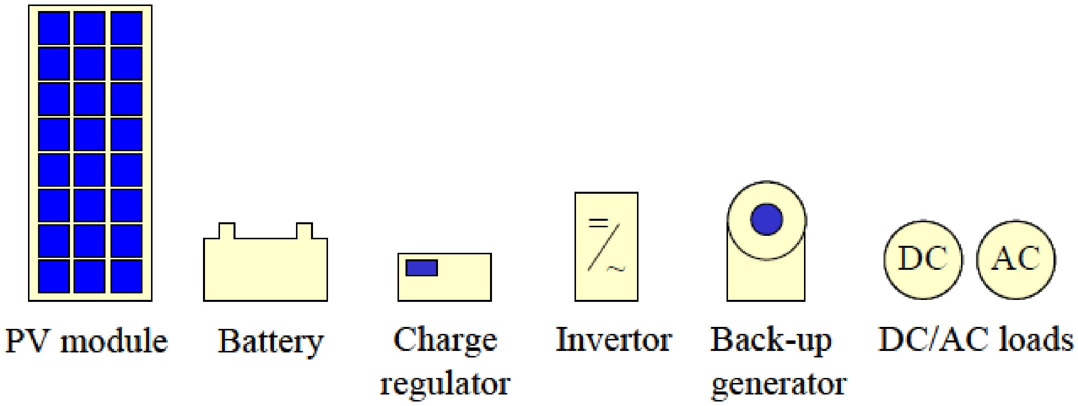


Figure 2.11: Components of a PV System (Zeman, 2013)

As seen on figure 2.11, a PV solar system consists of the following parts:

- **Solar array**; - can be defined as PV modules or solar panels wired together. Each solar module is made from solar cells. An individual cell typically produces power between 1 and 2W which is not enough to power most loads. Several cells are then connected to make a PV module or solar arrays. Solar panels are the heart of the system generating electricity in the form of Direct Current. These are usually called the power generators in the PV system.
- **Energy storage (Batteries**); - electric rechargeable batteries are used for storage purposes. The DC current from the PV modules can be used to charge the batteries. Lead acid batteries are the widely used storage batteries, but presently lithium-ion batteries are becoming more popular. The lithium Ion batteries have longer life and therefore more costly than the lead acid batteries. In some applications, nickel-cadmium batteries are used particularly in areas with extreme climate conditions. The major drawback with energy storage of Solar PV systems is the high cost of batteries particularly for commercial and industrial applications (Zeman, 2013).
- **Charge regulators**; - these devices regulate the direct current from the solar panels and using it to charge the batteries. They allow smooth operation of the batteries extending the life of the batteries.
- **Inverters**; - the PV system constitutes inverters which transform DC into AC. They also regulate the effective value of the AC output voltage. They are designed to operate by

tracking the maximum power point of the solar array. The efficiency of the inverter is important with most inverters designed with an efficiency of over 90% which may be affected by climate and environmental factors. The inverter's overload capability must be considered when sizing grid-connected inverters. It is best to use an inverter with a power rating of 70% to 90% of the PV array to achieve optimal system performance. This also depends on several factors such as climate and the inverter’s performance characteristics.

- **Back-Up Generator**- can be used in conjunction with the Grid and PV system. Particularly useful in off-grid installations in case of winter months where there is low solar radiation.
- **Electrical load**; - these are appliances, such as lights, plugs and other equipment powered by the PV system (Zeman, 2013)

Types of PV systems

Solar PV systems can be categorised into three main types;

1. **Off-grid systems**; - also known as stand-alone systems. They rely on PV modules as energy source. The common configuration consists of only PV modules with batteries for energy storage, a DC/AC inverter and a load.
2. **Grid connected systems**; - also known as Grid-Tie systems. The inverter is tied to the grid supplying power to the loads directly from the solar modules and feeding excess back into the grid. They do not require batteries for storage though sometimes they may have them for back-up.
3. **Grid Fallback systems**;- these systems are not popular as the rest of the types. In this configuration, the solar panels generate power which charge the battery bank. The energy in converted by the inverter into AC which feeds the loads. When the batteries are completely drained, the system switches back to the grid supply (Boxwell, 2012).
4. **Hybrid Systems**; - These consists PV modules connected to a DC/AC inverter with a complementary source of electricity generation for example a diesel, gas or wind generator (Zeman, 2013)

Grid-connected PV systems

Grid connected, also known as grid-tie systems are the most common type of PV system. They are designed using solar arrays, inverters and other balance of systems such as mounting structure, power transformers (for large plants) and may have back-up storage etc (Raj et al., 2016). A grid-connected system can be represented on a schematic as shown on figure 2.12.

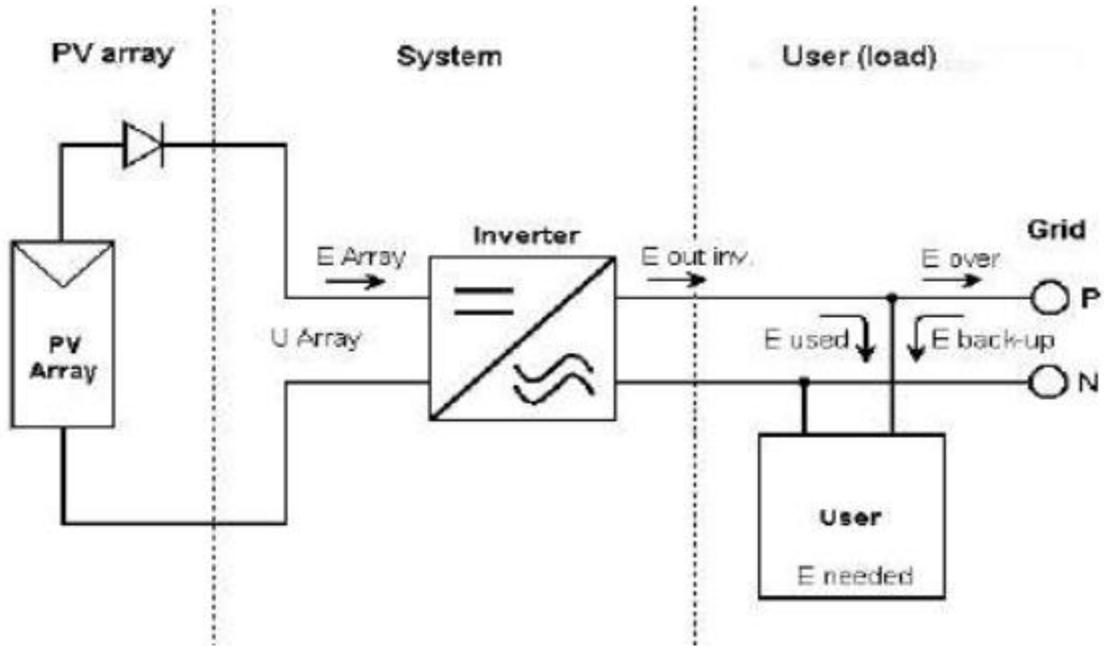


Figure 2.12: Grid-connected PV system schematic (Raj et al., 2016)

Different types of Grid-Tie inverters are being manufactured world-wide, which basically convert the DC from the solar arrays to Alternating Current (AC) (Raj et al., 2016). Grid-connected system in residential applications are connected before the utility meter with the Solar PV system supplying the loads during the day and the grid supplying loads at night. For applications in large power plants, voltage from the PV system is stepped up by power transformers to higher voltages and transmitted into the grid.

Solar PV System operation under fault conditions

The short-circuit phenomenon in an electric grid normally takes place typically from a few to 10 cycles (which is within the inverter's maximum interruption timeframe) of up to 170 milliseconds. During this period, circuit breakers must operate and should be able to interrupt the short-circuit current.

In the past, DG plants such as Solar PV could disengage from the grid during severe faults and allowed to reconnect after clearing of the fault. Nowadays however, due to the significant share of renewables, they may not be allowed to disconnect. The system may break down if several generating plants in the power system disconnect simultaneously which may result in a blackout. Most countries now outline grid connection requirements for DG through a grid code. The Low Voltage Ride Through requirement is established and is intended to warrant that the generating plants remain connected when there is a fault (Dirksen & Gmbh, 2013).

2.4.7 Fuel cells

Fuel cells can be defined as static energy conversion devices converting fuel chemical energy into direct current (Wang & Nehrir, 2006). The generation sizes are normally as small as 1kW up to 1MW (Guaitolini et al., 2018). They are not a common type of electricity generation in South Africa. The main types include;-

- SOFC- Solid Oxide Fuel Cells
- AFC- Alkaline Fuel Cells
- PAFC- Phosphoric Acid Fuel Cells
- MCFC- Molten Carbonate Fuel Cells and
- PEMFC- Polymer Electrolyte Membrane Fuel Cells (Guaitolini et al., 2018)

Main advantages; -

- High efficiency
- Flexible modular structure
- None or low emissions of gases and noise free
- Allow for grid reinforcement
- Defer the need for systems upgrades
- Improve system integrity, reliability & efficiency (Wang & Nehrir, 2006)

The basic operation of a grid-connected Fuel Cell

The FC (Fuel cells) convert chemical energy in fuel to DC, which require power electronics devices to produce AC power to be fed into the grid.

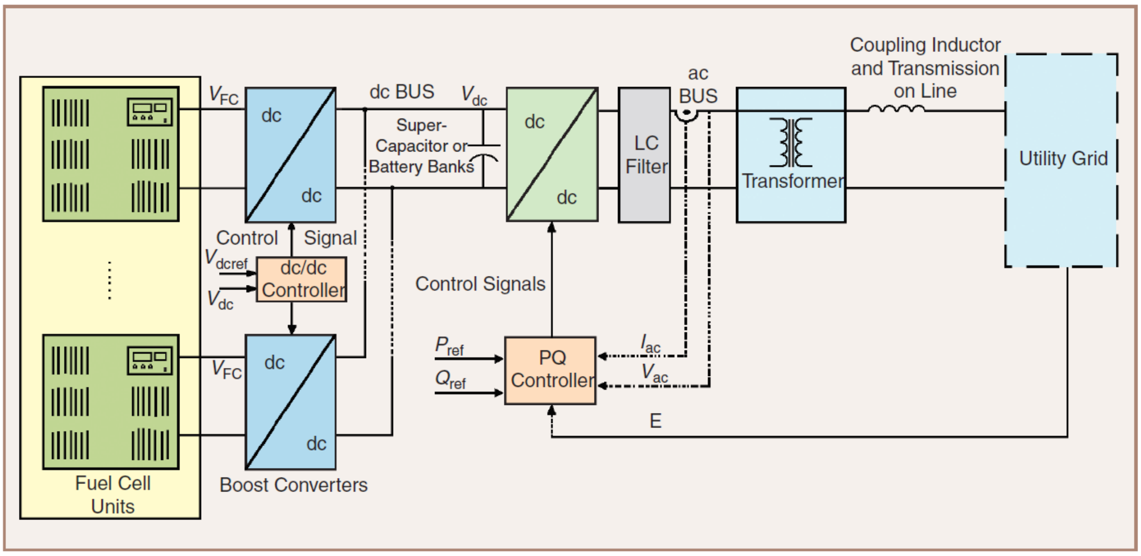


Figure 2.13: A schematic of a grid-connected Fuel cell (Nehrir et al., 2006)

They use DC/DC converters to control the output voltage to the desired DC voltage range. An inverter is subsequently used for the conversion of the fairly good input DC voltage to AC (Wang & Nehrir, 2006).

Figure 2.13 shows a block diagram of the Fuel cell power generation and the interface with utility grid. They use DC/DC converters and three phase Power Width Modulator (PWM) inverter for conversion. Batteries and super capacitors are normally used as storage devices in the system technology. Undesired harmonics are eliminated by the LC bandpass filter. In the PEMFC system a short transmission line is used to connect to the utility grid (Nehrir et al., 2006). The PEMFC is one of the most common type of fuel cells electricity generation used globally.

2.4.8 Microturbine Generation

Micro-turbine systems can be defined as a combination of elements normally gas or wind turbine combined with a generator which is normally a permanent magnet. One of the differences between a micro-turbine and regular turbine is that a micro-turbine works at high speed and is much more efficient than the regular turbine.

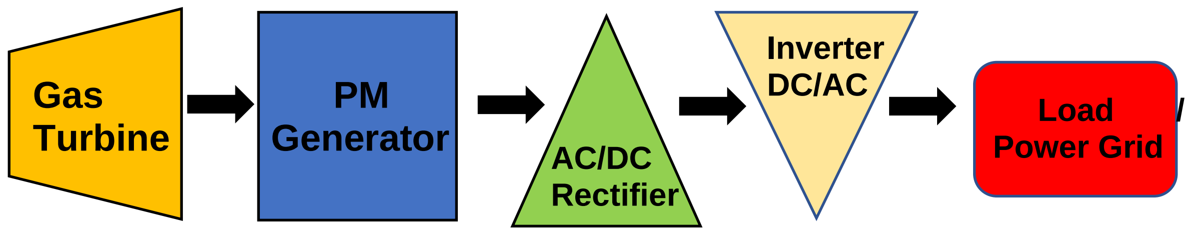


Figure 2.14: A Micro-turbine system (Báez-Rivera et al., 2006)

The figure above shows a simple Micro-turbine system with converters and the electric grid or load. These types of models are normally small in capacity size with low maintenance required, very durable and with low emissions. Natural gas, ethanol or diesel can be used with the turbines (Báez-Rivera et al., 2006).

Single shaft or split shaft are the two types of micro-turbines and are named according to their configurations. The single shaft has the generator and turbine connected while the split shaft connects the generator and turbine through a gearbox. The shaft runs at high speed and has no lubrication. Normally the power plant is air-cooled with two-pole permanent magnet generator (Lasseter, 2002).

.

2.4.9 Induction and Synchronous Generators

Induction and synchronous generators convert mechanical energy into electrical energy which is fed into a load or utility grid (Blaabjerg, 2014). Induction generators are popular in the Micro Hydro Power (MHP) and Pico Hydro Power (PHP) applications.

Advantages of induction generators;

- Low capital cost
- Low emissions of gases
- Less maintenance required
- Low fault levels
- Simple excitation system (Gawande et al., 2011)

Concept of operation

With induction generators, a prime mover which can be a turbine or engine is used to rotate the shaft quicker than the synchronous frequency. The flux direction and active currents should change direction for the machine to provide power. Induction generator power factors depend on the load and is normally lagging. They are much preferred than the synchronous generators. They use reactive power to build a magnetic field by using the mains. They can’t be easily used for backup generation particularly during islanded operation. The induction generators are asynchronous machines.

On the other hand, synchronous generators run at specific synchronous speed and can be called constant speed generators. Unlike the induction generators whose power factor is lagging, the synchronous generators have variable power factor, they work very well in power factor correction applications. They provide lagging power factors when they operate on infinite busbars and there is over-excitation and delivering leading power factors when there is under excitation. Nowadays, the synchronous generators are commonly used in hydro, wind and thermal power systems. System sizes range from 1kW to a few Mega-watts (Blaabjerg, 2014), (Józef et al., 2018).

2.5 Electrical Faults

During normal operating conditions, power flows through all components in an electrical power system. However due to unforeseen circumstances like lightning strikes and other natural events, faults occur. There various types of faults and they are normally classified into two main categories;

a. **Symmetrical Faults**- Can be referred to as balanced faults. They are normally excessive and occur intermittently in the power system. Examples include three-phase to ground faults and three phase faults.

b. **Asymmetrical Faults**- also known as unbalanced faults and occur more frequently in a power network. They are normally less severe compared to symmetrical faults. Examples include single-phase to ground faults, line to line faults and phase-phase to ground faults. The most common are the single-phase to ground faults, merely 65 to 70% in power systems (Thakur, 2016).

2.5.1 Types of faults in electrical power systems

a. Single-phase to ground faults

This type of fault occurs when one phase has contact with earth or ground. The fault currents can be calculated, and their concept is based on Ohms Law. These are the most common type of faults accounting about 70% of the faults that occur in a power network.

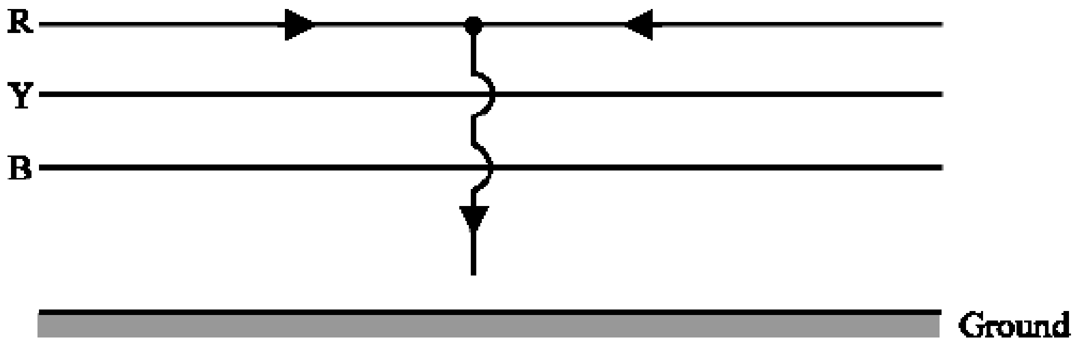


Figure 2.15: Single-phase to ground fault (A.O. Osahenvemwen, 2008)

b. Line to line faults

These types of faults occur when two phases have contact. An example is shown on the figure below where there is contact between the Yellow phase and the Blue phase.

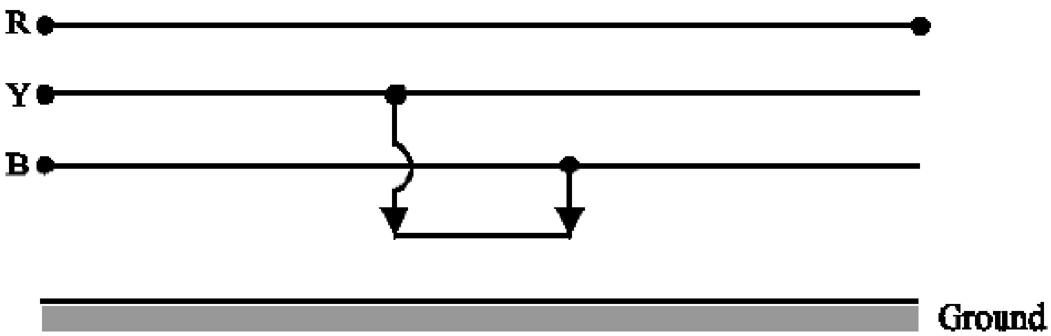


Figure 2.16: Line to line fault(A.O. Osahenvemwen, 2008)

c. Two lines to Ground faults or phase-phase to ground faults

Arises from contact between two phases/lines and ground. AN example is shown on the figure below with a fault between Yellow and Blue phase to Ground.

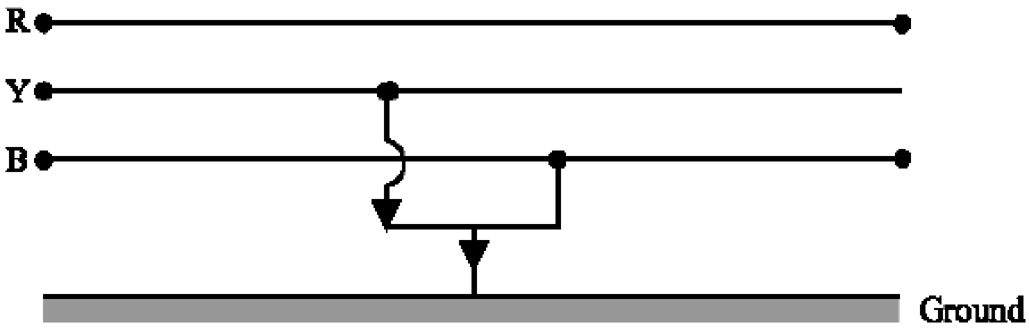


Figure 2.17: Two line to ground fault (A.O. Osahenvemwen, 2008)

d. Three-phase faults

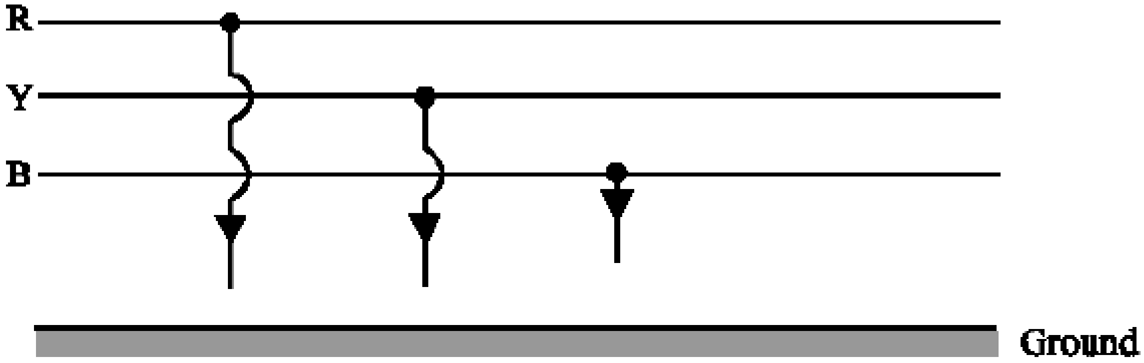


Figure 2.18: Three-Phase Fault (A.O. Osahenvemwen, 2008)**.**

These types of faults occur when three phases have contact (Red, Yellow and Blue). They normally account for about 5% of all faults in a power system. These types of faults are balanced, an illustration is shown on Figure 2.18

e. Three-phase to ground faults

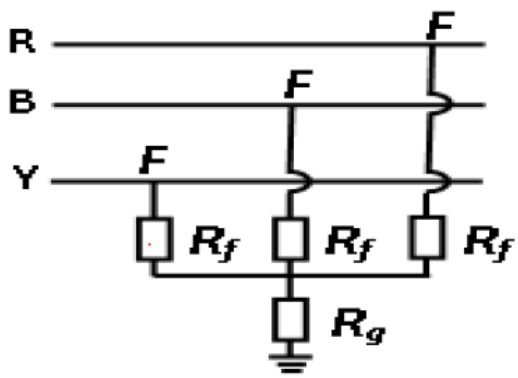


Figure 2.19: Three-Phase to Ground Fault (Folarin et al., 2018)

This type of fault normally occurs when there is contact between the three phases (Red Yellow and Blue) with Ground as illustrated on Figure 2.19.

2.6 General concept of relays

A relay is a device used in protection systems for opening and closing electrical contacts leading to the operation of other devices under electric control such as circuit breakers. The role of a relay is simply to detect intolerable or undesirable conditions within an allocated area. The relay acts to disconnect the area affected as means of protection to prevent damage to humans and equipment, by operating the suitable circuit breakers. Relays can be classified according to their functions, either as measuring devices or on/off relays also known as all-or-nothing relays. Examples of on/off relays include time-lag relays, auxiliary relays, and tripping relays (El-Hawary, 2015).

Some of the examples of relays are listed below;-

a. **Current relays**- These types of relays are triggered by current. They operate at predetermined current levels for example undercurrent or overcurrent relays.
b. **Voltage relays**- are triggered by voltage, operating at predetermined levels of voltage for example overvoltage or undervoltage relays
c. **Power relays**- are triggered by power operating at predetermined levels of power for example overpower or underpower relays.
d. **Directional relays**- these can be grouped into two types;
    - **(i)** **Alternating current**- these are triggered by the phase relationship between alternating quantities.
    - **(ii)** **Direct current**- these are activated according to the direction of the current. They are normally of the permanent-magnetic, moving-coil pattern.
e. **Frequency relays**- are triggered by frequency and operate and predetermined levels of frequency. Examples are overfrequency and underfrequency relays.
f. **Temperature relays**- are triggered by temperature and operate at predetermined levels of temperature.
g. **Differential relays**-these relays use scalar difference between two quantities such as current & voltage during their operation.
h. **Distance relays**- are commonly applied in distance protection of transmission lines. They operate according to the "distance" between the relay's current transformer and the fault. Three elements are used to measure the distance which are resistance, reactance, or impedance (El-Hawary, 2015).

2.7 Simulation Software (DigSilent PowerFactory)

DigSilent also known as PowerFactory is a leading power system analysis software typically used in generation, transmission, distribution and industrial systems. Some of its functionality over the recent years includes real-time simulation, wind power and distributed generation modelling. Some of its basic features include load flow and short circuit analysis, network modelling and basic MV/LV network analysis. It also has advanced features which are contingency analysis, network reduction, cable analysis, power quality and harmonic studies, protection coordination and reliability studies amongst others. The most important tool covered in this thesis is the Protection function and distributed generation (DigSILENT, 2019).

There are different methods of calculating short-circuit current which include the nodal method, complete method, symmetrical component method and dynamic time method (Brady, 2014). The most widely used is the symmetrical component method both when using DigSilent software or when doing hand calculations.

The IEC 60909 standard is used in this study is based on the superposition method of calculating short circuits by providing an equivalent voltage source at the fault location. The following assumptions are made;

a. Bus voltage is assumed to be equal to the rated voltage.
b. Load currents are disregarded
c. Loads are not taken into account in the positive and negative sequence of the network

2.8 Summary

This chapter provided a comprehensive literature review on the traditional power system which was known to be vertically integrated with one utility handling all the functions of the power system versus the new concept power systems which is more decentralized with the inclusion of distributed generation. The basics of power system components was covered, the protection system and different distributed generation sources including the South African energy mix with the 2030 vision of increasing their RE contribution. Part of the literature survey explained in the chapter covers the regulatory requirements around the connection of DG into the power grid particularly in the case of South Africa. The different types of faults that occur in a power system are explained with illustrations of the faults. The last part of the chapter explains the simulation software used in the study, (DigSilent PowerFactory) providing a description of what the software does and the IEC 60909 standard in calculating short circuit current.

CHAPTER THREE
IMPACT OF DG ON ELECTRIC PROTECTION SYSTEM

3.1 Introduction

Population in South Africa has been increasing day by day and there has been a high increase in infrastructural development in the country over the years. Infrastructural development requires the use energy. Many people in the rural developments still do not have access to electricity. This has led to a high demand for energy and the need to resort to other means of generating electricity apart from the traditional methods. The integration of DG has its own advantages which include improved voltage profile, security of supply, cleaner energy sources and improved reliability of the network (Bari et al., 2017).

While the penetration of DG has its pros, their integration in power systems initiate some challenges for grid operation. DG integration creates a full spectrum of problems, ranging from voltage profile, power flow, protection, and stability. The existence of DG elements in power systems and transmission lines may also cause maloperation of protection devices which may result in failure to correctly identify faults. Furthermore, the increasing penetration of DG using power electronics-based devices in power systems is also raising important challenges regarding the overall power system stability. Most DG technologies are usually based on power electronic converters and these systems are likely to interact with each other, triggering instability in power systems in certain conditions.

The most common impact in protection systems is on protection coordination of Relay devices. It is important for a protection system to be highly effective and capable of isolating a faults in a network (Choudhary et al., 2015). This chapter covers the impact of DG on the electric protection system as identified by other sources and different ways to mitigate them.

3.2 Requirements of a Protection System

Below are the requirements of a Protection system;

a. **Reliability**- the protection system must be dependable and secure. There must be assurance that it will work as is it designed to work. In the event of a fault , the protection system closest to the fault must isolate the fault. It should also be secure enough to avoid unnecessary operation during normal operation.
b. **Sensitivity**- must be able to detect every small internal fault current.
c. **Discrimination-** ability to distinguish between external and internal faults in a zone. Protection coordination in Overcurrent Relays is an example of discrimination in protection systems.

d. **Simplicity**- they must be simple and easy to repair or maintain.
e. **Economy**- must be cheap, achieving the best protection system and minimum cost.
f. **Speed-** response time must be quick in the event of a fault (Onah, 2019).

3.3 Potential problems to protection

According to previous studies, DG can cause several problems to the existing network particularly at distribution level. Some of the common challenges include;

a. False tripping
b. Nuisance tripping of the DG source
c. Increase or reduction in short circuit current/ fault levels
d. Blinding of protection
e. Unsynchronised reclosing
f. Unsolicited islanding
g. Prevention of automatic reclosing

The appearance of the challenges depends on numerous factors including the kind of DG source. Most of the time, penetration of DG requires changing of the existing protection (Kumpulainen, 2004).

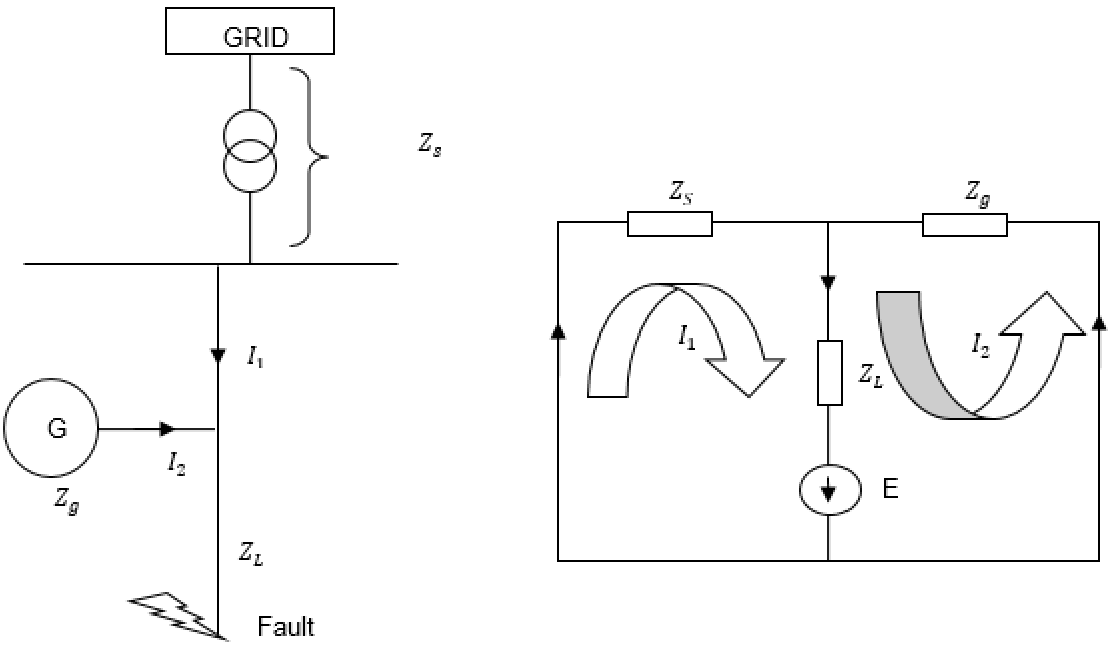


Figure 3.1: Short circuit fault in MV network (Kumpulainen, 2004)

Theoretically, Figure 3.1 can be used to explain the concept of how DG can contribute to the fault current. In the event of a fault at the end of the feeder as shown on the diagram, the total fault current with be the addition of I_1 and I_2. The impedances will be as follows;

Z_S= Grid and primary transformer impedance

Z_g= Generator impedance

Z_L= Line/ Feeder impedance

From Thevenin equivalent circuit, if we assume the feeder relay sees current I_F, when there is no production from DG. The ratio between I_F and I_1 can be derived as;

$$\frac{I_1}{I_F} = \frac{Z_g(Z_S + Z_L)}{Z_S(Z_L + Z_g) + Z_L Z_g}$$

The generator's short circuit impedance may be expressed using the short circuit impedance of feeding network will be;

$$Z_g = aZ_S$$

While the impedance of the line can be expressed as

$$Z_L = bZ_S$$

The ratio of the currents can be simplified as below;

$$\frac{I_1}{I_F} = \frac{a+ab}{a+b+ab}$$

Representing currents with and without the generator (Kumpulainen, 2004).

3.4 Distance Protection

Distance protection relies on the tolerance of the impedance measurement at the feeding point of a relay to the position of the fault. This type of protection is normally used in transmission lines on the HV and MV networks. A schematic is shown in Figure 3.2

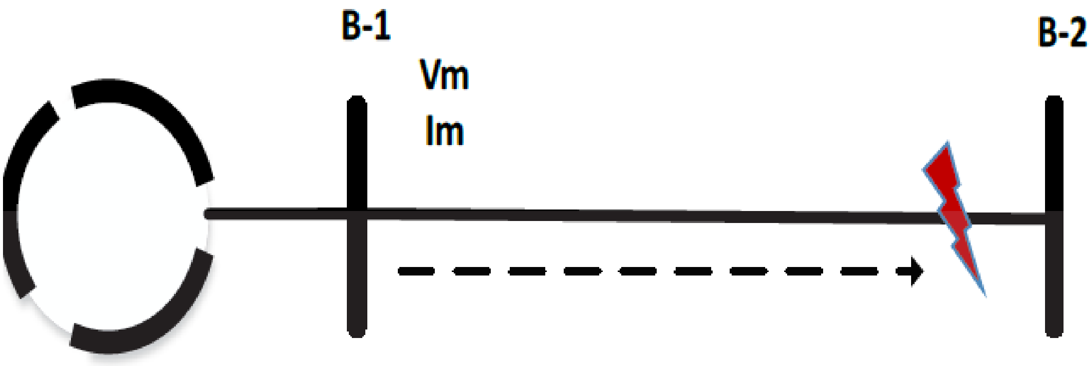


Figure 3.2: Fault in a transmission line (Distance Protection) (Saad et al., 2018)

From Figure 3.2, $Z_m = V_m / I_m$ (Saad et al., 2018). In normal operation, the impedance Z_m is measured by the Distance relay which will be approximately equal to the load impedance.

When there is a fault in the protected zone, the impedance of the distance relay will be lower than that of the transmission line. Whenever the impedance value is lower than the set value, then the fault is within the relay protection zone.

In summary, the standard operation of distance relays involves dividing of voltage at the relaying point by the current measured. The apparent impedance is compared to the reach point impedance. A fault in the line is assumed by the relay in the event of the measured impedance being lower than the reach point impedance. Operating time and reach accuracy are used to assess the distance relay performance. The level of voltage seen by the relay when there is a fault is one of the factors that affect its reach accuracy (Edvard Csanyi, 2012).

3.4.1 Setting Distance Protection Relays in transmission lines.

This process is normally done by separating the protection zone into three zones with different tripping times, Zone 1, Zone 2 and Zone 3. Zone 1 is the primary Zone while the other two Zones provide Backup protection.

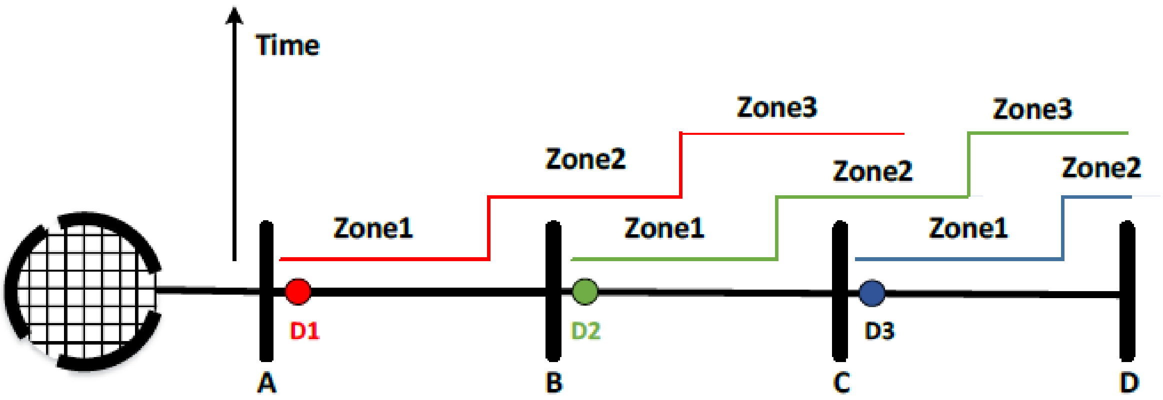


Figure 3.3: Time Grading in Distance Protection (Saad et al., 2018)

Figure 3.3 shows time grading of Distance relays in a power system. Zone typically covers 80% to 90% of the line (Ahmad & Bukka, 2015). This is the primary protection and hence the tripping time is minimum. It is represented by the equation;

$$Z_{1A} = 0.8\, Z_{AB}$$

Zone 2 is set at minimum 120% of the protected line. Common practice is to set Zone 2 reach equal to 100% of the protected line as well as 50% of the shortest adjacent line. This is Backup protection hence the tripping time is higher than that of Zone 1. Time grading of 0.4 seconds is commonly used. This is represented by the equation below;

$$Z_{2A} = 0.8\,(Z_{AB} + 0.8\, Z_{BC})$$

The rest of the protection zone is covered by Zone 3 which is normally 0.7 seconds. It is represented by the equation;

$$Z_{3A} = 0.8\ [Z_{AB} + 0.8\ (Z_{BC} + 0.8\ Z_{CD})] \qquad \text{(Saad et al., 2018)}$$

3.4.2 Integration of DG in Distance Protection network

The integration of DG into the power network may increase the fault current. This will result in the relays' measured impedance measured to change. An example is shown on the below illustration.

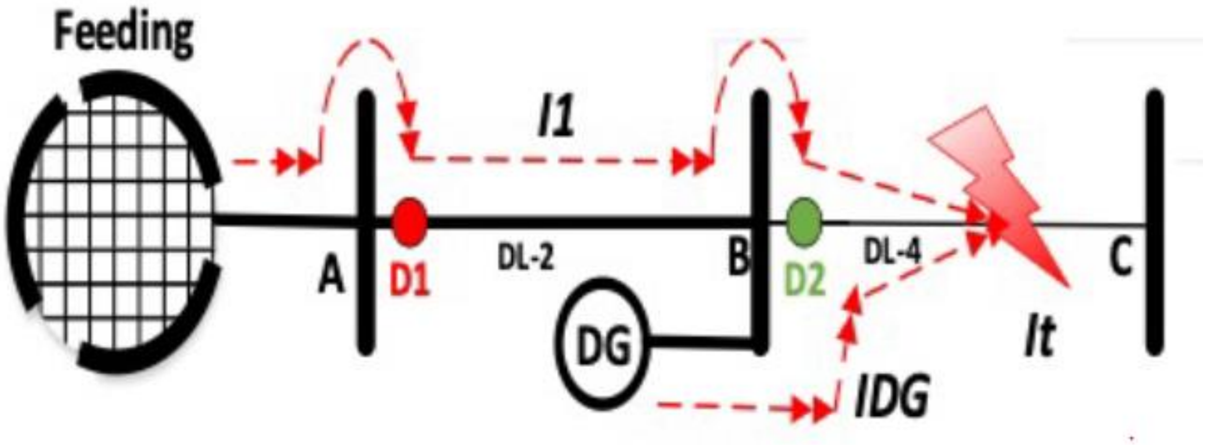


Figure 3.4: Integration of DG in Distance Protection network (Saad et al., 2018)

The impedance measured by Distance relay S1 on line B1 will change with the penetration of DG and may exceed the measured values in a case where the sources aren't connected. The impedance Z_m can be calculated using the formula;

$$Z_m = \frac{U_m}{I_m} = \frac{I_1 Z_{DL-2} + I_t * Z_k}{I_1} \qquad \text{(Saad et al., 2018).}$$

There is a change in the impedance measured due to the advent of DG into the network. This may result in non-selective tripping of the relays which can be calculated by the below equation;

$$K_{if} = \frac{I_t}{I_1} = \frac{I_1 + I_{DG}}{I_1}$$

The K coefficient in the equation compensates for the change in fault current to restore the distance relay protection settings. The three zones will then be defined by the equations;

$$Z_{1A} = 0.8\ Z_{AB}$$

$$Z_{2A} = 0.8\ (Z_{AB} + 0.8\ Z_{BC}\_K_{if})$$

$$Z_{3A} = 0.8\ [Z_{AB} + 0.8\ (Z_{BC} + 0.8\ Z_{CD})K_{if}]$$

Zone 1 is barely affected as it is the primary protection, Zone 2 and 3 impedances may change (Saad et al., 2018).

3.4.3 Distance Protection relay characteristic curves

May also be referred to as the R-X plot. At the operation frequency of the power network, the relative values of Resistance (R) and inductance (X) are used to determine the fault angle. The fault angle in distance protection affects the impedance relay of a relay.

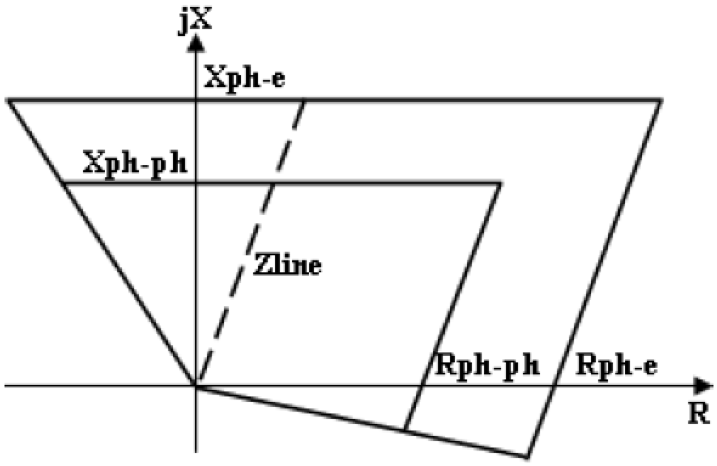


Figure 3.5: Operating characteristic for one distance protection relay (Iagăr et al., 2018)

Figure 3.5 illustrated the distance relay characteristic curve of one protection zone when operation in forward direction. The distance protection zones can operate autonomously in directional mode (Forward, reverse or non-directional mode) (Iagăr et al., 2018).

Xph-e represents the reactive reach during single phase to ground faults
Xph-ph represents reactive reach during phase to phase faults
Rph-e is the resistive reach during single phase to ground faults
Rph-ph is the resistive reach during phase to phase faults
Zline is the line impedance (Iagăr et al., 2018)

Arcs and other earth faults may be involved as part of the resistive component of the fault impedance hence may affect the impedance angle. Under-reach may occur which is a situation where the characteristic angle of the relay is set to the angle of the line under resistive fault circumstances (Abdulfetah Shobole, Mustafa Baysal, Mohammed Wadi, 2017).

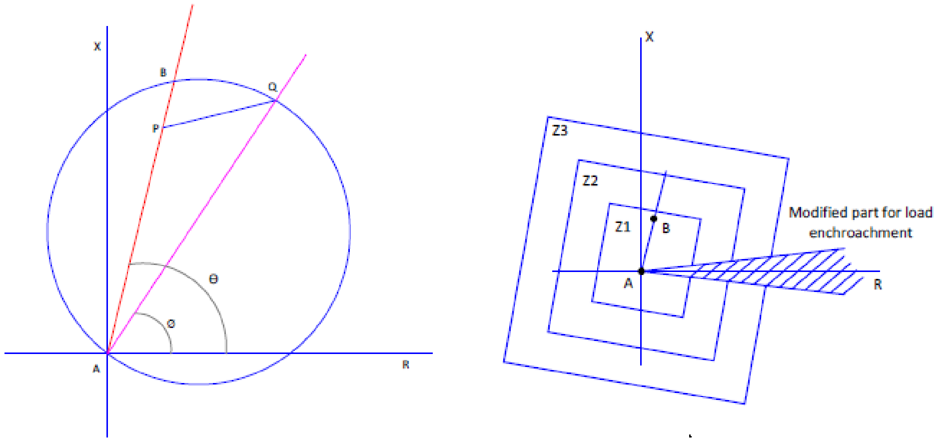


Figure 3.6: Distance relay characteristic curve with arc resistance coverage and load encroachment (Abdulfetah Shobole, Mustafa Baysal, Mohammed Wadi, 2017)

Figure 3.6 illustrates the distance relay characteristic curves with increased arc resistance coverage. PQ shown in the diagram is the arc resistance

$$AQ = \frac{AB}{Cos\ (\emptyset - \theta)}$$

Where;

AQ = Relay impedance setting

AB = Impedance of protected line (Abdulfetah Shobole, Mustafa Baysal, Mohammed Wadi, 2017)

The main advantage of distance protection over other types of protection like overcurrent protection is its ability to isolate a fault of a protected circuit, which may be independent of source impedance variations (Edvard Csanyi, 2012).

3.4.4 Potential Distance Protection Coordination Problems

There are some problems associated with distance relays particularly with the integration of DG. Some of the key issues are discussed below.

a. Under-reach

According to (Brady, 2014) this is an area of concern particularly for networks with numerous in-feed feeders. As previously discussed, distance protection works on the concept of zones where the firsts zone is the primary protection and covers about 80% of the line, while zone 2 protects the remaining section and a margin of the remote line. On the other hand, zone 3 provides the remote line with back-up protection. On the other hand, the reach of the second and third zones can be affected by the presence of in-feed feeders. This may impact the protection system by introducing security and selectivity issues.

An example of under-reaching of relays can be illustrated as shown in Figure 3.7

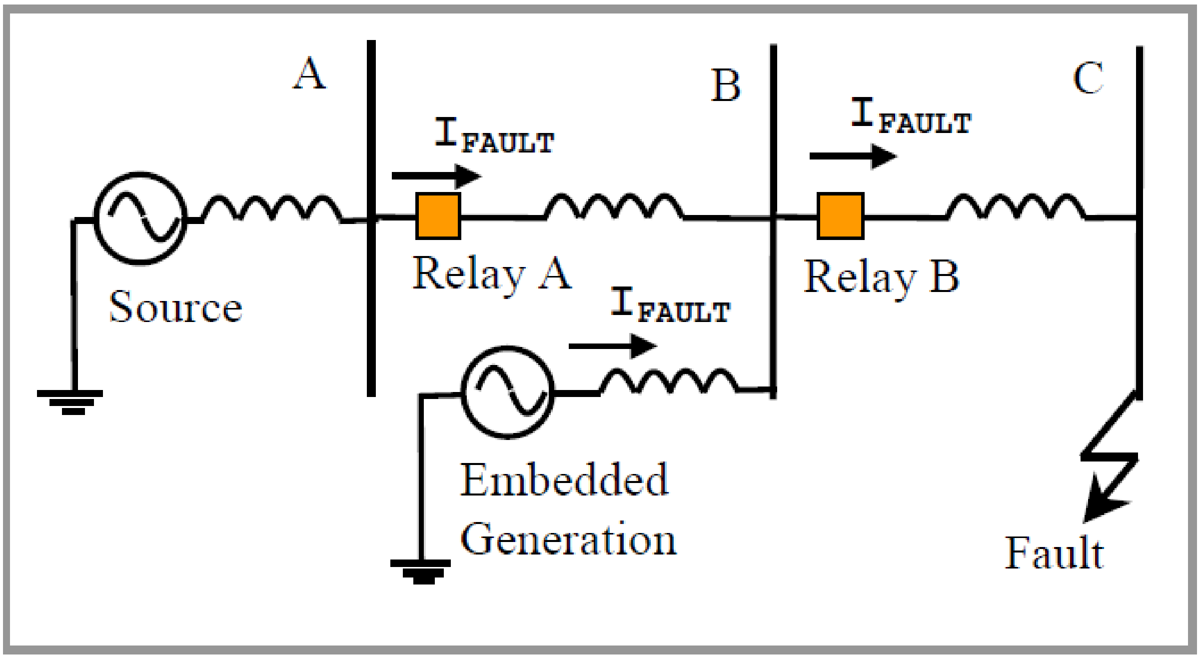


Figure 3.7: Under-reaching of Relays (Klopotan, 2012)

Considering the example of the 38kV radial network, where the parameters are given as below;

$Z_{source} = 6.499 + 13.89j\,\Omega$ which is the source impedance

$Z_{Gen} = 1.591 + 37.305j\,\Omega$ Impedance of the Embedded Generation

$Z_{Gen} = 4.347 + 4.42j\,\Omega$ Impedance of Line from B to C

Before connection of DG at Busbar B, the fault current at Busbar C is;

$$I_{Fault} = \frac{System\ Voltage\ x\ 1.07}{\sqrt{3}\ x\ (Z_{source} + Z_{AB})} \approx 1\,102 \angle 59°$$

Assuming per unit pre-fault voltage is 1.07 pu

Relay at Busbar Qis the backup relay, while relay at Busbar B is set as the primary relay. With the integration of DG, the fault current at Busbar C will be;

$$I_{Fault} = \frac{System\ Voltage\ x\ 1.07}{\sqrt{3}\ x\ (Z_{parallel} + Z_{AB})} \approx 1\,393 \angle 62°$$

Where $Z_{parallel}$ is the combination of Z_{source} and Z_{Gen}. The fault current is a total of

$$I_{system} \approx 1004\angle 56° \text{ A per phase}$$

$$I_{Generation} \approx 412\angle 78° \text{ A per phase}$$

It can be depicted that there is a reduction in the system fault current from 1102A to 1004A with the integration of DG. This may lead to a delay in relay trip time and the required fault clearance time for the Backup relay may no longer be provided (Klopotan, 2012).

To curb the under-reach problem, there is need for Zone 2 and Zone 3 settings to be increased which may also lead to loadability reduction (Brady, 2014).

b. Over-reaching of relays

The reverse of under-reaching of relays is over-reaching. Figure 3.7 can be used to illustrate over-reaching of relays in protection systems.

Before connection of DG;

$$I_{Fault} = \frac{System\ Voltage\ x\ 1.07}{\sqrt{3}\ x\ (Z_{source} +\ Z_{AB})} \approx 1\ 102\ \angle 59°$$

Relay at Busbar B is set as the primary relay, tripping at current 1102Amps.

With the integration of DG;

$$I_{Fault} = \frac{System\ Voltage\ x\ 1.07}{\sqrt{3}\ x\ (Z_{parallel} + Z_{AB})} \approx 1\ 393\ \angle 62°$$

If overcurrent relays or an Impedance relay (Overcurrent started) are used in the system, DG could result in over-reach of the relays (Brady, 2014).

c. Loadability reduction

Basically, relay loadability means the capability of the relay to function under high load conditions. The maximum current a conductor can carry before it anneals losing its elasticity can be used to describe maximum loadability limit of transmission lines. Usually, calculations are done to limit the amount of current a conductor can carry before annealing.

Loadability problems in a protection system may be caused by over-reaching in protection zones (Brady, 2014).

d. Cascade Tripping

Unexpected loading conditions may result in undesired third zone operations resulting in cascade tripping. An example is shown on the figure below

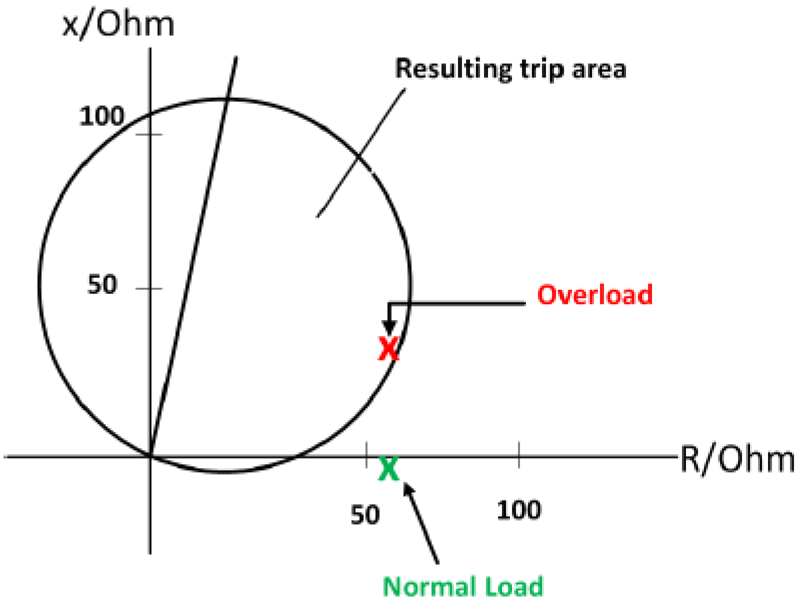


Figure 3.8: Example of Cascade tripping in distance relays (Brady, 2014)

Overload conditions in the line led to the load reaching third zone reach of the relays. Subsequent to the line tripping, loading condition may increase on the part of the line that remains connected leading to the reach of third zone relays as shown in Figure 3.8. The outcome is further highlighted if the initial tripping happens in the in-feed feeder. Normally this occurs in networks with high penetration of DG (Brady, 2014).

3.5 Overcurrent Protection

Overcurrent protection is important to equipment protection and human safety. Overcurrent protection is used in the in the whole electric grid from generation, transmission to distribution in residential homes, commercial and industrial institutions. Protection devices are used to protect against Overload current and short circuit currents (Keller, 2010).

The calculation of overcurrent relay settings involves the calculation of the current and time setting. The load current is used to determine the current setting. Time setting can be calculated using the formula below;

$$t = \frac{TMS\ x\ 0.14}{\left(\left[\frac{I_F}{I_{set}}\right]^{0.02} - 1\right)} \qquad \text{(Hudananta et al., 2018)}$$

Where;

t= Time of operation in seconds

I_F= Short circuit current in Amps

I_{set}= Current setting

TMS= Time multiplier setting

The current setting of pickup current can be determined in two ways, namely;

a. It is two times the value of the maximum load current or

$\frac{1}{3}$ x Minimum fault current at nearest bar

b. Can be selected between 1.25 x maximum load current and $\frac{2}{3}$ x minimum load current (Ilik & Arsoy, 2017).

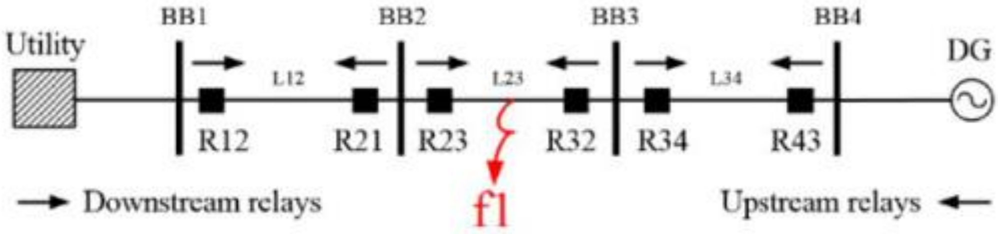


Figure 3.9: Multiple sources radial system (Ilik & Arsoy, 2017)

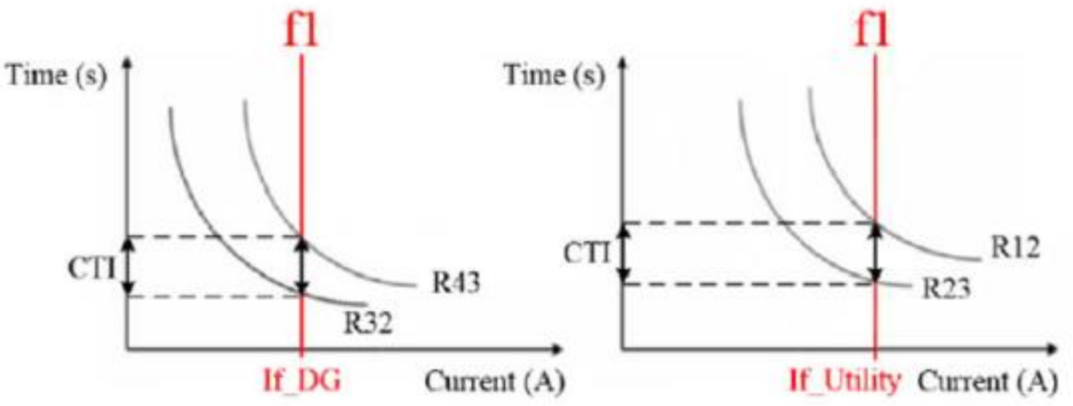


Figure 3.10: Upstream and downstream relays for f1 fault (Ilik & Arsoy, 2017)

The coordination of the directional overcurrent relay can be explained by Figure 3.9 and 3.10. Relays (R12, R23 and R34) are the downstream relays while (R21, R32 and R43) are the upstream relays. The downstream relays are coordinated together and only trip from a utility fault while upstream relays are also coordinated to trip from the DG fault contributions. If a three-phase fault occurs at f1, then relays R12, R23, R32 and R43 will detect the fault current.

The behaviour of the relays is illustrated in figure 3.10, R23 being the main protection relay for the downstream currents which should trip first. R12 is a back-up relay which will trip if R23 fails to isolate the downstream fault current. Normally the time intervals between the relays is set between 0.2 to 0.5 seconds. The same applies for the upstream currents, R32 should trip first as it is the main protection relay. If it fails to isolate the upstream fault currents, then R43 will trip (Ilik & Arsoy, 2017).

3.5 Time Grading

It is highly important that the protection system keeps its operating time minimum to increase the life of equipment and improve voltage quality of a network. Two types of relays will be analysed in this section.

3.5.1 Definite Operating Time Relays

According to (Onah, 2019), these types of relays are normally used in situations where there is a small difference between the levels of currents flowing for faults in various points of a network. In such cases, series wired sections do not have substantial impedances at their junctions. Normally the impedances of the sections will be less than the source impedance.

The tripping time differences of the relays linked to the adjacent sections is made in such a way that it is enough to trip the suitable circuit breaker clearing the fault. Generally, time grading of up to 0.5 seconds is adequate. An example if shown on Figures 3.11 (a) and (b) below;

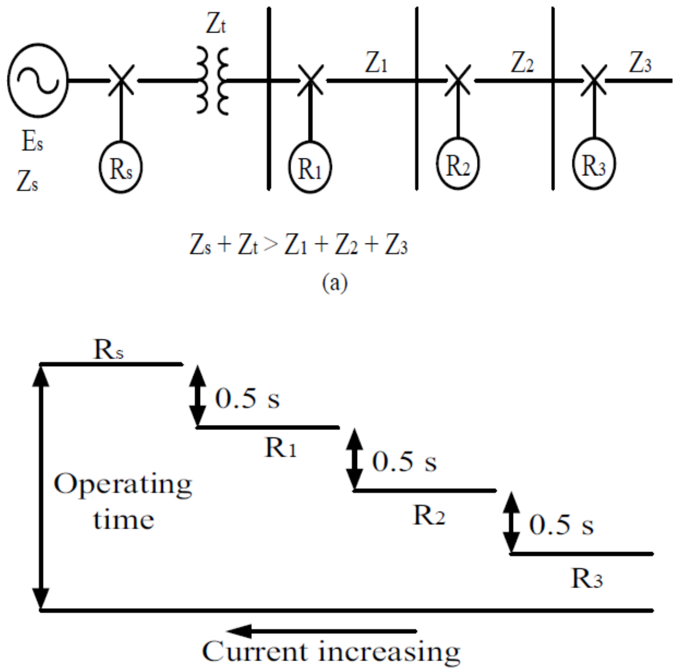


Figure 3.11: Definite Time Relays (Onah, 2019)

Figure 3.11 (a) shows an example of a protection system network with definite time relays, Figure 3.11 (b) illustrates the time grading of 0.5 seconds between the relays. Discrimination is only dependent on time (Onah, 2019).

3.5.2 Definite Current Relays

These types of relays operate when the current in a power system reaches a predetermined value. An example is shown below.

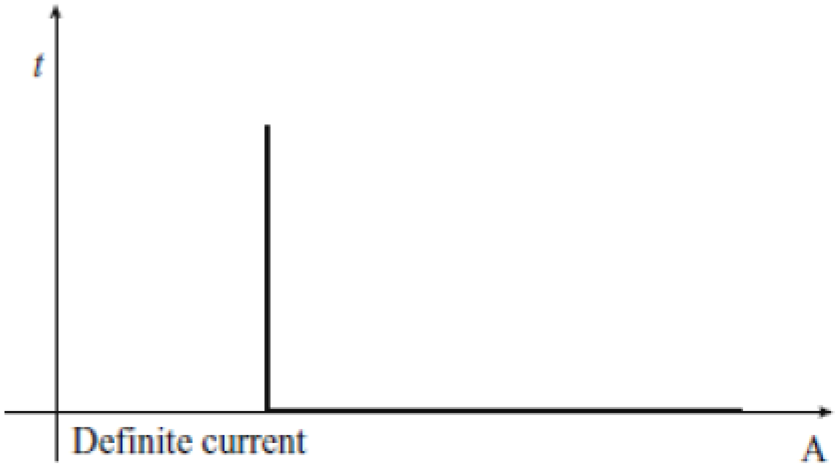


Figure 3.12: Definite current relay characteristic curve (Fernnandez Sarabia, 2011)

Settings of the relays are configured such that the relay closest to the source will operate at the highest current values while the relays furthest to the source operates at small current values. The relay furthest to the source, operates first isolating the loads from the fault. Protection settings are based on maximum fault conditions particularly on three phase faults. A fault will not be cleared until it reaches the protection setting value. The downside of these relays is that the fault may damage equipment before it is cleared when clearance is prolonged. Hence definite current relays are rarely used as the only protection devices but rather in combination with other protection devices (Fernnandez Sarabia, 2011).

3.5.3 Inverse Time/ Current characteristic Relays

The limitation of definite time relays is overcome by using inverse time/ current relays as they can interrupt bigger faults quickly. An example is shown on Figure 3.13.

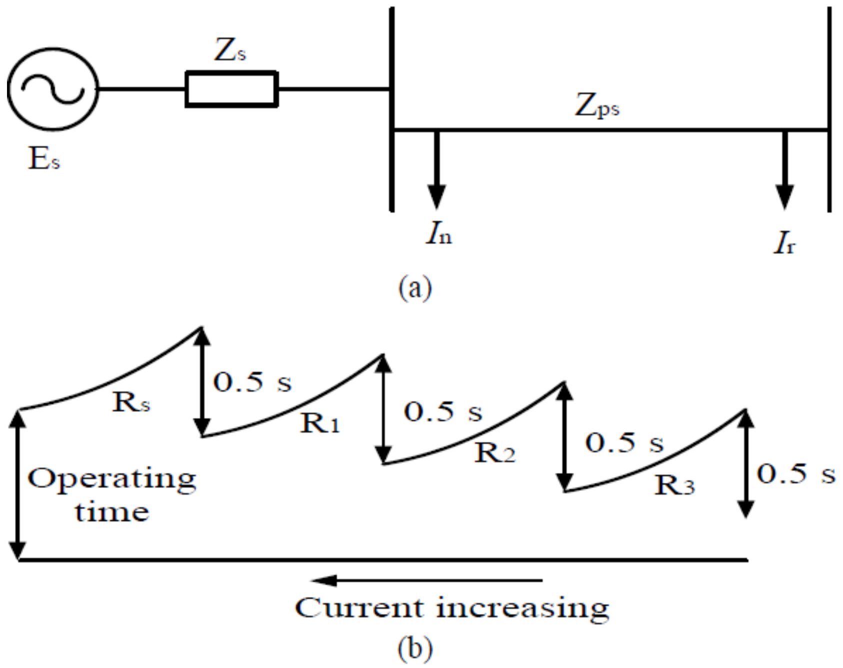


Figure 3.13: Inverse Time/Current Characteristic Relays (Onah, 2019)

As shown in Figure 3.13 (a) the impedance between the source (E_s) which is represented by Z_s and the input end of the network (I_n) is smaller compared to impedance Z_{ps}. This means there is a difference in the fault levels I_n and I_r. I_n will be greater than I_r. In the case, inverse time/current relays are used as protection devices.

Figure 3.13 (b) shows the relay characteristic curves of the inverse time/current relays. These relays normally operate under definite minimum operating times greater than certain current levels and hence why they are called Inverse Definite Minimum Time Relays (IDMT). Their main advantage is the quick interruption time at high fault currents (Barsoum & Lee, 2018).

Factors to consider when determining the IDMT Relay Settings;

a. Circuit Breaker operating times which should be ideally 0.15 seconds
b. Relay overshoot time
c. Time grading of 0.4 to 0.5 seconds between adjacent relays
d. Current Transformer failure/ error.

3.6 The impact of DG interconnection to the traditional distribution protection

The connection of DG in the distribution network changes the traditional single-supply radial system to a multi-source network. The connection of DG influences the power flow. The current direction, and distribution of short-circuit current also changes. With no time, the operation and control of the distribution network will become undesirable.

An example is shown on Figure 3.14;

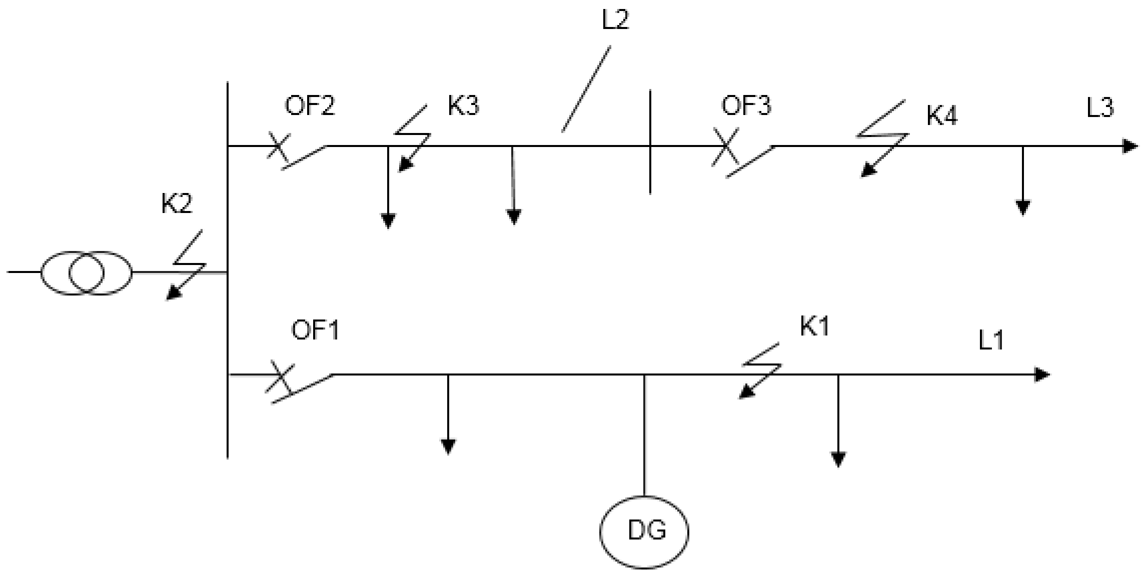


Figure 3.14: Example of the impact of DG on the distribution network (Wang et al., 2008)

The DG interconnection shown in Figure 3.14 may impact relay protection in the distribution network. For instance, if a fault occurs at K1, without the connection of DG then the short circuit current would be solely from the grid. However, with the connection of DG, then it will add onto the short circuit current. This means that at point OF1 will be affected by the short circuit current from both, the DG source and the grid. The impact of the protection sensitivity increases as the DG capacity increases (Wang et al., 2008)

The same happens when a fault occurs at point K2 or K3, without the connection of DG then OF1 will only see the fault current from the grid and only see short-circuit contribution from DG when connected. This may impact the line protection when the fault current is large enough. Relay protection at OF2 will see the short circuit current when a fault occurs at K4 and may result in wrongful tripping of the instantaneous overcurrent protection of the feeder when DG is connected. The connection of DG only means there are more than one power source in the network lines. In the event that there is a fault in one of the lines, but the DG continues to operate then it may continuously provide short circuit current resulting in the unbound state of the fault (Wang et al., 2008).

3.7 Impact of DG on the protection of the power system

Performance of the network system may be affected by the connection of DG into the power network. Some of the effects include short circuit current levels, voltage and power quality, stability of the network amongst others.

3.7.1 Short Circuit levels of the Network

Short-circuit current levels may be increased by the connection of DG into the power system. Fault currents increase with the penetration of DG as opposed to the operation of the network when there is only one generating unit. The contribution of the DG sources depends on several factors including the generating capacity, type of DG and the distance of the DG source from the fault (Bhise et al., 2017).

3.7.2 False tripping of feeder

The connection of DG can cause false tripping by the feeder protection devices. As explained on Figure 3.14, when there is a fault on an adjacent feeder, then the DG connected to that feeder will contribute to the fault current. If the contributions are more than the rated short circuit current of the protection devices, then this may cause the feeder to be out of service until the fault is cleared (Bhise et al., 2017)

3.7.3 Nuisance tripping of feeder

When there are power surges within the DG, the DG source may disconnect which is called nuisance tripping. These power surges may occur when there is a sudden loss of load for instance, when running a motor connected to a DG, then the motor is suddenly switched off, then there is power surge which result in nuisance tripping. Any fault that occurs outside the protection zone, may cause nuisance tripping (Bhise et al., 2017).

3.7.4 Protection Coordination

It is essential to coordinate DG protection system with the current feeder design in order to have a positive benefit. The interconnection at which DG is connected is called the Point of Common Coupling (PCC). Protection settings at the PCC should be done appropriately to protect DG from any damages and lessen the impact on the grid when there is a fault. The same applies when interconnecting DG to the utility grid, the right protection should be used based on numerous factors such as the transformer size, type of generator and the interconnection point.

Part of the design for the interconnection of DG includes, installation of the Distributed Generator as per transformer characteristics and the earthing arrangement which should be compatible with the utility system. Failure to properly ground equipment may result in over-voltages which can damage equipment (Fernnandez Sarabia, 2011).

In radial networks, there are ways that can be used to check that the protection system is well coordinated. The primary protection device that is closest to the fault must operate first before other protection devices. The below methods can be used to verify protection coordination, time based, current based and logic coordination (Nsengiyumva et al., 2018).

a. Time Based Relay Coordination

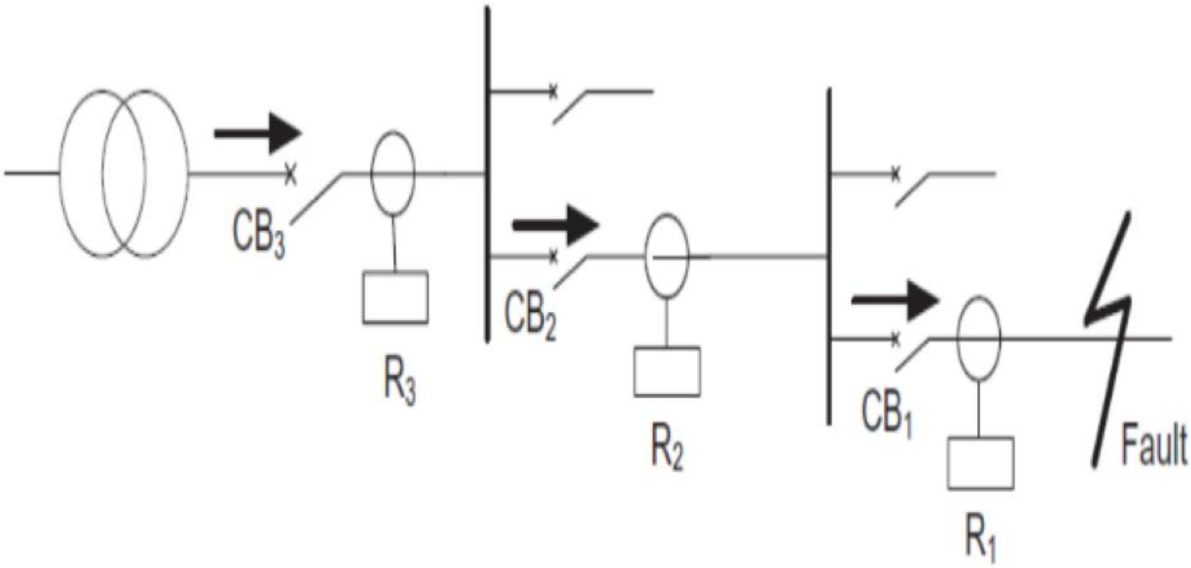


Figure 3.15: Time Based Relay Coordination (Nsengiyumva et al., 2018)

This procedure is done by giving the right time to all the relays controlling the circuit breakers in the protection network. The aim is to ensure the first breaker to trip is the one closest to the fault and the next backup breaker has a longer time delay. Figure 3.15 shows an example of how this is done. When there is a fault, then Relays R1 should operate before R2 and R3 as it is closer to the fault. All three relays will see the fault, R2 will isolate the fault if R1 fails. The same applies for R3, it will isolate the fault in the event of R1 and R2 failing to operate (Nsengiyumva et al., 2018).

b. Current Based Coordination

In this type of protection coordination, relays are set in a way that they trip the circuit breaker at different values of fault current. This is due to the changes in impedance values between the source and a fault which changes the fault currents at different locations in the network. The relays closest to the fault trips the circuit breaker first (Nsengiyumva et al., 2018).

c. Logic Coordination

This type of protection coordination overcomes the limitation of the time based and current coordination. An additional advantage is the reduced tripping time delay for the circuit breaker closest to the source.

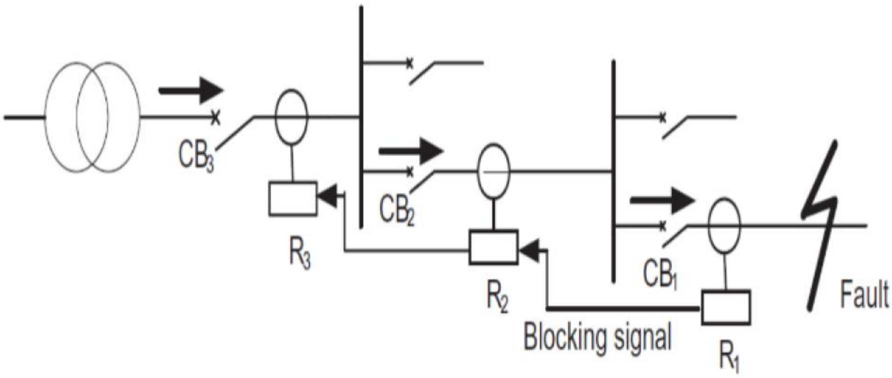


Figure 3.16: Logic Coordination

As shown in Figure 3.16 Relays R1, R2 and R3 will be activated in the event of a fault. When the first relay closest to the fault R1 is activated, it immediately delivers a blocking signal to Relay R2 to allow it to increase the upstream relay time delay. The same applies to Relay R2 and R3 when they get activated. This makes the coordination much more efficient and increases reduced the time delay in eliminating faults (Nsengiyumva et al., 2018).

Loss of Coordination due to the penetration of DG

The violation of Coordination Time interval (CTI) between the primary and backup relays is loss of coordination in a protection system.

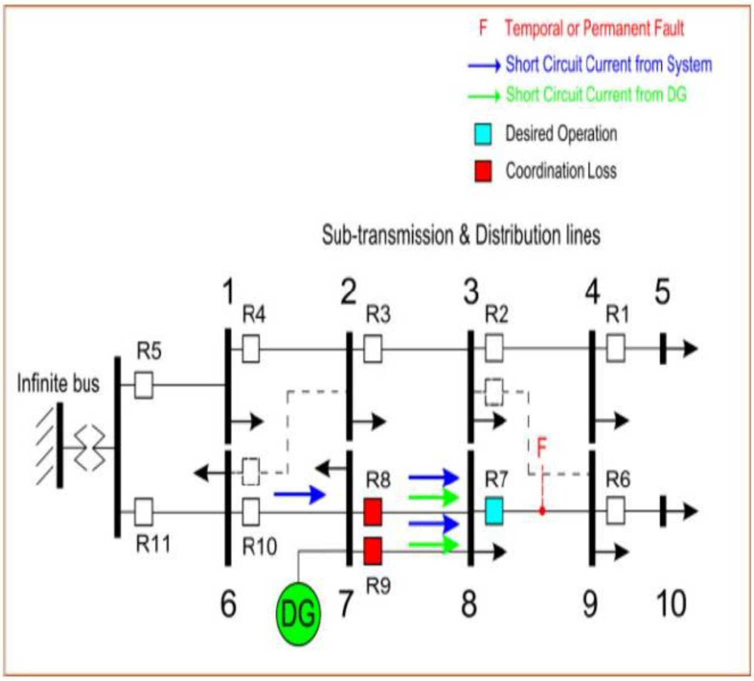


Figure 3.17: Loss of protection coordination

Figure 3.17 demonstrates the loss of coordination between protection relays derived from the advent of DG. For instance, when there is a fault at point F, Relay R7 being the primary relay while R8 and R9 are backup relays with respect to R7 (R7-R8 and R7-R9). Both pairs will sense an increase in fault currents when there is a fault. The impact on R7 is not as critical compared to R8 and R9 as it is the primary relay. The CTI for R8 and R9 with respect to R7 may change compared to when the network had no DG (Nsengiyumva et al., 2018).

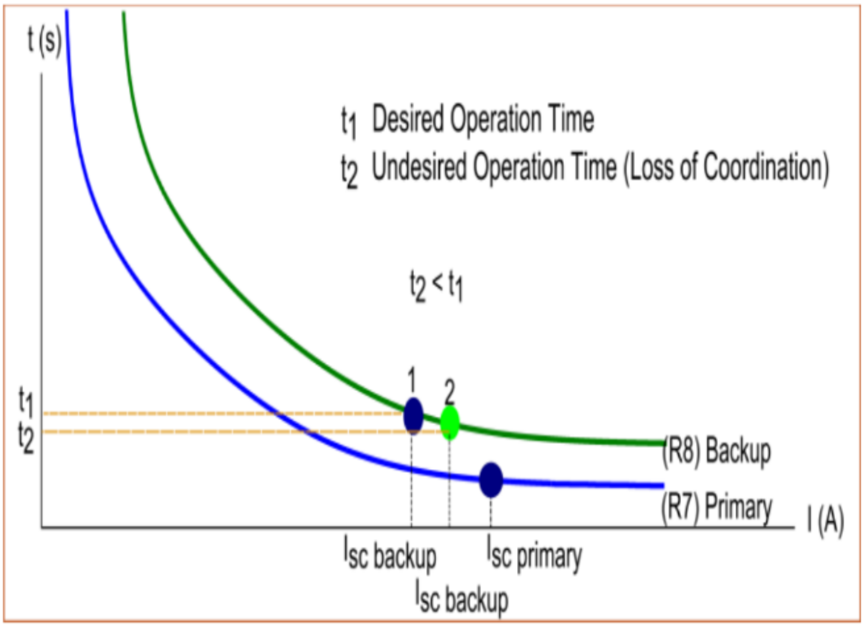


Figure 3.18: Relay R7-R8 Inverse Time Relay Characteristic Curves

Furthermore, the loss of coordination can also be demonstrated using the Inverse Time relay graphs for R7 and R8 coordination. From Figure 3.18 it is evident that the backup Relay R8 speeds up its tripping time with the integration of DG which increase the fault current. R7 is not affected due to the fact that its tripping time is at the horizontal asymptote curve (Nsengiyumva et al., 2018). Therefore, the loss of coordination is caused by the fact that CTI can no longer be conserved between the relay pairs R7-R8.

3.7.5 Islanding

Islanding is the isolation of a portion of a network either naturally or due to dispatch. Islanding can be demonstrated as seen on Figure 3.19

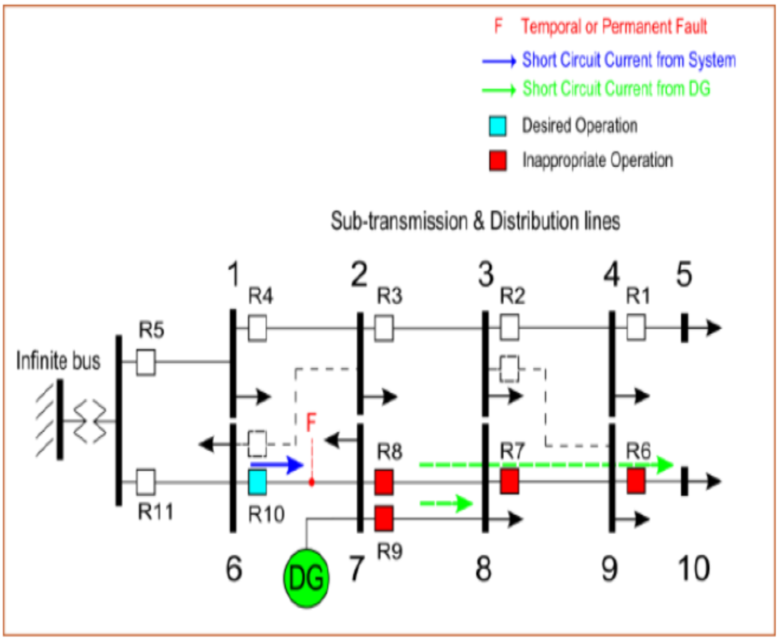


Figure 3.19: Islanding operation (Nsengiyumva et al., 2018)

If there is a fault at point F as seen on Figure 3.19, Relay R10 will isolate the fault. However, Bus 7 to Bus 10 will create an island network which will be powered by the Distributed Generation source (DG) (assumption being that it can carry the network and maintain stable operation).

The impact of islanding on Relay pairs (R7-R8) can further be illustrated by the inverse time relay graphs as seen on Figure 3.20. When the system enters the islanding mode, backup Relay R8 will increase its interruption time because there is a reduction in the fault current while R7 is not affected as it is the primary relay. This may result in an undesired tripping time of the backup relay when there is a fault (Nsengiyumva et al., 2018).

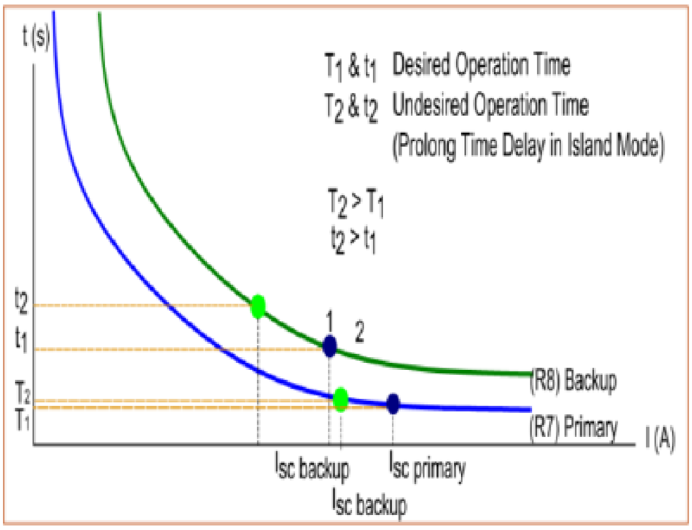


Figure 3.20: The impact of islanding on Operation of Relays (Nsengiyumva et al., 2018)

3.7.6 Protection Blinding

When DG is injected between the feeding substation and a fault location, then the fault current measured by the relays may be reduced by a size negatively contributed by the DG source. However, this may negatively impact Overcurrent relays and is undesirable. This is because the relays see less fault current when there is DG compared to when there is no DG in this particular situation. This can be illustrated on Figure 3.21

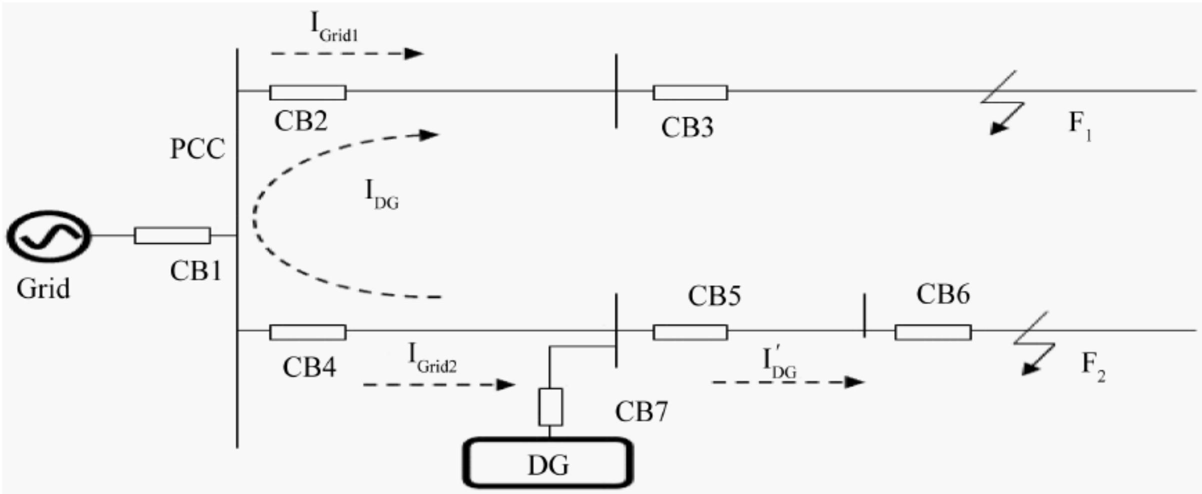


Figure 3.21: Protection Blinding in a protection system (Choudhary et al., 2015)

In the event of a fault at F2, the Relay connected to CB4 will not respond to the fault due to protection blinding.

3.8 Solutions adopted to curb the impact of DG on the protection system

a. **Limiting capacity of distributed generation;-** in the early stages of DG development, utilities decreased the effects of DG sources on the protection system by limiting the number and capacity of DG in particular locations. In South Africa for instance, municipalities limit the energy that households may feed back into the grid when they have grid-tied systems (Wang et al., 2008), (Nsengiyumva et al., 2018).

b. **Microgrids**;- they are a good way to connect DG without affecting the protection system of the utility. Microgrids can be designed with their own storage and protection devices. They can also be interconnected to the grid, or in a self-sufficient way, by being completely being independent with no connection to the main grid (Wang et al., 2008).

c. **Disconnection of Distributed Generation immediately after a fault is detected.** In networks with auto reclosing, this is normally done by allowing the DG to disconnect before the fast reclosing time has elapsed, leaving the system running as a radial system until the fault cleared. However, this could lead to more problems if the DG disconnects too quickly or too slowly. Normally countries have rules and regulations that stipulate how DG must be disconnected when there is a fault or abnormalities in the DG source's voltage and frequency. In case of automatic reclosing in a network, DG must disconnect before initial reclosing (Conti, 2009).

d. Increase the installed protection devices in a protection system (Nsengiyumva et al., 2018)**.**

e. Using Fault Current Limiters (FCL) to restore relay settings when there is a fault (Nsengiyumva et al., 2018)**.**

f. Using fault ride through strategy to control all inverter based DGs (Nsengiyumva et al., 2018)**.** This method is employed by most countries including South Africa.

g. **Adaptive Protection schemes (APS).** According to (Nsengiyumva et al., 2018), this is an online activity method of modifying the preferred protective response to a change in system conditions by generating signals externally. Microprocessor based relays are commonly used in this method as it is easy to change their tripping characteristics.

CHAPTER FOUR

MODELLING AND SIMULATION

4.4 Introduction

This chapter analyses how the system was modelled on DigSilent. The West Coast was used in the studies. This is part of the Western Cape province in South Africa. Data collection was done at Eskom (South Africa's utility provider). The modelling of Busbars, transformers, Circuit Breakers, Loads and other components of the system are described thoroughly. Two types of DG were modelled in the studies, Wind and Solar PV Generators. The end of the chapter describes the modelling of the protection relays and their protection settings.

4.2 Modelling of the network

DigSilent PowerFactory modelling software was used to model the network from HV, MV to LV network. Data was collected from Eskom, South Africa's main supplier of electricity, refer to **Appendix A**. A certain portion of the West coast network was selected for data analysis with the DG, Solar PV and Wind generation. The overview of the network design is shown below.

4.2.1 Busbars

The first step of simulating the West Coast network was to model the Busbars. The network consisted of 14 Busbars in total. The Table below shows the Busbar parameters which were simulated in accordance with the South African Grid in order to reflect the true effect of connecting embedded generation into the network.

Table 4.1 Busbar Parameters

Busbar	Area	Voltage
1	Helios	400kV
2	Aurora	400kV
3	Juno	400kV
4	Juno	132kV
5	Koekenaap	132kV
6	Skaapvlei	132kV
7	Sere Windfarm	33kV
8	Juno	66kV
9	Vredendal	66kV
10	Butle	66kV
11	Vanrhysdorp	66kV
12	Vanrhysdorp	22kV
13	Bulte Substation	11kV
14	Bulte Solar PV	11kV

Figures below show an example of how the Busbars were modelled in DigSilent showing load flow data. The same procedure was used to populate all the Busbars.

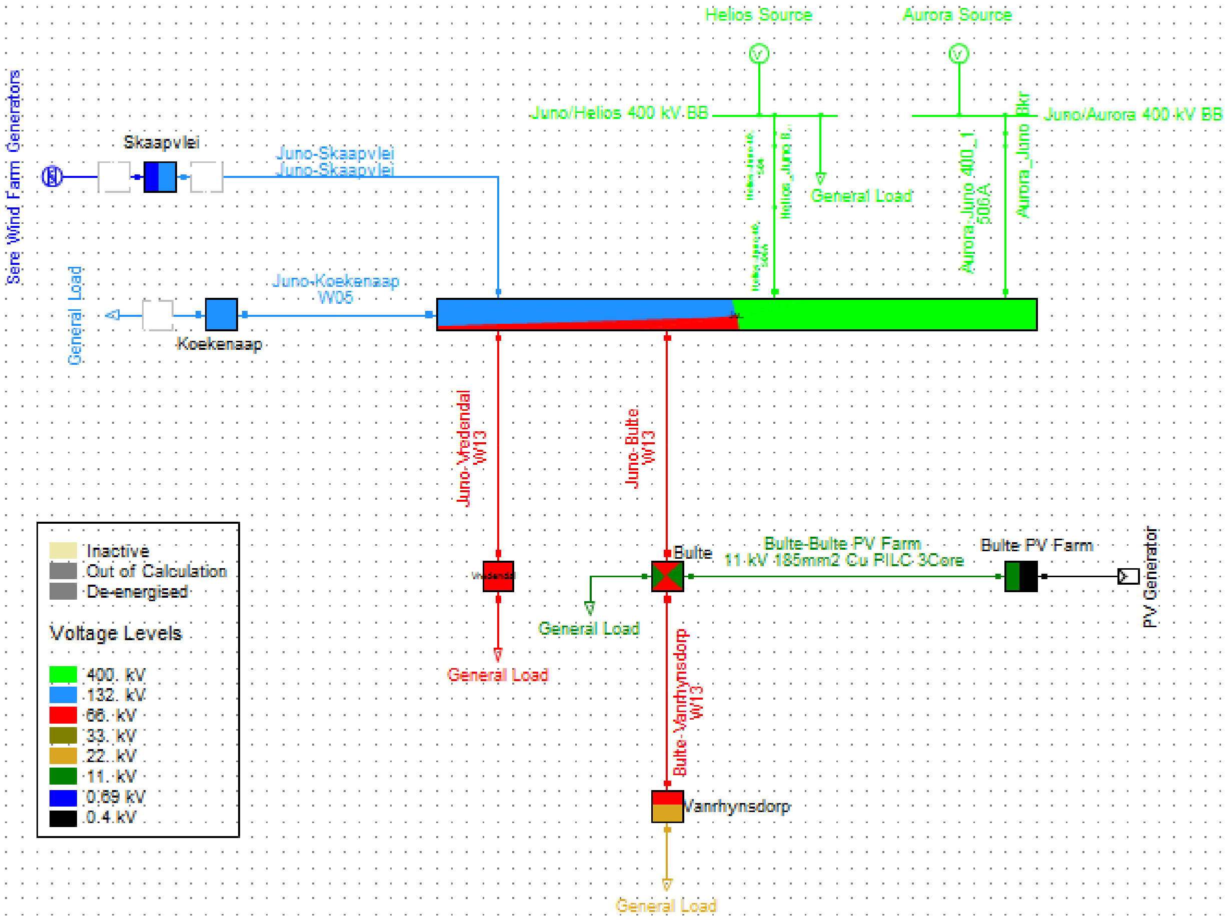


Figure 4.1: West Coast Overview modelled in DigSilent Software

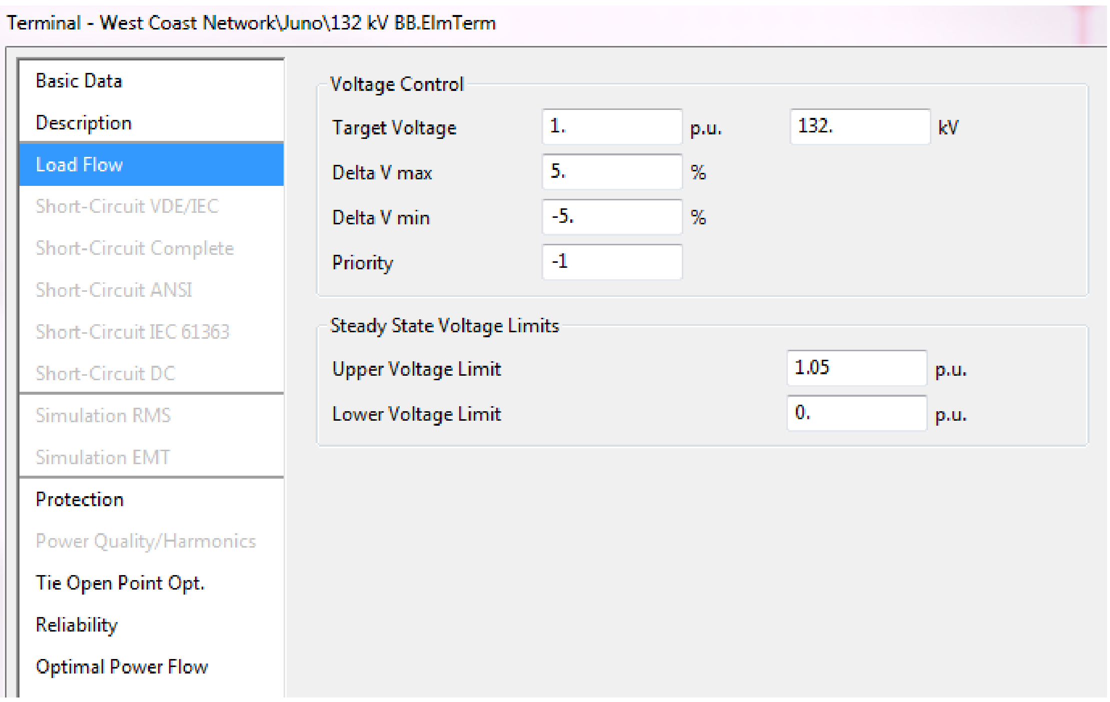


Figure 4.2: Busbar Modelling

4.2.2 Circuit Breakers and Terminal Nodes

Circuit Breakers (CBs) were modelled by connecting them between a Busbar and the terminal nodes. The circuit breakers are part of the protection system for the power system network. The nodes were rated at the same voltage as the Busbars at which they were connected. Figures below illustrate the CB and node data used.

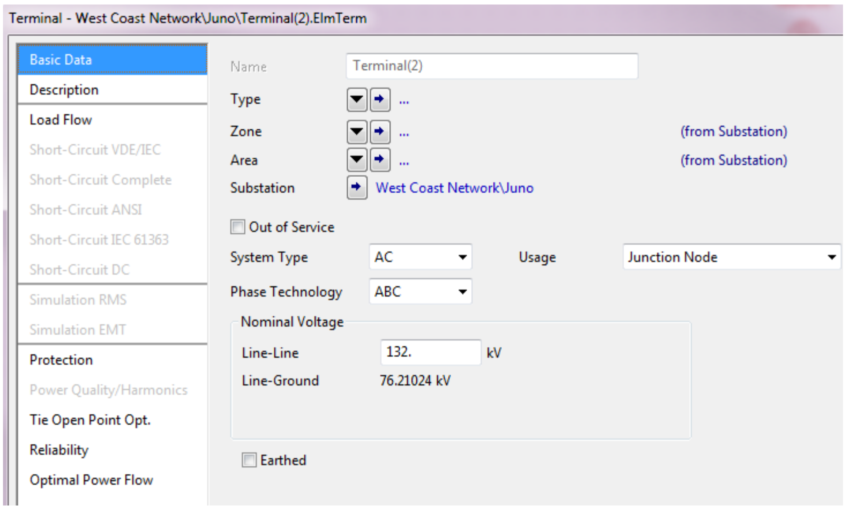


Figure 4.3: Circuit Breaker and Terminal Nodes Modelling

4.2.3 Voltage Sources

The network comprises of two sources, one from Helios and the other from Aurora at 400kV. Using the specifications obtained from Eskom, the voltage sources was populated as shown below

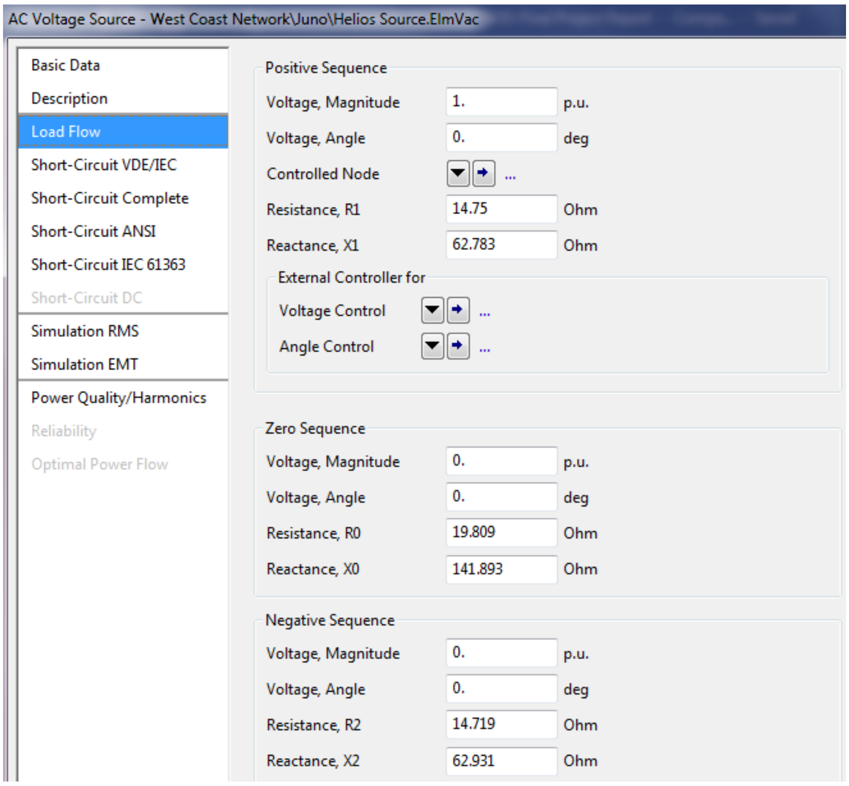
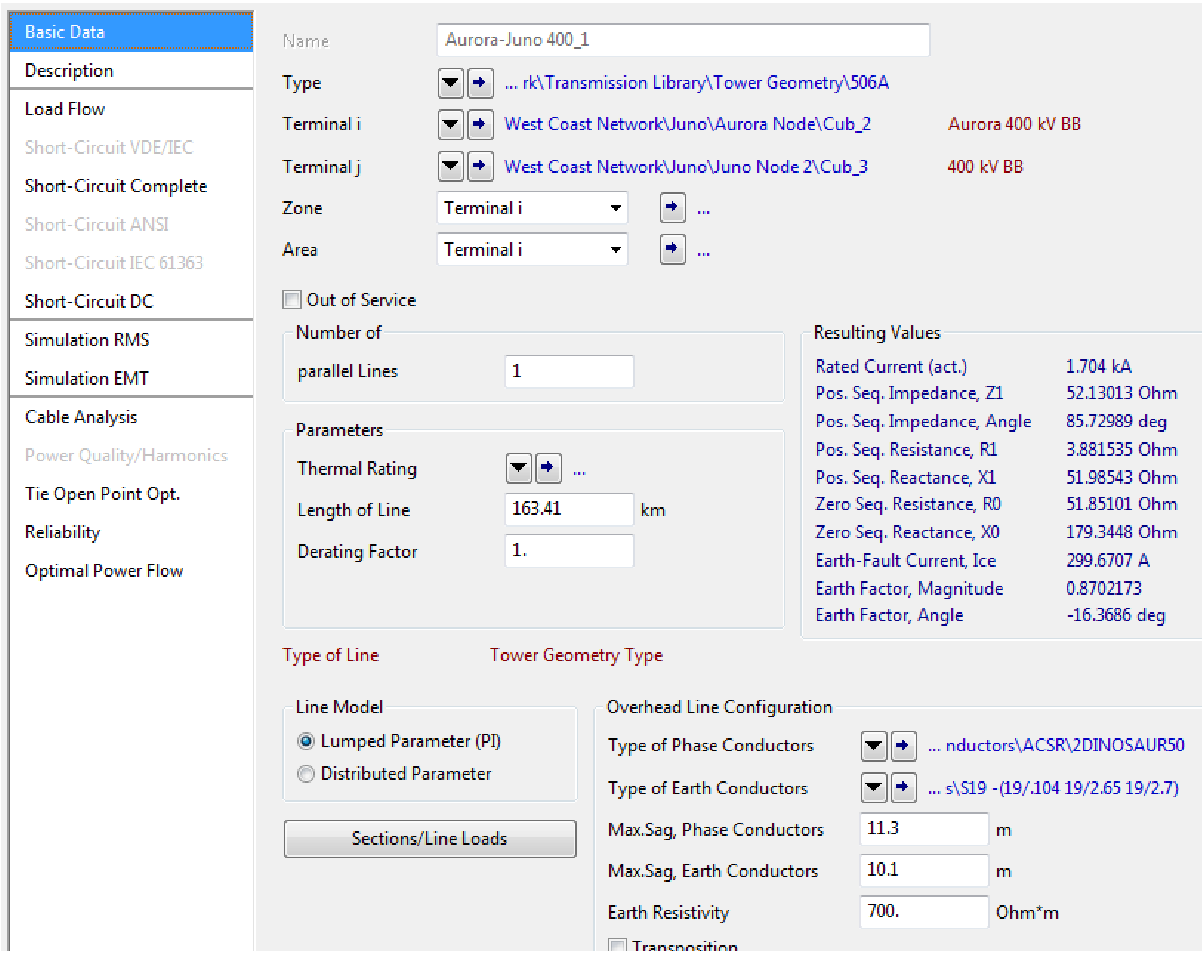


Figure 4.4: Voltage Sources Modelling

4.2.4 Line Modelling

Line parameters are shown in Appendix B. The towers and lines were populated on the same template. The network comprises of overhead lines only with the same type of towers but different types of conductors. Below is an example of how one of the lines were modelled.



igure 4.5: Line Modelling (a)

Tower geometry type model was used. All line parameter specifications were as per Eskom's West Coast network.

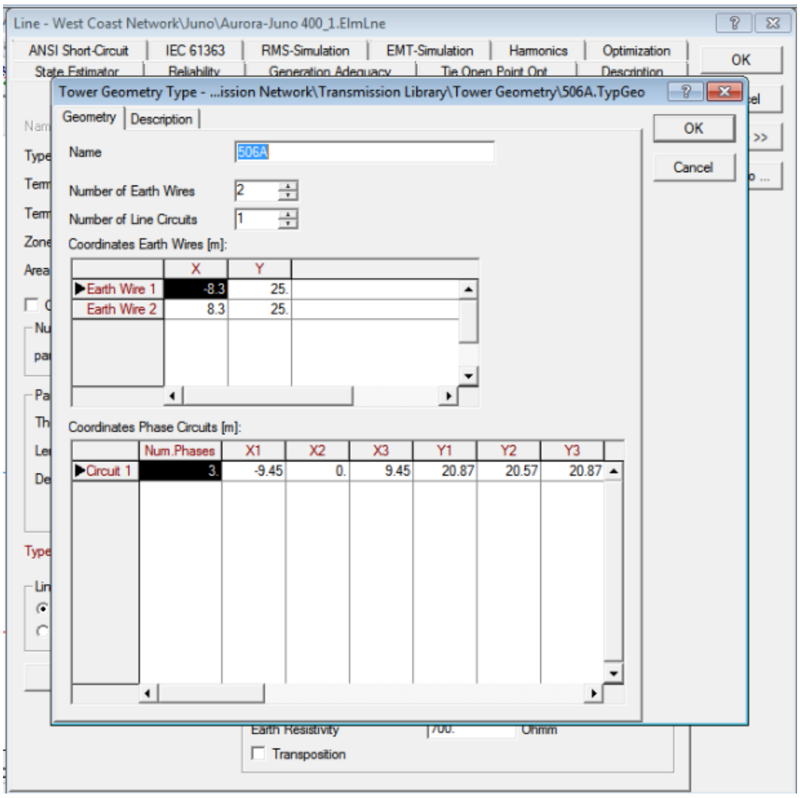


Figure 4.6: Line Modelling (b)

4.2.5 Transformers

Refer to Appendix D for transformer specifications. The network comprises of three different transformer types;

a) Auto-transformers- the basic idea of the autotransformers is to allow the interconnection of windings electrically. The rating of these transformers is normally higher than the original two-winding configuration rating (El-Hawary, 2015).

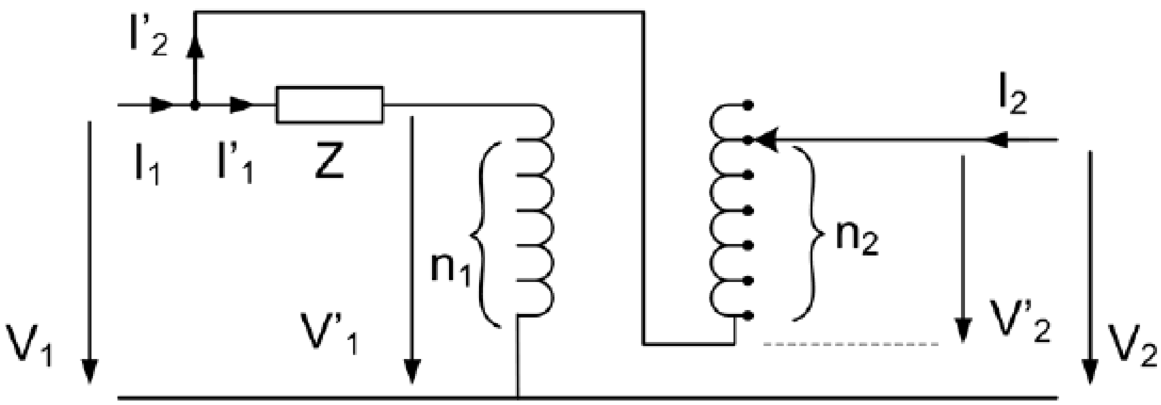


Figure 4.7: Two winding transformer connected as an auto-transformer (Neisius et al., 2012)

Figure 4.7 shows the basic concept of auto transformers with the windings connected in series. The network comprises of two autotransformers with the load flow information modelled as shown on Figure 4.8.

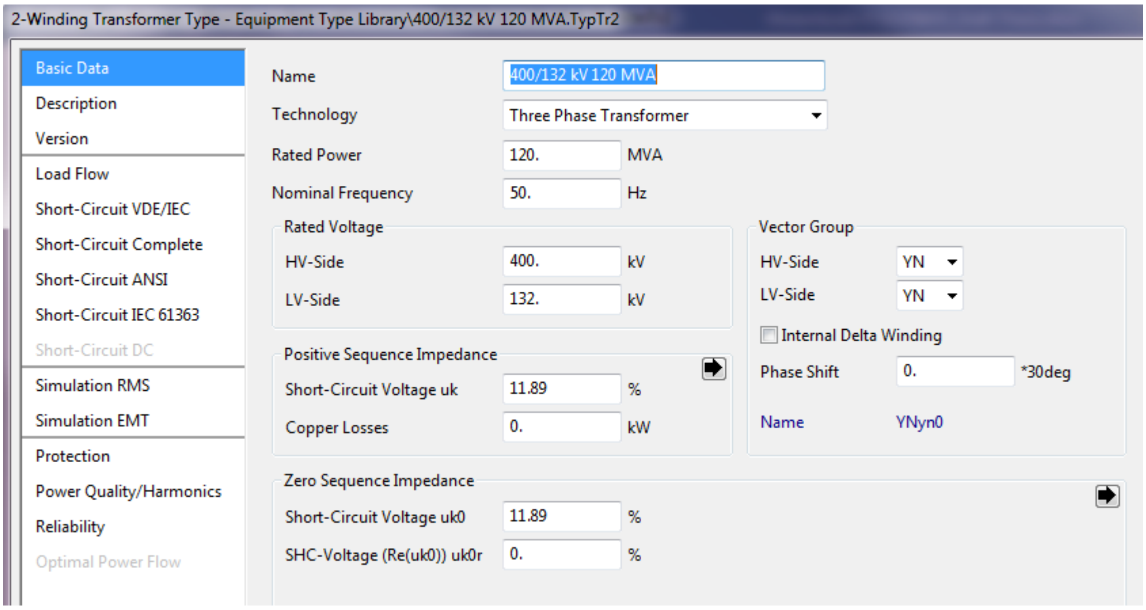


Figure 4.8: Auto-Transformer Modelling

b) Two winding transformers- these are the most common with two windings connected on the primary and secondary core of the transformer (El-Hawary, 2015). Modelling of the two winding transformers is similar to that of the auto transformers. The modelling is shown below;

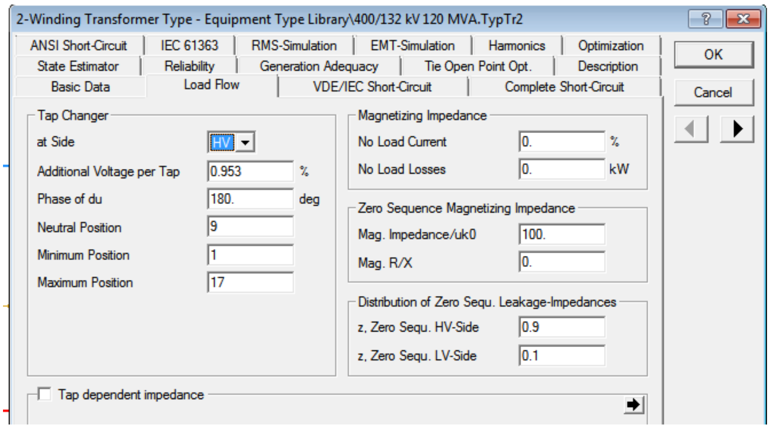


Figure 4.9: Two winding Transformer Modelling

Autotransformer and two winding transformer difference

One winding is used in autotransformers which acts as the primary and secondary winding. Unlike the auto-transformer, two winding transformers use separate windings between the primary and secondary winding (El-Hawary, 2015).

c) Three Winding Transformers

These type of transformers are widely used for the economy achieved when using three windings on one core (El-Hawary, 2015). Load flow information of the three-phase winding is different from that of the autotransformers and the two winding transformers. Figure 4.10 shows the modelling of the three-winding transformers.

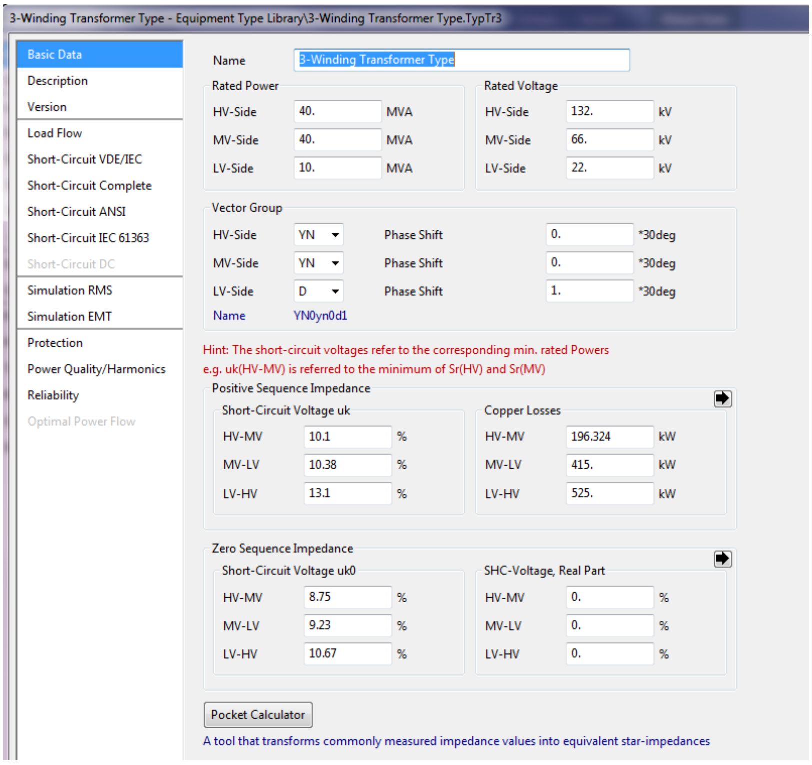


Figure 4.10: Three winding Transformer Modelling

4.2.6 NECR modelling

Neutral Electromagnetic Coupler with a Neutral Earthing resistor or intentional resistance per Phase is abbreviated NECR. These are normally used to limit current flowing through the neutral point in generators or transformers in MV networks when there is an earth fault. They form part of the protection scheme of the power system. The protect equipment in the power system by limiting fault currents to a value low enough to not cause any harm (Eskom Holdings SOC Ltd, 2010). The NECR were modelled at the (Low Voltage) LV side of the transformer as shown below.

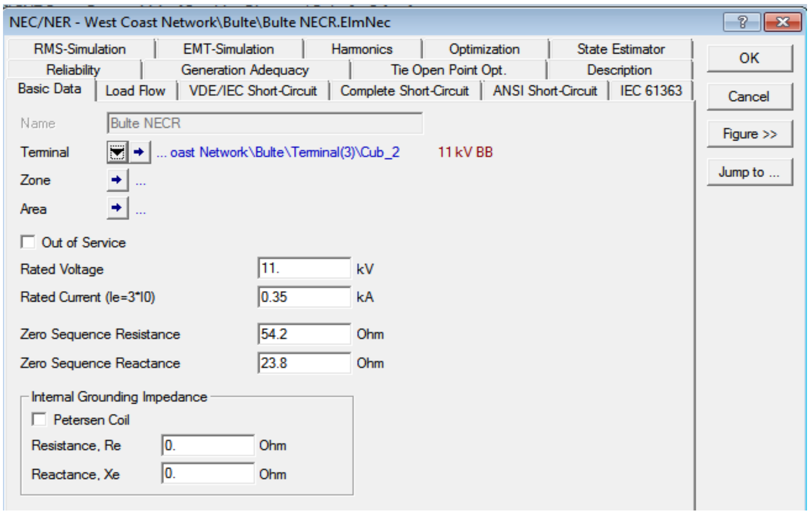


Figure 4.11: NECR Modelling

4.2.7 Wind Generator Modelling

The model is representation of Sere wind farm, a wind generator plant in Western Cape Province, South Africa. Sere windfarm comprises of 44 wind turbines each with an output of 2.3MVA. The combined real power output from the windfarm is 100MW. It is an Eskom owned windfarm and is situated in an area called Skaapvlei in West Coast.

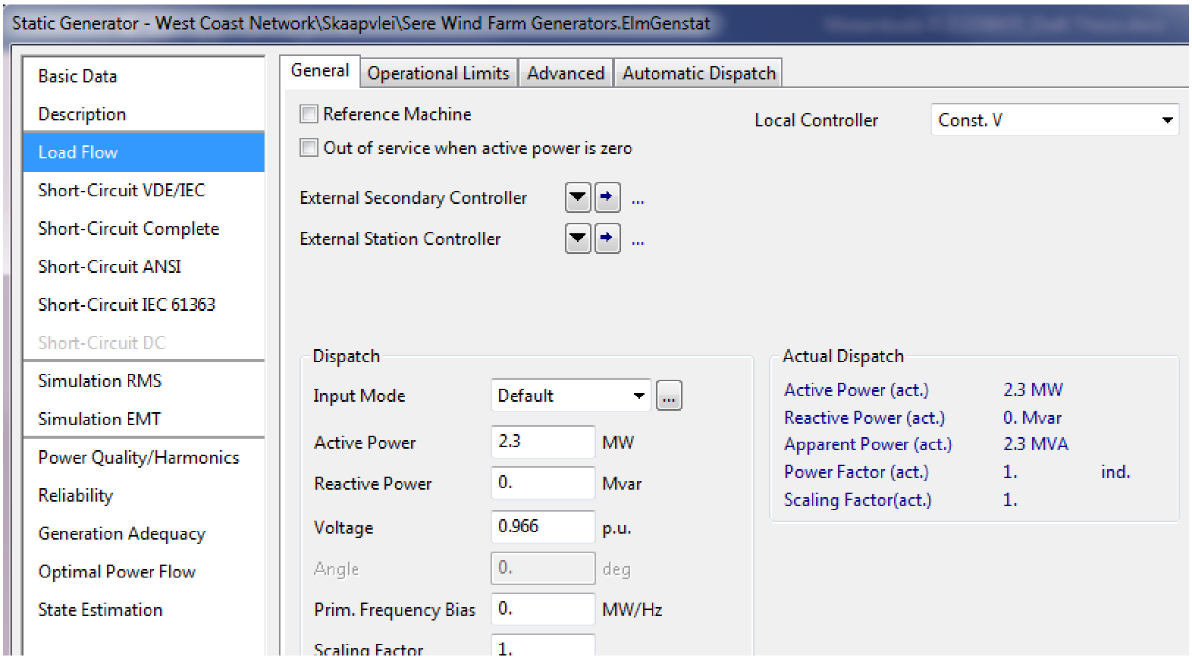


Figure 4.12: Wind Farm Modelling

A DigSilent generic model of the wind generator was used to model the plant and the information is shown on the figure below. The plant has a two winding transformer which steps the voltage up from 0.69kV generation voltage to 33kV feeding Koekenaap load and into the West Coast network.

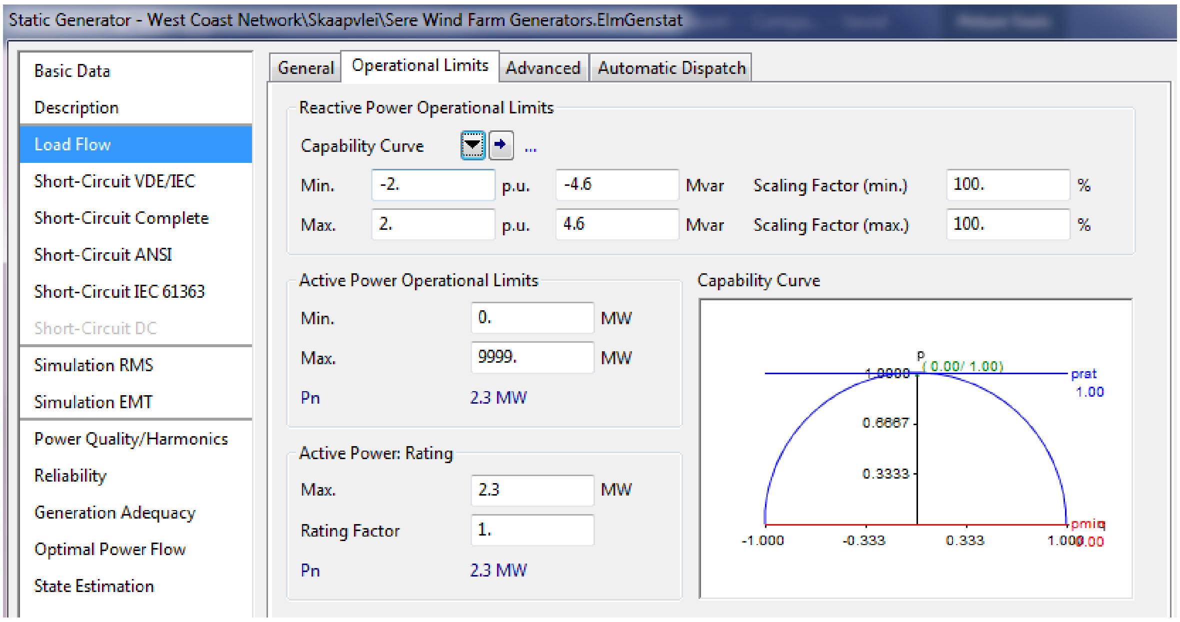


Figure 4.13: Operational Limits of the Wind Farm

Single line diagram of the Windfarm

Figure 4.14 shows the single line diagram of the windfarm modelled on DigSilent. The wind generator has been modelled such that it supplies a load at 33kV Bus while excess power is fed into the grid.

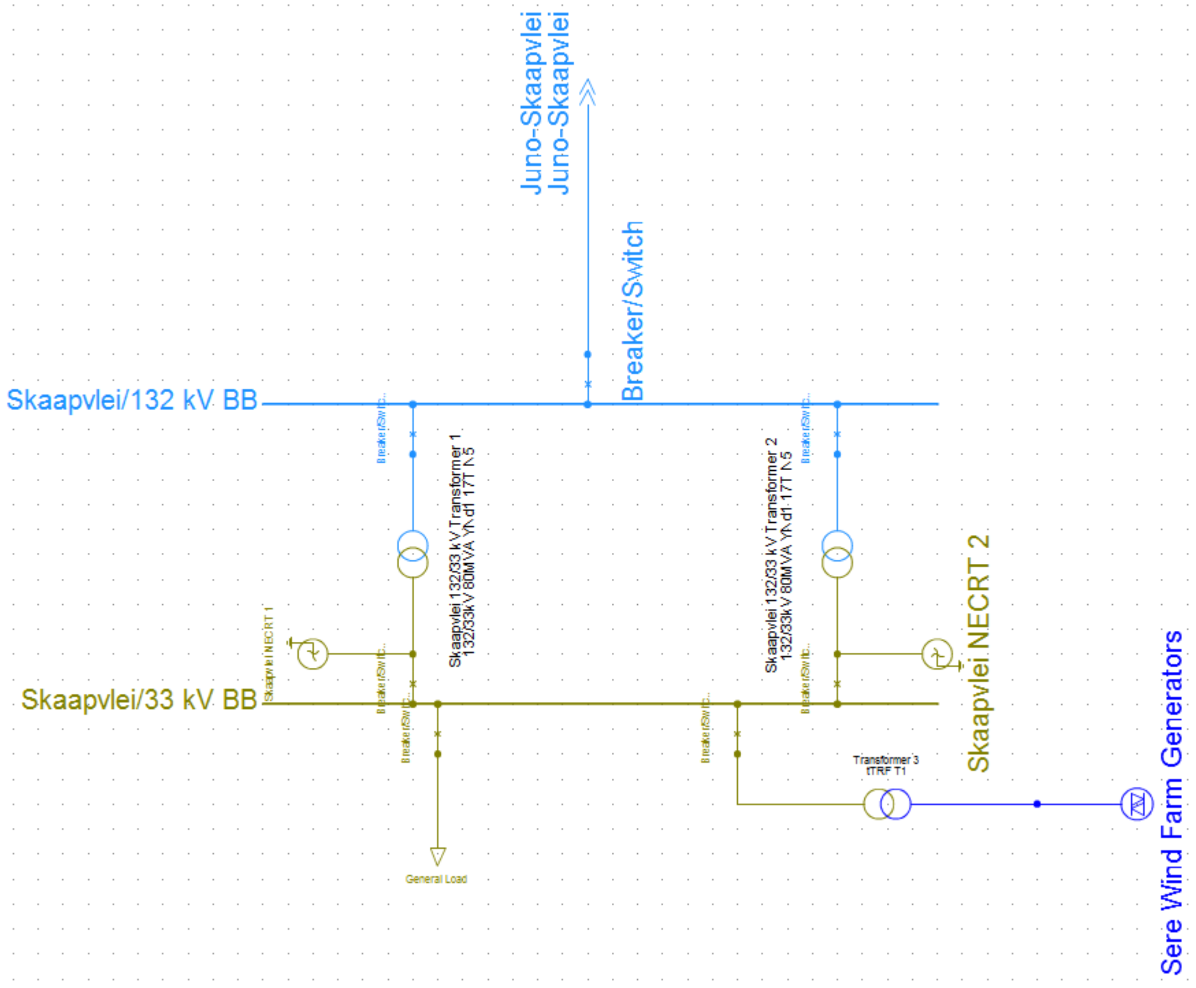


Figure 4.14: Single line diagram of the Wind Farm

4.2.8 Solar Photovoltaic

The grid connected Bulte Solar PV farm was used as a model in this study. Bulte PV Farm is found in the Western Cape region of South Africa. A DigSilent generic Photovoltaic model was used to simulate Bulte Solar PV generator. The Plant is an independent power plant which supplies the Bulte load and feeds into the Eskom network. The plant consists of 20 machines each with an output of 2.5MVA which gives a total output of 10MW.

The plant specifications were populated as shown on the figure below. Bulte PV plant has a transformer connected to it which steps the voltage up from the generation voltage of 0.4kV to 11kV into the West Coast Network.

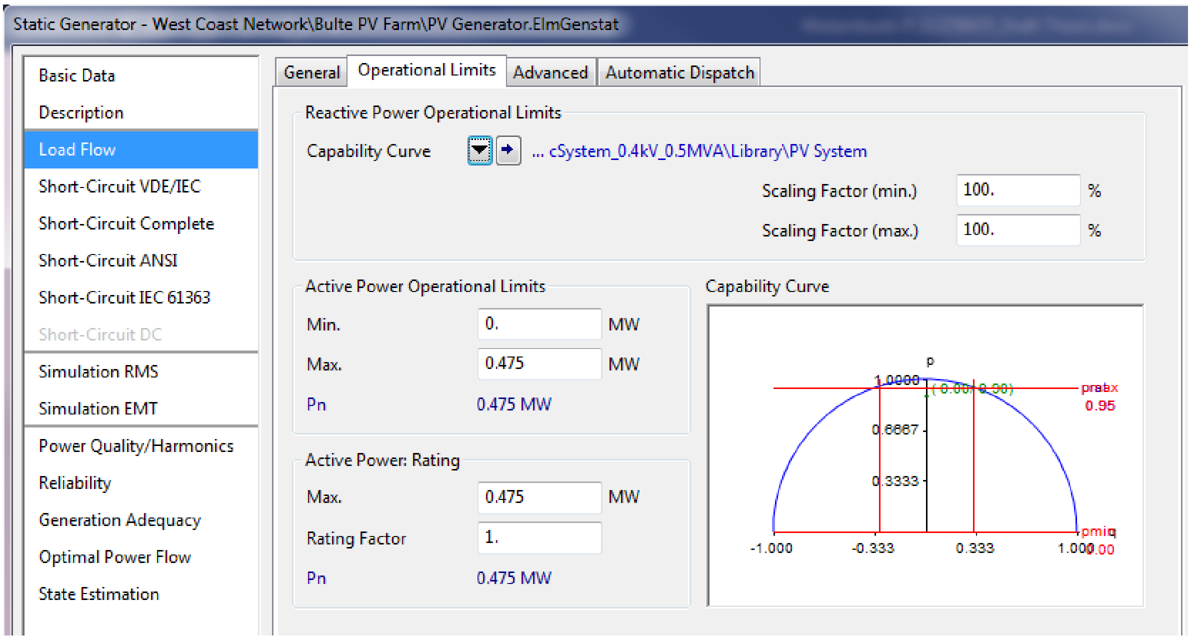


Figure 4.15: Solar PV Modelling

The capability curve reflects the operating regions of the PV plant, see figure below.

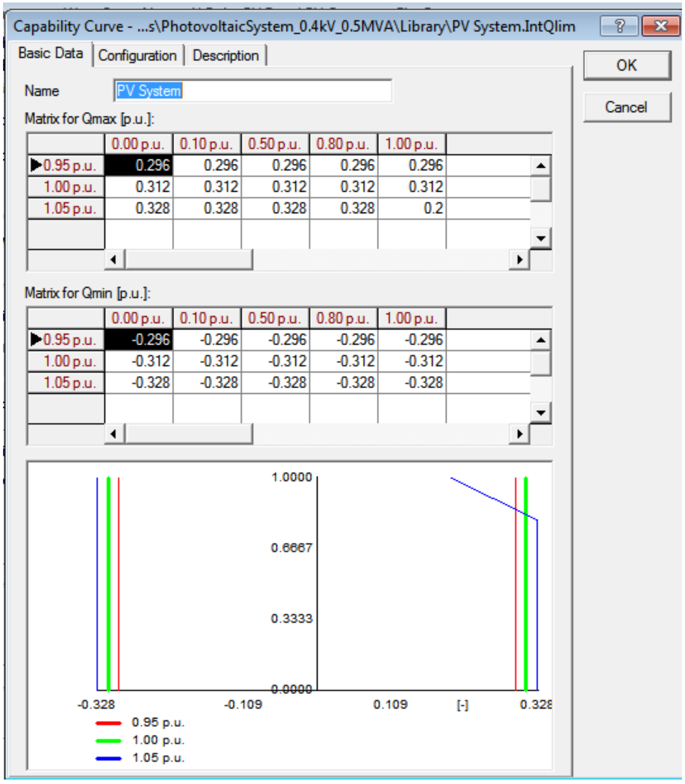


Figure 4.16: Capability Curve of the Solar PV Generator

4.2.9 General Loads

All loads were populated in the same way with the real power, reactive power and per unit voltages for load flow analysis. Refer to Appendix E for load parameters.

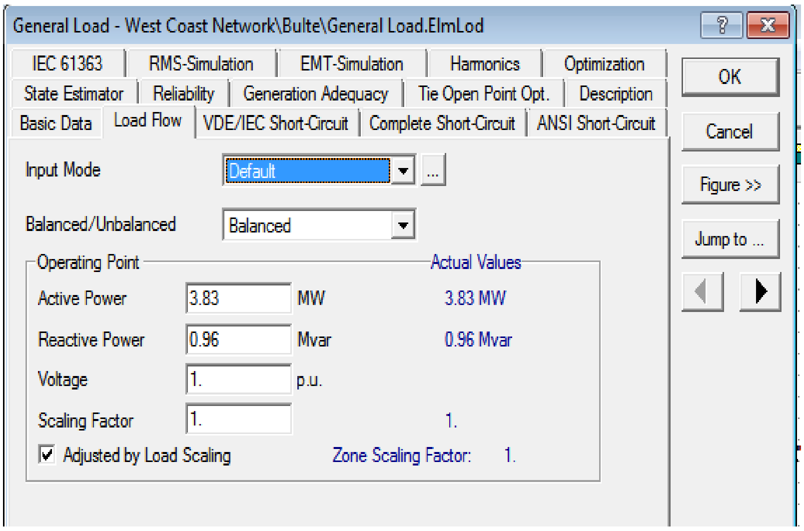


Figure 4.17: General Load Modelling

4.3 Single Line Diagram

The single line diagram of the complete network is shown below with different colour coding showing the different voltage levels

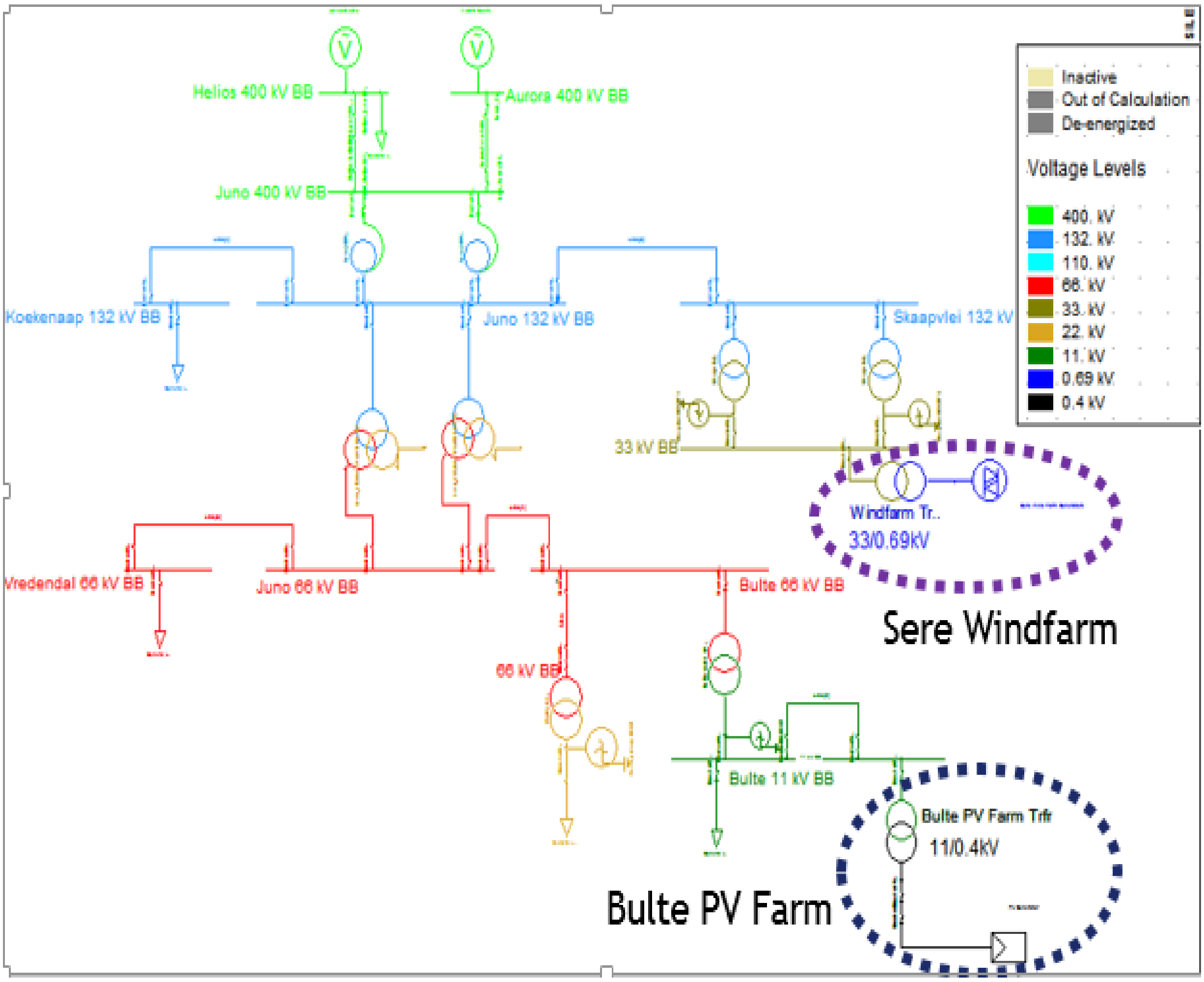


Figure 4.18: West Coast Network (Single line diagram)

4.4 Protection system modelling

Apart from the Circuit breakers and NECR for earthing, current transformers and relay settings were populated into the network. The impedance relays were modelled on the HV network and partially on the MV network whilst Overcurrent and Earth fault relays were populated as back-up on HV network and main protection on MV and LV network.

4.4.1 Current Transformers

The correct CTs were chosen by considering the fault current. Figure 4.19 shows the current settings populated in DigSilent.

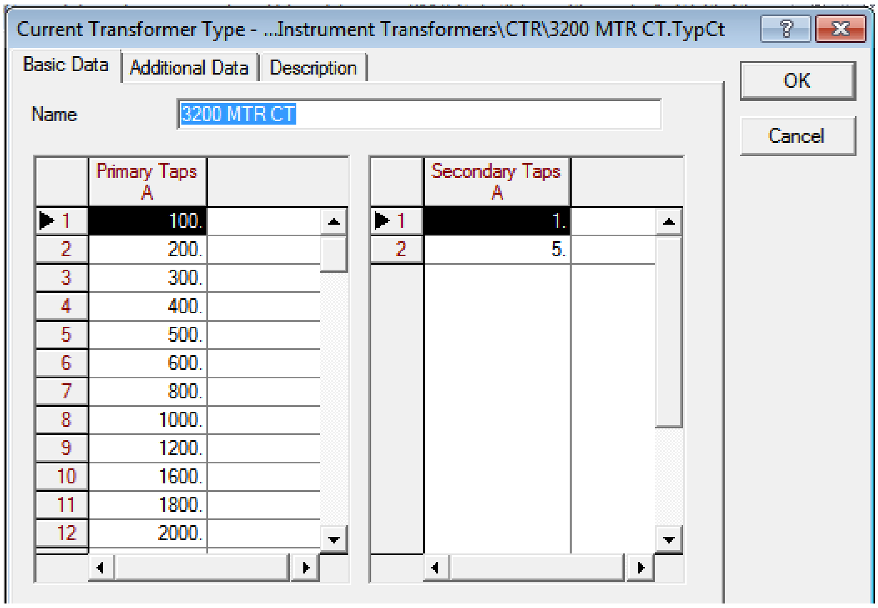


Figure 4.19: Current Transformer Modelling (a)

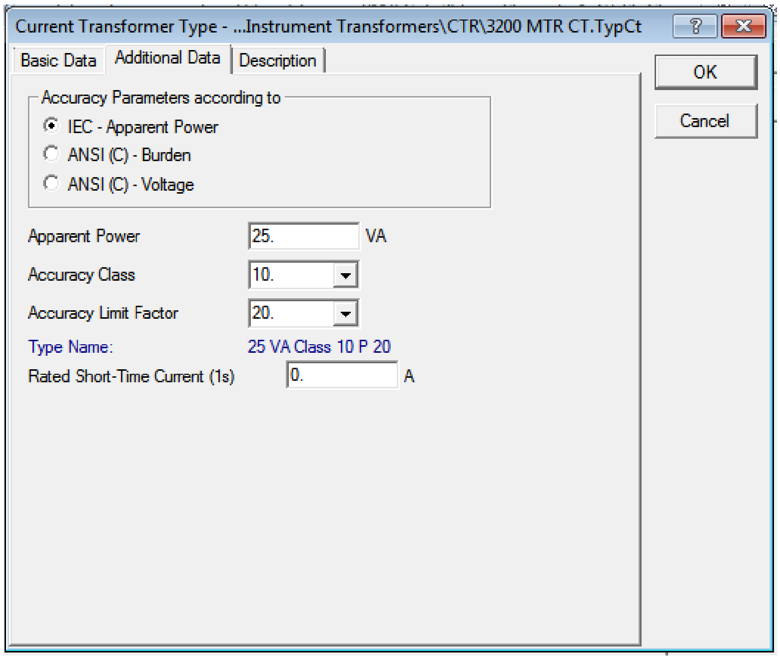


Figure 4.20: Current Transformer Modelling (b)

4.4.2 Relays

On the HV network, the RED 670 and REF 615 ABB models were used, refer to Table 4.1. RED 670 ABB is a differential protection Relay normally used on HV Networks. Apart from the relays' main role of protection in the power system, it is also used for control and monitoring of cables and all overhead lines from generation, transmission to distribution networks. The REF 615 ABB relay is a feeder protection relay. It is seamlessly aligned for measurement, protection, control and supervision of substations and power systems (El-Hawary, 2015).

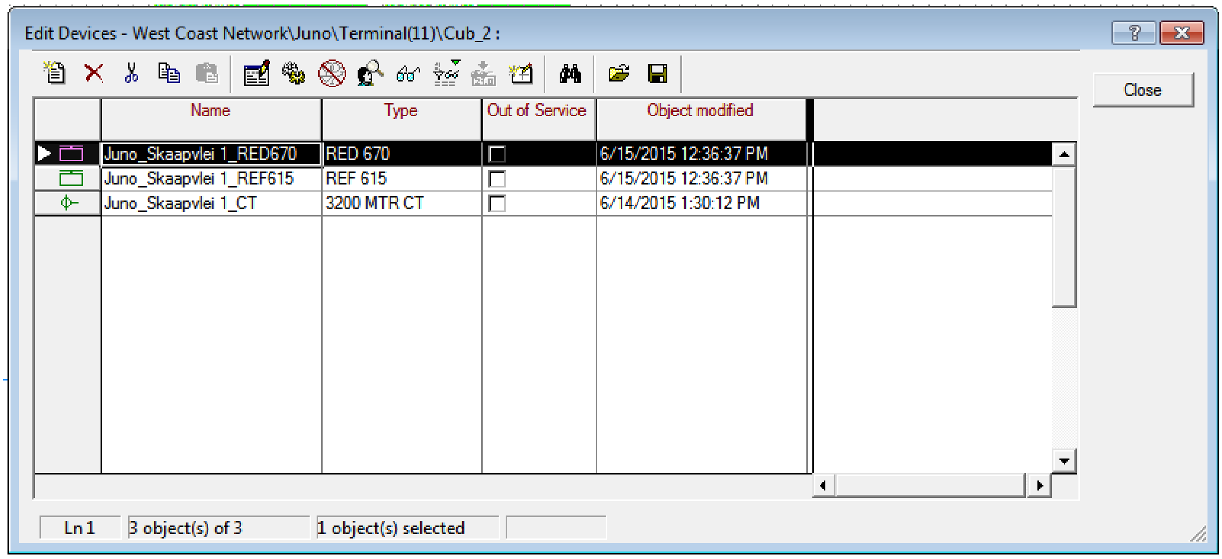


Figure 4.21: Distance Relay Modelling

The Vamp 140 relay, 7SJ50_IT relay and REL 511 relay ABB manufactured relays were used to model the network in the MV and LV networks.

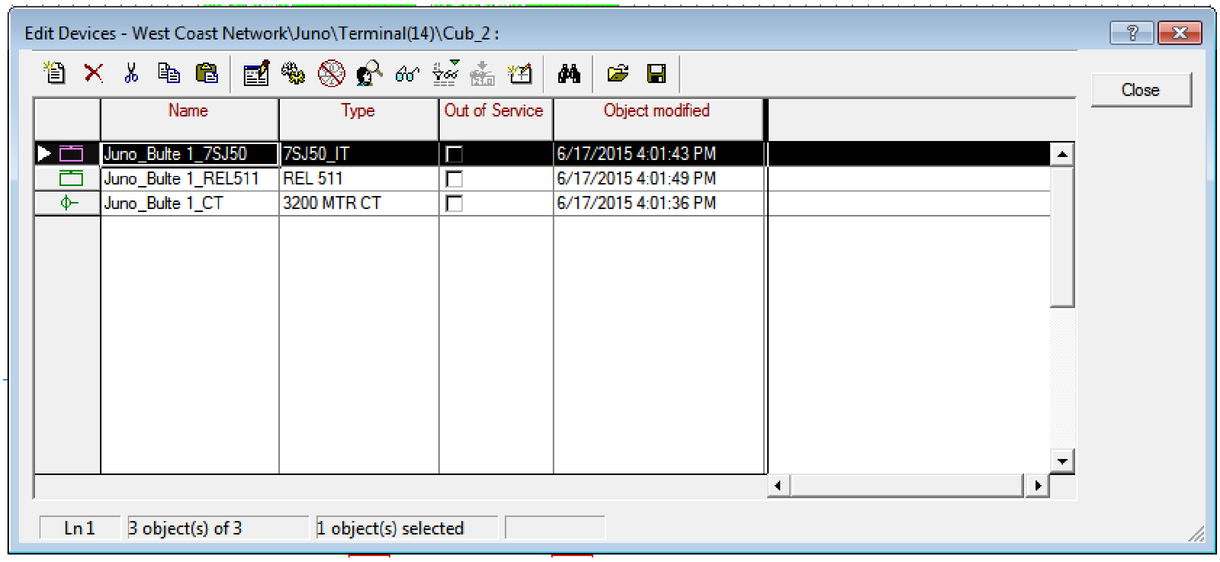


Figure 4.22: Overcurrent Protection Relay Modelling

An outline of all the relays employed in the network is shown in Tables 4.1 and 4.2.

Table 4.5: Relay Protection Settings (Distance Protection)

	Protection Device	Location	Branch	Manufacturer	Model	Stage (Phase)	Reactance [pri. Ohm]	Reactance [sec. Ohm]	Resistance [pri. Ohm]	Resistance [sec. Ohm]	Time	Directional	Stage (Earth)	Reactance [pri. Ohm]	Reactance [sec. Ohm]	Resistance [pri. Ohm]	Resistance [sec. Ohm]	Time	Directional
1	Juno_Bulte 1_REL511	Juno/66 kV BB	Juno-Bulte	ABB	REL 511	Z1P	3.000	3.000	1.970	1.970	0.00	Forward	Z1G	3.000	3.000	1.970	1.970	0.00	Forward
						Z2P	9.370	9.370	6.160	6.160	0.40	Forward	Z2G	9.370	9.370	6.160	6.160	0.40	Forward
						Z3P	0.940	0.940	0.620	0.620	2.50	Reverse	Z3G	0.940	0.940	0.620	0.620	2.50	Reverse
						Z4P	45.140	45.140	29.620	29.620	3.00	Forward	Z4G	45.150	45.150	29.620	29.620	3.00	Forward
2	Juno_Skaapvlei 1_RED670	Juno/132 kV BB	Juno-Skaapvlei	ABB	RED 670	ZMQ1	12.570	12.570	3.050	3.050	0.00	Forward	ZMQ1	12.570	12.570	3.050	3.050	0.00	Forward
						ZMQ2	18.850	18.850	4.560	4.560	0.40	Forward	ZMQ2	18.850	18.850	4.560	4.560	0.40	Forward
						ZMQ3	3.930	3.930	0.950	0.950	1.50	Reverse	ZMQ3	3.930	3.930	0.950	0.950	1.50	Reverse
						ZMQ4	43.850	43.850	10.600	10.600	3.00	Forward	ZMQ4	43.850	43.850	10.600	10.600	3.00	Forward
3	Skaapvlei_Juno 1_RED670	Skaapvlei/132 kV BB	Juno-Skaapvlei	ABB	RED 670	ZMQ1	12.720	12.720	3.070	3.070	0.00	Forward	ZMQ1	12.720	12.720	3.070	3.070	0.00	Forward
						ZMQ2	20.420	20.420	4.930	4.930	0.40	Forward	ZMQ2	20.420	20.420	4.930	4.930	0.40	Forward
						ZMQ3	7.850	7.850	1.900	1.900	60.00	Reverse	ZMQ3	7.850	7.850	1.900	1.900	60.00	Reverse
						ZMQ4	27.640	27.640	6.680	6.680	3.00	Forward	ZMQ4	27.640	27.640	6.680	6.680	3.00	Forward

Table 4.6: Overcurrent Protection Relay Settings

	Protection Device	Location	Branch	Manufacturer	Model	Stage (Phase)	Current [pri.A]	Current [sec.A]	Current [p.u.]	Time	Characteristic	Directional	Stage (Earth)	Current [pri.A]	Current [sec.A]	Current [p.u.]	Time	Characteristic	Directional
1	Bulte_Municipal_GAD	Bulte/11 kV BB	General Load	Reyrolle	GAD_2xOC_EF<0.1-0.9>_SEF_1A	A>	350	1.75	1.75	0.25	NI	None	EF>	60	0.30	0.30	0.20	NI	None
2	Bulte_PV 1_P145	Bulte/11 kV BB	Bulte-Bulte PV Farm	Areva	P14x 100-120 V	I>1	672	0.84	0.84	0.31	IEC standard inverse	Forward	IN1>1	96	0.12	0.12	0.19	IEC standard inverse	Forward
3	Bulte_Transformer 1_VAMP 140	Bulte/11 kV BB	Bulte 66/11 kV T1	VAMP	VAMP 140	I>	750	1.25	1.25	0.40	Normal Inverse	None	Io>	30	0.10	0.10	8.60	Definite	None
4	Bulte_Transformer 1_VAMP 140_HV B/U E/F	Bulte/66 kV BB	Bulte 66/11 kV T1	VAMP	VAMP 140								Io>>	120	0.60	0.60	0.30	Normal Inverse	None
5	Bulte_Vanrhynsdorp 1_VAMP 140	Bulte/66 kV BB	Bulte-Vanrhynsdorp	VAMP	VAMP 140								Io>>	160	0.40	0.40	0.15	Normal Inverse	None
6	Juno_Bulte 1_7SJ50	Juno/66 kV BB	Juno-Bulte	Siemens	7SJ50_IT	I>	420	0.70	0.70	0.25	IEC 255-3 inverse	None	Ie>	180	0.30	0.30	0.35	IEC 255-3 inverse	None
7	Juno_Koekenaap 1_7SJ50	Juno/132 kV BB	Juno-Koekenaap	Siemens	7SJ50_IT	I>	360	0.60	0.60	0.35	IEC 255-3 inverse	None	Ie>	180	0.30	0.30	0.30	IEC 255-3 inverse	None
8	Juno_Skaapvlei 1_REF615	Juno/132 kV BB	Juno-Skaapvlei	ABB	REF 615	51P-2(1)	1200	1.00	1.00	0.20	IEC Norm. Inv.	None	51N-2(1)	240	0.20	0.20	0.35	IEC Norm. Inv.	None
9	Juno_Vredendal 1_7SJ50	Juno/66 kV BB	Juno-Vredendal	Siemens	7SJ50_IT	I>	300	0.50	0.50	0.40	IEC 255-3 inverse	None	Ie>	180	0.30	0.30	0.20	IEC 255-3 inverse	None
10	Skaapvlei_Juno 1_REF615	Skaapvlei/132 kV BB	Juno-Skaapvlei	ABB	REF 615	67-1(2)	1200	1.00	1.00	0.20	IEC Inv.	Forward	67N-1(2)	120	0.10	0.10	0.30	IEC Inv.	Forward
11	Skaapvlei_Transformer 1_SEL487E	Skaapvlei/132 kV BB	Skaapvlei 132/33 kV Transformer 1	Schweitzer	SEL 387-1A	51P	480	0.80	0.80	0.24	C1 - IEC Class A (Standard Inverse)	None	50N2	15	0.15	0.15	10.00	Definite	None
12	Skaapvlei_Transformer 2_SEL487E	Skaapvlei/132 kV BB	Skaapvlei 132/33 kV Transformer 2	Schweitzer	SEL 387-1A	51P	480	0.80	0.80	0.24	C1 - IEC Class A (Standard Inverse)	None	50N2	15	0.15	0.15	10.00	Definite	None
13	Vanrhynsdorp_Transfor VAMP 140_HV B/U E/F	Vanrhynsdorp/66 kV BB	Vanrhynsdorp 66/11 kV T1	VAMP	VAMP 140								Io>>	120	0.60	0.60	0.25	Normal Inverse	None
14	Vanrhynsdorp_Transformer 1_VAMP 140	Terminal(2)	Vanrhynsdorp 66/11 kV T1	VAMP	VAMP 140	I>	375	1.25	1.25	0.35	Normal Inverse	None	Io>	30	0.10	0.10	8.60	Definite	None

Table 4.7: Instrument Transformer Settings

	Protection Device	Location	Branch	Manufacturer	Model	CT	Slot	Ratio [pri.A/sec.A]	VT	Slot	Ratio [pri.V/sec.V]
1	Bulte_Municipal_GAD	Bulte/11 kV BB	General Load	Reyrolle	GAD_2xOC_EF<0.1-0.9>_SEF_1A	Bulte_Municipal_CT	Ct-3p	200A/1A			
2	Bulte_PV 1_P145	Bulte/11 kV BB	Bulte-Bulte PV Farm	Areva	P14x 100-120 V	Bulte_PV 1_CT	Ct-3P	800A/1A	Bulte_11 kV BB_VT	Vt-3P	11000V/110V
3	Bulte_Transformer 1_VAMP 140	Bulte/11 kV BB	Bulte 66/11 kV T1	VAMP	VAMP 140	Bulte_Transformer 1_MVOC_CT	Ct-3p	600A/1A			
4	Bulte_Transformer 1_VAMP 140_HV B/U E/F	Bulte/66 kV BB	Bulte 66/11 kV T1	VAMP	VAMP 140	Bulte_Transformer 1_HVEF_CT	Ct-3I0	200A/1A			
5	Bulte_Vanrhynsdorp 1_VAMP 140	Bulte/66 kV BB	Bulte-Vanrhynsdorp	VAMP	VAMP 140	Bulte_Vanrhynsdorp 1_CT	Ct-3p	400A/1A			
6	Juno_Bulte 1_7SJ50	Juno/66 kV BB	Juno-Bulte	Siemens	7SJ50_IT	Juno_Bulte 1_CT	Ct-3P/3xI0	600A/1A			
7	Juno_Bulte 1_REL511	Juno/66 kV BB	Juno-Bulte	ABB	REL 511	Juno_Bulte 1_CT	Ct	600A/1A	Juno_66 kV BB_VT	Vt	66000V/110V
8	Juno_Koekenaap 1_7SJ50	Juno/132 kV BB	Juno-Koekenaap	Siemens	7SJ50_IT	Juno_Koekenaap 1_CT	Ct-3P/3xI0	600A/1A			
9	Juno_Skaapvlei 1_RED670	Juno/132 kV BB	Juno-Skaapvlei	ABB	RED 670	Juno_Skaapvlei 1_CT	Ct	1200A/1A	Juno_132 kV BB_VT	Vt	132000V/110V
10	Juno_Skaapvlei 1_REF615	Juno/132 kV BB	Juno-Skaapvlei	ABB	REF 615	Juno_Skaapvlei 1_CT	Ct-3P	1200A/1A	Juno_132 kV BB_VT	Vt-3P	132000V/110V
11	Juno_Vredendal 1_7SJ50	Juno/66 kV BB	Juno-Vredendal	Siemens	7SJ50_IT	Juno_Vredendal 1_CT	Ct-3P/3xI0	600A/1A			
12	Skaapvlei_Juno 1_RED670	Skaapvlei/132 kV BB	Juno-Skaapvlei	ABB	RED 670	Skaapvlei_Juno 1_CT	Ct	1200A/1A	Skaapvlei_132 kV	Vt	132000V/110V
13	Skaapvlei_Juno 1_REF615	Skaapvlei/132 kV BB	Juno-Skaapvlei	ABB	REF 615	Skaapvlei_Juno 1_CT	Ct-3P	1200A/1A	_132 kV BB_VT	Vt-3P	132000V/110V
14	Skaapvlei_Transformer 1_SEL487E	Skaapvlei/132 kV BB	Skaapvlei 132/33 kV Transformer 1	Schweitzer	SEL 387-1A	Skaapvlei_Transformer 1_HV_CT	Wd-1 Ct	600A/1A			
15	Skaapvlei_Transformer 2_SEL487E	Skaapvlei/132 kV BB	Skaapvlei 132/33 kV Transformer 2	Schweitzer	SEL 387-1A	Skaapvlei_Transformer 2_HV_CT	Wd-1 Ct	600A/1A			
16	Vanrhynsdorp_TransforVAMP 140_HV B/U E/F	Vanrhynsdorp/66 kV BB	Vanrhynsdorp 66/11 kV T1	VAMP	VAMP 140	Vanrhynsdorp_Transformer 1_HVEF_CT	Ct-3I0	200A/1A			
17	Vanrhynsdorp_Transformer 1_VAMP 140	Terminal(2)	Vanrhynsdorp 66/11 kV T1	VAMP	VAMP 140	Vanrhynsdorp_Transformer 1_MVOC_CT	Ct-3p	300A/1A			

CHAPTER 5
RESULTS

5.1 Introduction

This chapter analyses the results obtained from the network model simulated in DigSilent PowerFactory. The chapter begins by analysing the fault levels before and after the connection of DG. Three-phase faults are analysed on Busbars and single-phase to ground fault on the network lines. The results of the fault currents will be populated in tables and discussed as part of case study 1.

Case study 2 will cover results obtained from Overcurrent relays and the characteristic curves of the IDMT Relays before and after the connection of DG. Time grading of the protection relays will also be analysed. Part of the results also includes Case study 3 which outlines the results obtained from the Distance Relays.

5.2 Case Study 1: Fault Levels

The IEC 60909 was used to analyse the fault current levels before and after the connection of DG. The impact of the DG on the network will be analysed by comparing the fault level currents on the conventional network and when it includes DG. Two types of faults are covered which are single-phase to ground faults (accounts for about 70% of faults in a power system) and three-phase faults (symmetrical).

In order to determine some of the effects on the protection system of connecting DG to the utility grid, it is important to analyse the percentage change in fault currents before and after the connection of DG. All DG sources connected to the grid contribute to fault current levels and can have a substantial impact on the performance of protection devices.

a) Single phase to Ground fault on lines

Distance Protection was applied on the HV lines. Single phase to ground fault calculations were conducted on DigSilent to depict the fault currents at different intervals of the lines. Figure 5.1 shows an example of the Single phase to Ground short circuit current calculated using the IEC 60909 method on the Bulte to Juno 400kV at 80% distance.

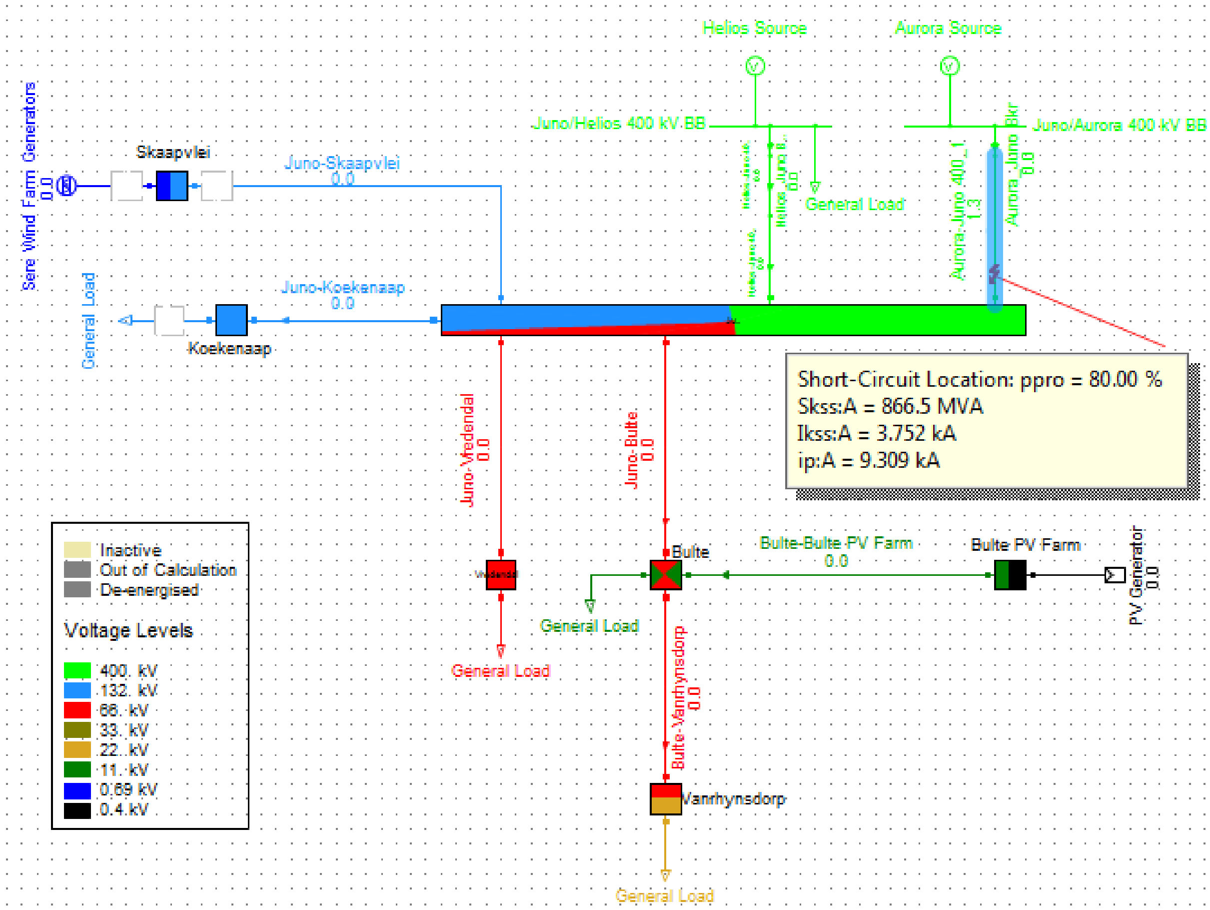


Figure 5.1: Single-phase to Ground Fault on transmission line

A summary of the fault levels on the Aurora to Juno 400kV line is shown on Table 5.1 shows the short circuit currents at different distances of the 400kV line from Bulte to Juno substation.

Table 5.1: Single-phase to Ground fault (Aurora to Juno Line)

Single phase to Ground Fault (Aurora to Juno 400kV line)							
Distance of the line	**Before both DG**	**After Bulte PV farm**	**% Change**	**After Skaapvlei Wind Generator**	**% Change**	**After both DG plants**	**% Change**
	Amps	**Amps**	**%**	**Amps**	**%**	**Amps**	**%**
0%	**10778**	**10780**	**0.01**	**10828**	**0.46**	**10830**	**0.5**
20%	6331	6333	0.03	6416	1.3	6418	1.4
50%	4278	4280	0.05	4413	3.2	4414	3.2
80%	3550	3551	0.03	3751	5.7	3752	5.7
100%	**3359**	**3361**	**0.06**	**3626**	**7.9**	**3628**	**8.0**
Maximum impact			**0.06%**		**7.9%**		**8%**
Minimum impact			**0.01%**		**0.46%**		**0.5%**

From Table 5.1, it can be depicted that the most impact is at 100% of the Juno to Bulte line after the connection of DG. Skaapvlei Wind Generator contributing the most fault currents with a 7.9% increase in fault levels.

Table 5.2: Single-phase to Ground fault (Juno to Bulte Line)

Single Phase to Ground Fault (Juno to Bulte 66kV line)							
Distance of the line	**Before both DG**	**After Bulte PV farm**	**% Change**	**After Skaapvlei Wind Generator**	**% Change**	**After both DG plants**	**% Change**
	Amps	**Amps**	**%**	**Amps**	**%**	**Amps**	**%**
0%	**4827**	**4861**	**0.7**	**4985**	**3.3**	**5020**	**4.0**
20%	4215	4246	**0.7**	4323	2.6	4354	3.3
50%	3611	3640	0.8	3677	1.8	3705	2.6
80%	3229	3258	0.9	3273	1.4	3301	2.2
100%	3053	3082	**0.9**	3088	**1.1**	3117	**2.1**
Maximum impact			**0.9%**		**3.3%**		**4%**
Minimum impact			**0.7%**		**1.1%**		**2.1%**

A summary of the fault levels in case of a single-phase to ground fault on the Juno to Bulte 66kV line is summarised in Table 5.2. DG input to the fault current levels is very low with the highest increase in fault levels of 4% after the combined connection of the Solar and Wind Generators, 0% of the line.

Table 5.3: Single Phase to Ground Fault (Bulte 11kV Line)

Single Phase to Ground Fault (Bulte 11kV line)							
Distance of the line	**Before both DG**	**After Bulte PV Generator**	**% Change**	**After Skaapvlei Wind Generator**	**% Change**	**After both DG plants**	**% Change**
	Amps	**Amps**		**Amps**		**Amps**	
0%	**4 249**	**4 287**	**0.89%**	**4 303**	**1.27%**	**4340**	**2.14%**
100%	**3 076**	**3 271**	**6.34%**	**3 072**	**-0.13%**	**3 267**	**6.21%**

Table 5.3 shows the fault levels at 0% and 100% of Bulte 11kV line. It can be depicted that there is an increase in the fault levels with the worst-case scenario at 100% of the line which is towards the Solar PV Generator. 6.34% increase in fault levels is a result of the Bulte PV Generator. Earth Fault and overcurrent protection is applied on the MV and LV networks using

the IDMT Relays. The fault current results were used to model the IDMT curves in case of a fault which is explained in Case Study 3.

b) Three-phase faults

DigSilent Software was used to calculate the fault currents in the event of a three-phase fault at each Busbar in the network with and without the connection of DG.

Table 5.4: Three-phase fault on Busbars

SUBSTATION	BEFORE DG	AFTER BULTE PV FARM	% CHANGE	AFTER SKAAPVLEI WINDFARM ONLY	% CHANGE	WITH BOTH DG PLANTS	% CHANGE
	Amps	Amps		Amps		Amps	
Juno 400 kV BB	5017	5032	0.30%	5133	2.31%	5146	2.57%
Juno 132 kV BB	5674	5718	0.78%	6035	6.36%	6077	7.10%
Juno 66 kV BB	4401	4491	2.04%	4460	1.34%	4549	3.36%
Koekenaap 132 kV BB	3155	3170	0.48%	3251	3.04%	3263	3.42%
Skaapvlei 132 kV BB	0	0	0	3028	0	3037	0
Vredendal 66 kV BB	2346	2374	1.19%	2349	0.13%	2376	1.28%
Bulte 66 kV BB	2986	3080	3.15%	3003	0.57%	3095	3.65%
Bulte 11 kV BB	**4652**	**5235**	**12.53%**	**4606**	**-0.99%**	**5187**	**11.50%**
Vanrhynsdorp 66 kV BB	1628	1662	2.09%	1622	-0.37%	1656	1.72%
Vanrhynsdorp 22 kV BB	**1870**	**1889**	**1.02%**	**1850**	**-1.07%**	**1868**	**-0.11%**
Maximum Impact			**12.53%**	**Maximum Impact**	**6.36%**	**Overall Maximum Impact**	**11.50%**
Minimum Impact			**0.30%**	**Minimum Impact**	**-1.07%**	**Overall Minimum Impact**	**-0.11%**

5.3 Case study 2: Overcurrent Protection (MV & LV Networks)

This section will outline the results obtained from the DigSilent modelled Overcurrent relay settings. The results will be shown in the form of Overcurrent relay graphs reflecting the time delay settings on each relay when there is a three-phase fault.

Three-phase fault at Bulte 11kV Busbar

Using the results obtained in the event of a Three-phase fault, the most impact of the DG on the network is at Bulte 11kV Busbar. Figure 5.2 shows the IDMT relay characteristic graph before the connection of Bulte Solar PV Farm.

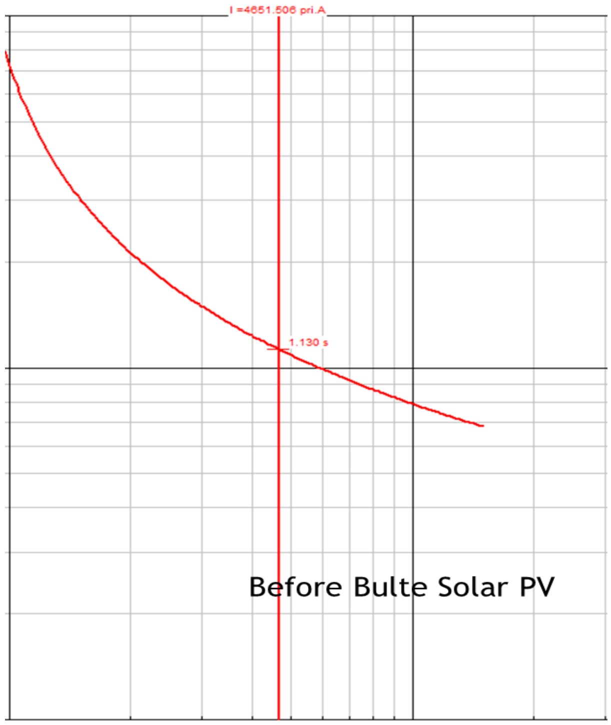


Figure 5.2: IDMT Relay Curve before connection of DG

The figure above shows an illustration of the overcurrent relay connected to the LV side of the two-winding transformer. IDMT relays are used on the network and the relay characteristic is shown on the figure above. The fault current of 4 652kA is symbolised by a vertical line cutting the relay characteristic curve at 1.13s. The IDMT relay will trip in 1.13s when a fault occurs at Bulte 11kV BB before the connection of Distributed Generation. The 1.13s is because there are two more relays that would trip before the relay at the transformer however to illustrate the impact of the connection of DG, the relay at the LV side of the transformer is analysed.

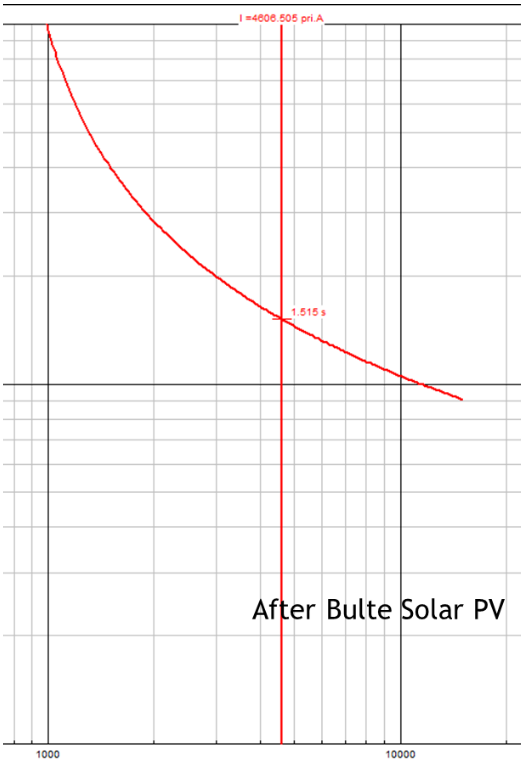


Figure 5.3: IDMT Relay characteristic after connection of DG

Figure 5.3 shows the IDMT relay characteristic of the relay connected to the LV side of the two-winding transformer after the connection of DG. There is fault current contribution mostly from the Bulte Solar PV Farm causing a shift in the IDMT Curve. The relay trip time is 1.51s compared to 1.1s before connection of DG. This is because the relay at the Solar PV Farm would trip before the transformer relay.

Protection Coordination with the connection of DG

The relay characteristic curves of the IDMT relays and their grade margins in the event of a fault were displayed using DigSilent PowerFactory software**.** The relays have a grading margin of 0.4s which is the IEC requirement/standard.

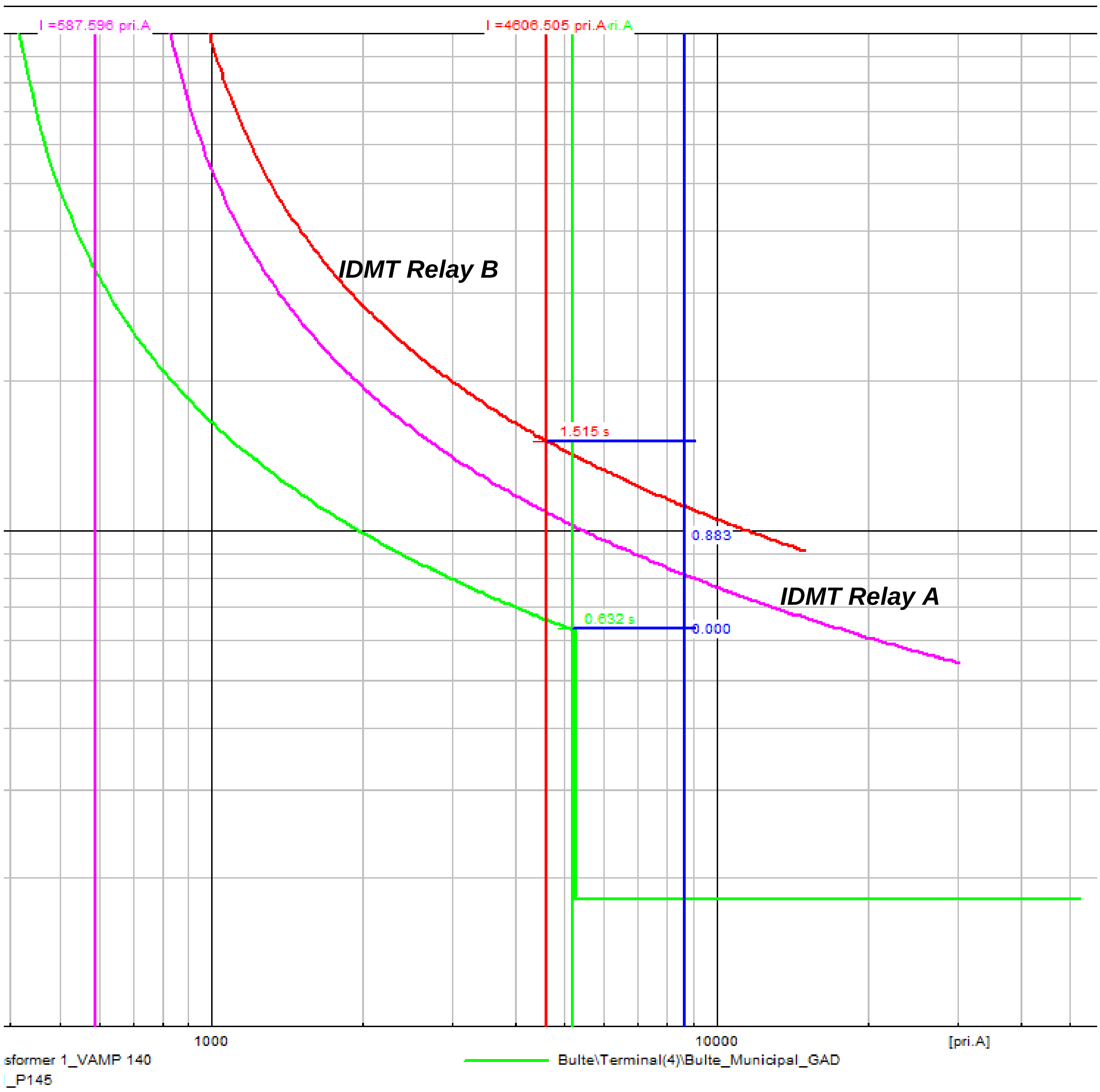


Figure 5.4: Time-Grading of the IDMT Relays

The above figure shows the relay characteristic curves of the Overcurrent relays, the fault currents and grade margins. When there is a three-phase fault at Bulte 11kV Busbar, IDMT Relay A (purple), the one closest to the Solar PV Farm is set to trip within 1.1 seconds. IDMT Relay, (Red curve) represents the relay on the LV side of Bulte Transformer which would trip in 1.5 seconds. Other relays connected in the network have not been demonstrated, one relay would trip instantaneously and the other within 0.4 seconds.

Using the Time-based coordination explained in Chapter 3, IDMT Relay A is closest to the fault and should see the fault before IDMT Relay B.

5.4 Case study 3: Distance Protection Relays

Characteristics of the distance relays were derived from the network in the event of fault. Figure 5.5 shows the fault location in the network. Figure 5.6 shows the characteristic of Skaapvlei distance relay when there is a three-phase fault on the Skaapvlei to Juno line. The short-circuit currents were calculated using the IEC 60909 method

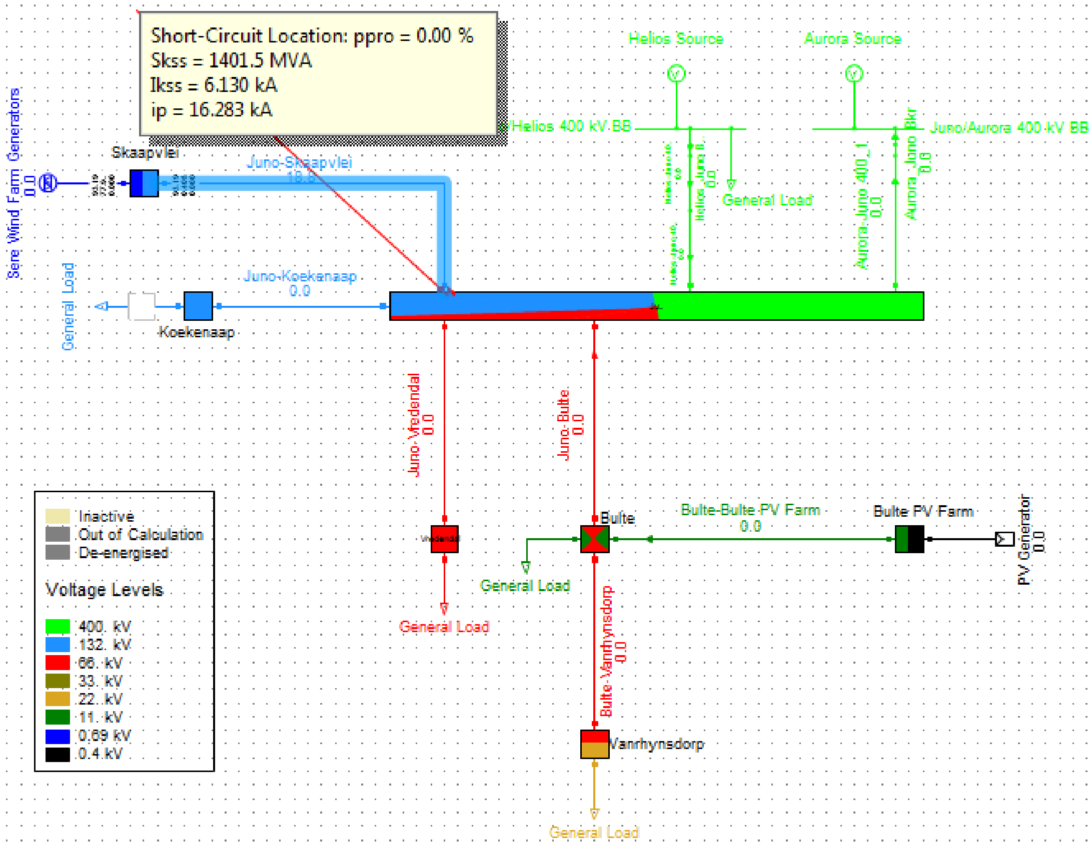


Figure 5.5: Single-Phase to Ground Fault on 0% of Skaapvlei line

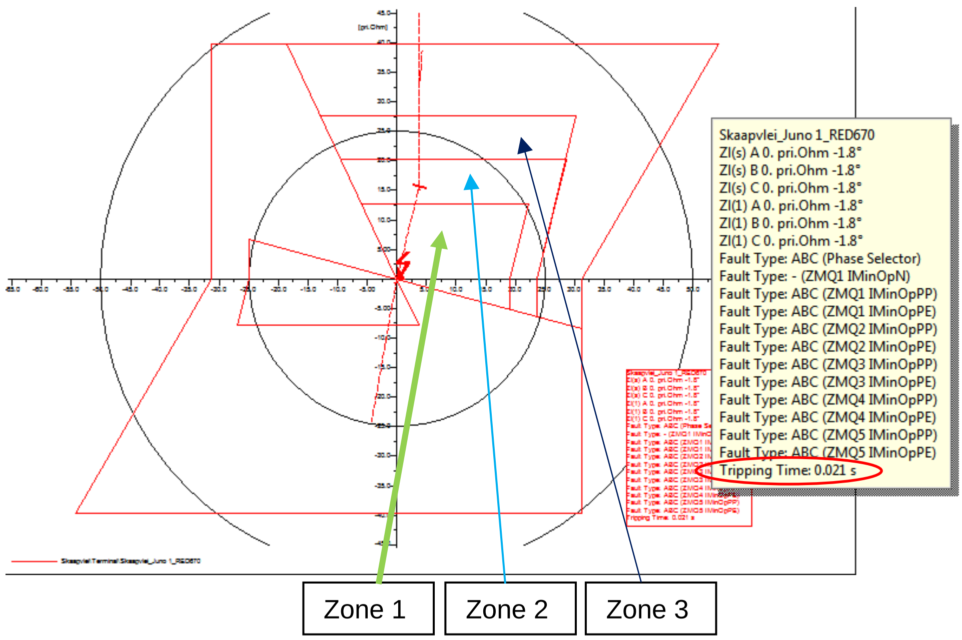


Figure 5.6: Distance Relays characteristic curves

In the event of a fault at 0% of line, Zone 1 will trip instantaneously as shown in Figure 5.6. Distance relays are also used in all the zones with a time grading of 0.4s. When there is a fault in Zone 1, the relay will trip instantaneously while Zone 2 will trip in 0.4s**.** For a fault at 100% of line, the fault will be seen in Zone 2 time as shown in Figure 5.8 and will trip in 0.4s. Zone 1 is set to cover 80% of line whilst Zone 2 should cover 120% of line.

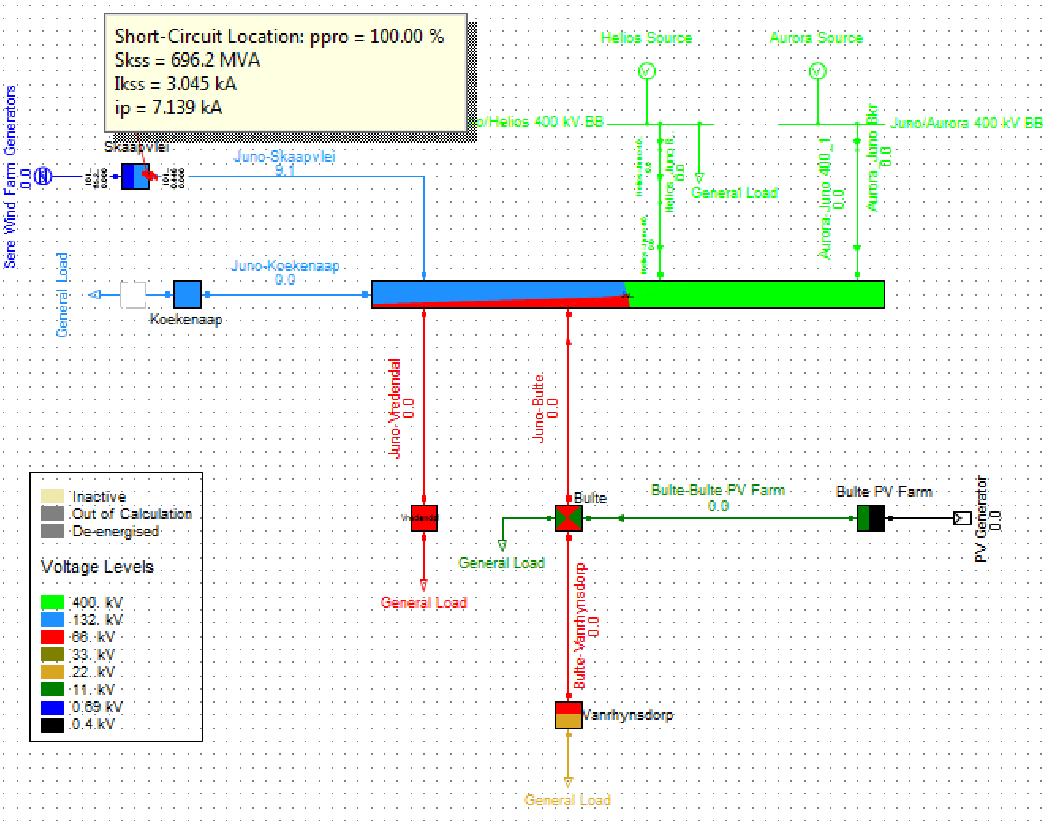


Figure 5.7: Single-phase to ground fault on 100% of Skaapvlei line

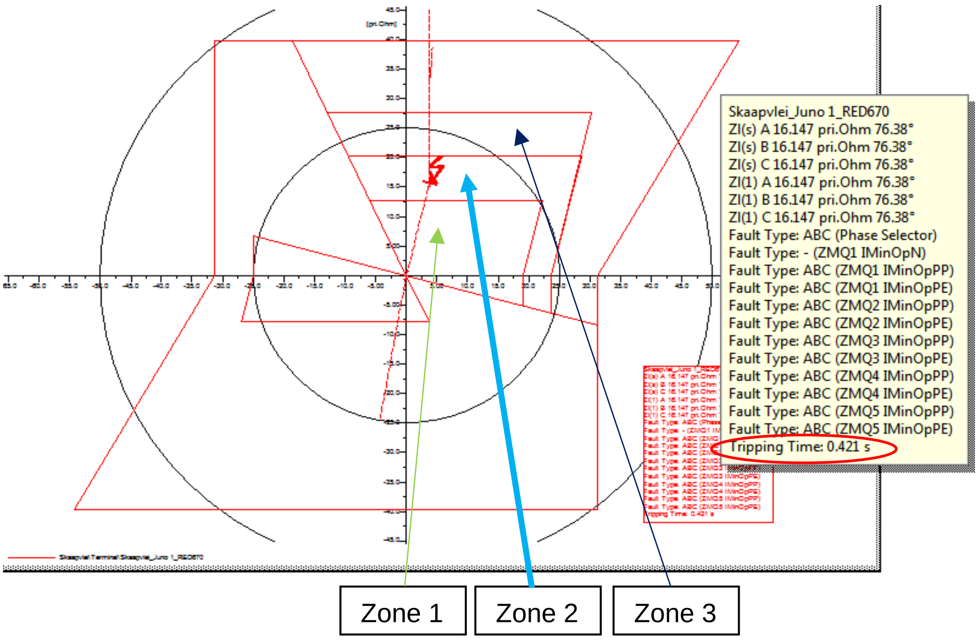


Figure 5.8: Distance Relays characteristic curve after Skaapvlei fault at 100% of the line

If Zone 1 and Zone 2 relays do not isolate the fault, then Zone 3 Relay will trip in 0.8 seconds.

CHAPTER 6
DISCUSSION, CONCLUSION AND RECOMMENDATIONS

6.1 Introduction

This chapter gives a general discussion of the thesis particularly of the results obtained. A conclusion is drawn and ends with recommendations to curb the impact of DG on the electric protection system.

6.2 General Discussion

The main aim of the research was to investigate the impact of DG on the electric protection system by using DigSilent software to simulate a network showing pre- and post- connections of DG particularly wind and solar Photovoltaic (PV) to clearly show fault levels and any change in the relay settings/protection system. The two types of DG technologies investigated are the most common in South Africa. Based on the results obtained in Chapter 5, there was an increase in fault levels in the event of three phase faults on Busbars and single-phase to ground faults on the lines. The most impact occurred at the point closest to the DG sources which led to an increase in fault levels.

The relays were coordinated with a time grading of 0.4seconds and it could be seen on the Overcurrent relays that the relay trip time changed from 0.4 seconds to 0.8 seconds to accommodate the penetration of DG. High penetration of DG into the network could easily result in loss of coordination therefore it is important that utilities design their protection systems to accommodate the penetration of DG in the future.

Other studies have identified some of the problems related to the connection of DG to the power network particularly on the protection system including nuisance tripping, islanding, protection blinding amongst others, two particular impacts have been identified in this study which is the impact on short circuit levels and protection coordination. The radial characteristic of the traditional power system also changes with the penetration of DG. Some of the solutions adopted to curb the effects of the connection of DG include limiting the generation sizes, using Fault Current Limiters and adaptive protections schemes.

6.3 Conclusion

Global concern regarding energy costs, security and greenhouse gases has left the power industry resorting to Flexible AC Transmission Systems elements and Renewable Energy Sources mostly in the form of DG. The penetration of DG into the power network which was primarily designed to work as a radial network can create a full spectrum of problems ranging from voltage profile, power flow, protection and stability. The study carried out focused on the impact of DG on the protection system.

Based on the analysis and results obtained from the study, it is apparent that these DG sources contribute to the level of fault current. In order to limit some of the effects on the protection system of connecting DG to the utility grid, it is important to know the percentage change in fault currents before and after the connection of DG. The IEC60909 method was used to analyse fault current pre and post connection of DG. There was an overall increase in short circuit current with the connection of DG. The maximum fault current increase was seen on the Busbars closest to the DG sources. Overcurrent protection was applied in the MV and LV networks, clearly indicating the impact of DG on protection coordination of the relays. The study analysed the fault current contribution percentage increase on transmission lines with the connection of DG. This was seen to impact distance relays and could significantly impact coordination of the relays. It can be concluded that DG has an impact on the short circuit levels and on protection coordination in an electric grid.

While the size of the DG sources currently embedded in the South African grid are insignificant enough to pose a big threat on the protection devices, there is a huge growth in the development and integration of these generators and hence it is important to make sure the protection system can handle the fault currents.

6.4 Recommendations

1. Utilities that are still expanding and adopting cleaner energy like South Africa need to take DG into account when designing their utility expansion by making sure the protection devices can accommodate numerous generation sources at any level of the power network. While this can be a costly move, it avoids any serious implication of the penetration of DG into the network.
2. A study of the penetration of DG into the network and how it might affect the protection system needs to be carried out before the DG sources are connected into the utility grid. Plant owners to need to seek approval from Municipalities or relevant authorities before they can connect into the network.

Bibliography

A.O. Osahenvemwen, O.O. 2008. Electric Power Transmission line Faults in Nigeria.pdf. *International Journal of Electrical and Power Engineering*, 2(6).

Abdulfetah Shobole, Mustafa Baysal, Mohammed Wadi, M.R.T. 2017. … Coordination Practice in Electrical Substation Part-1 Overcurrent and Earth Fault Protection Case Study of Siddik Kardesler Substation (SKS), Istanbul, Turkey. *Gazi University Journal of …*, 30(4): 163–178. http://dergipark.gov.tr/gujs/issue/32802/281488.

Ahmad, A. & Bukka, S.K. 2015. Implementation of Adaptive Zone-2 Protection for Transmission Lines. *International Journal Of Modern Engineering Research (IJMER)*, 5(6): 6–13. www.ijmer.com.

Báez-Rivera, Y., Schulz, N.N. & Gao, W. 2006. Advanced modeling of micro-turbine controls for system analysis. *Power Systems Conference 2006: Advanced Metering, Protection, Control, Communication and Distributed Resources, PSC, IEEE*, 229: 219–223.

Bari, N.A., Jawale, S.D. & Deshmuikh, B.T. 2017. Adaptive Over-Current Protection for Distribution System with Distributed Generation. *International Journal of Innovative Research in Electrical, Electronics, Instrumentation and Control Engineering (IJIREEICE)*, 5(9): 13–18.

Barsoum, N. & Lee, K. 2018. Simulation of Overcurrent Relay in 33kV Power Grid Protection. *Open Science Journal of Electrical and Electronic Engineering*, 5(5): 54–63. http://www.openscienceonline.com/journal/j3e.

Bello, M., Smit, R., Carter-Brown, C. & Davidson, I.E. 2013. Power Planning for renewable energy grid integration - Case Study of South Africa. *IEEE Power and Energy Society General Meeting*: 1–5.

Bhise, D.R., Kankale, R.S. & Jadhao, S. 2017. Impact of distributed generation on protection of power system. *IEEE International Conference on Innovative Mechanisms for Industry Applications, ICIMIA 2017 - Proceedings*, (Icimia): 399–405.

Blaabjerg, F. 2014. Wind Energy Systems. *IEEE*: 1–16. http://www.ieee.org/publications standards/publications/rights/index.html.

Bohlmann, H.R., Horridge, J.M., Inglesi-Lotz, R., Roos, E.L. & Stander, L. 2019. Regional employment and economic growth effects of South Africa’s transition to low-carbon energy supply mix. *Energy Policy, Elsevier*, 128(January): 830–837. https://doi.org/10.1016/j.enpol.2019.01.065.

Boxwell, M. 2012. *Solar Electricity Handbook*. 6th Editio. S. Glasbey, ed. Warwickshire, United Kingdom: Greenstream Publishing. www.GreenstreamPublishing.com.

Brady, C. 2014. Investigation of Relay Protection Systems in MV Networks With Large in-feed of DIstributed Generation. *Department of Enrgy Technology, Aalborg University, Denmark*, (June): 96. www.et.aau.dk.

Chiradeja, P. 2005. Benefit of Distributed Generation : A Line Loss Reduction Analysis. *IEEE Power and Energy Society General Meeting*: 1–5.

Choudhary, N.K., Mohanty, S.R. & Kumar Singh, R. 2015. Coordination of Overcurrent Relay in Distributed System for Different Network Configuration. *Journal of Power and Energy Engineering*, 03(10): 1–9. http://dx.doi.org/10.4236/jpee.2015.310001.

Conti, S. 2009. Analysis of distribution network protection issues in presence of dispersed generation. *Elsevier*, 79(1): 49–56. https://doi.org/10.1016/j.epsr.2008.05.002.

Department of Energy. 2011. Integrated Resource Plan for Electricity 2010-2030. *Department of Energy (South Africa)*, (March): 78. http://www.energy.gov.za/IRP/irp files/IRP2010_2030_Final_Report_20110325.pdf.

DigSILENT. 2019. PowerFactory - DigSILENT. https://www.digsilent.de/en/powerfactory.html 23 June 2019.

Dirksen, J. & Gmbh, D. 2013. Low Voltage Ride-Through. , (43): 56–60.

Edvard Csanyi. 2012. Principles and Characteristics of Distance Protection. *Electrical Engineering Portal (EEP)*. https://electrical-engineering-portal.com/principles-characteristics-distance-protection 21 June 2019.

El-Hawary, M. 2015. *Electrical Power Systems*. P. M. Anderson, ed. New York, USA: IEEE Press.

Eskom Holdings SOC Ltd. 2019. Coal Power. *Eskom Holdings SOC Ltd*.

http://www.eskom.co.za/AboutElectricity/ElectricityTechnologies/Pages/Coal_Power.aspx 26 March 2019.

Eskom Holdings SOC Ltd. 2010. Distribution Policy: POLICY FOR NEUTRAL EARTHING OF ELECTRICAL NETWORKS. *Policy Document*, (May). http://www.eskom.co.za/Whatweredoing/Documents/Eskom_policy_for_neutral_earthing_of_electrical_networks_DPL_34-2149.pdf.

Fernnandez Sarabia, A. 2011. Impact of distributed generation on distribution system By. *Aalborg University Denmark*, (June): 106.

Folarin, A., Sakala, J.D., Matlotse, E. & Gasennelwe-jeffrey, M.A. 2018. Modeling and Simulation of Faults in Distribution Network System Using MATLAB / Simulink 1 Dauda. *IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE)*, 13(3): 43–51. www.iosrjournals.org.

Frede Blaabjerg, Yongheng Yang, D.Y. 2017. Distributed Power-Generation Systems and Protection. *IEEE*: 1–21.

Gawande, S.P., Porate, K.B., Thakre, K.L. & Bodhe, G.L. 2011. Synchronization of Synchronous Generator and Induction Generator for Voltage. *2010 3rd International Conference on Emerging Trends in Engineering and Technology*: 407–412. http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5698358&isnumber=5698278%0A.

Guaitolini, S.V.M., Yahyaoui, I., Fardin, J.F., Encarnacao, L.F. & Tadeo, F. 2018. A review of fuel cell and energy cogeneration technologies. *2018 9th International Renewable Energy Congress, IREC 2018 (IEEE)*, (Irec): 1–6. http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8362573&isnumber=8362442.

Herbert, G.M.J., Iniyan, S., Sreevalsan, E. & Rajapandian, S. 2007. A review of wind energy technologies. *Renewable and Sustainable Energy Reviews, Elsevier*, 11: 1117–1145.

Hudananta, S., Haryono, T. & Sarjiya. 2018. Study of overcurrent protection on distribution network with distributed generation: An Indonesian case. *Proceedings - 2017 International Seminar on Application for Technology of Information and Communication: Empowering Technology for a Better Human Life, iSemantic 2017*, 2018-Janua: 126–131.

Iagăr, A., Popa, G.N. & Diniş, C.M. 2018. Study of a phase-to-ground fault on a 400 kV overhead transmission line. *IOP Conference Series: Materials Science and Engineering*, 294(1): 14.

Ilik, S.C. & Arsoy, A.B. 2017. Effects of Distributed Generation on Overcurrent Relay Coordination and an Adaptive Protection Scheme. *IOP Conference Series: Earth and Environmental Science*, 73(1).

International Finance Corporation, W.B.G. 2015. Utility-Scale Solar Photovoltaic Power Plants. *World Bank Group*.

Jain, S. & Jain, P.K. 2017. The rise of Renewable Energy implementation in South Africa. *Energy Procedia, Elsevier*, 143: 721–726. https://doi.org/10.1016/j.egypro.2017.12.752.

Jauch, C., Sørensen, P., Norheim, I. & Rasmussen, C. 2007. Simulation of the impact of wind power on the transient fault behavior of the Nordic power system. , 77: 135–144.

Józef, L., Bartosz, O. & Aleksandra, S. 2018. Overcurrent Protections in MV Grid with Local Energy Sources. *Institute of Electrical Power Engineering, Poznań University of Technology, Poznań, Poland*, 64: 08005.

Keller, K. 2010. Overcurrent Protection Learn more about Overcurrent Protection Electrical System Grounding and Bonding Protection of DERs. *Elsevier*: 16. https://www.sciencedirect.com/topics/engineering/overcurrent-protection 23 June 2019.

Klopotan, T.G.L.M.D. 2012. Impact of Distributed Generation on Distribution Network Protection. *ESBI Engineering & Facility Management, Ireland*, 433–440: 5.

Krupa, J. & Burch, S. 2011. A new energy future for South Africa: The political ecology of South African renewable energy. *Energy Policy, Elsevier*, 39(10): 6254–6261. http://dx.doi.org/10.1016/j.enpol.2011.07.024.

Kumpulainen, K. 2004. IMPACT OF DISTRIBUTED GENERATION ON THE PROTECTION OF DISTRIBUTION NETWORKS. *Eighth IEE International Conference on Developments in Power System Protection*, 2004: 315–318. http://ieeexplore.ieee.org/xpl/articleDetails.jsp?tp=&arnumber=1364869&contentType=Conference+Publications&searchField%3DSearch_All%26queryText%3DImpact+of+Distributed+Generation+on+the+Protection+of+Distribution+Networks.

Lasseter, R. 2002. Dynamic models for micro-turbines and fuel cells. *2001 Power Engineering Society Summer Meeting. Conference Proceedings (Cat. No.01CH37262), IEEE*, 2: 761–766 vol.2.

MUSONI, N.E. 2018. ANALYSIS OF THE EFFECT OF RENEWABLE GENERATION ON THE POWER QUALITY OF THE GRID , MODELLING AND ANALYIS OF HARMONIC AND VOLTAGE DISTORTION By NKUSI EMMANUEL MUSONI, *Cape Peninsula University of Technology*, (February): 183. www.cput.ac.za.

Nakumuryango, A. & 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, Elsevier*, 56: 999–1007. http://dx.doi.org/10.1016/j.rser.2015.12.013.

Nehrir, H., Caish & Shaw, S.R. 2006. Fuel cells: promising devices for distributed generation. *IEEE Power and Energy Magazine*, 4(1): 47–53. http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1578531&isnumber=33348%0A.

Neisius, H.T., Dzafic, I., Henselmeyer, S., Ablakovic, D. & Lecek, N. 2012. Modeling of auto-transformers for load flow calculations. *IEEE PES Innovative Smart Grid Technologies Conference Europe*: 1–6. http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6465850&isnumber=6465601.

NERSA. 2014. GRID CONNECTION CODE FOR RENEWABLE POWER PLANTS (RPPs) CONNECTED TO THE ELECTRICITY TRANSMISSION SYSTEM (TS) OR THE DISTRIBUTION SYSTEM (DS) IN SOUTH AFRICA. *NERSA*, 8(July).

Niwas, S., Singh, S., Østergaard, J. & Jain, N. 2009. Distributed Generation in Power Systems: An Overview and Key Issues. *Proceedings of IEC*. http://orbit.dtu.dk/files/5202512/24IEC_paper.pdf.

Nsengiyumva, E., Saulo, J.M. & Nyakoe, G.N. 2018. APPLICATION OF ADAPTIVE PROTECTION SCHEME IN DISTRIBUTION NETWORKS WITH DISTRIBUTED GENERATION : A REVIEW. *International Journal of Engineering Technology and Scientific Innovation*, 03(05): 14. www.ijetsi.org.

Onah, A.J. 2019. Investigating Phase Over-Current (OC) Protection in Medium-Voltage networks. *European Journal of Engineering Research and Science (EJERS)*, 4(6): 41–49. http://dx.doi.org/10.24018/ejers.2019.4.6.1307.

P Manditereza, R.B. 2015. Renewable distributed generation : The hidden challenges – A review from the protection perspective. *Elsevier*, 58: 1457–1465. http://dx.doi.org/10.1016/j.rser.2015.12.276.

Pegels, A. 2010. Renewable energy in South Africa: Potentials, barriers and options for support. *Energy Policy*, 38(9): 4945–4954. http://dx.doi.org/10.1016/j.enpol.2010.03.077.

Pepermans, G., Driesen, J., Haeseldonckx, D., Belmans, R. & D, W. 2005. Distributed generation : definition , benefits and issues $. *Elsevier*, 33: 787–798.

Raj, A., Gupta, M. & Panda, S. 2016. Design Simulation and Performance Assessment of Yield and Loss Forecasting for 100 KWp Grid Connected Solar PV System. *2016 2nd International Conference on Next Generation Computing Technologies (NGCT), IEEE*, (October): 528–533.

Saad, S.M., El Naily, N. & Mohamed, F.A. 2018. Investigating the effect of DG infeed on the effective cover of distance protection scheme in mixed-MV distribution network. *International Journal of Renewable Energy Development (IJRED)*, 7(3): 223. http://ejournal.undip.ac.id/index.php/ijred.

Tao, M. 2014. Roadblocks to Terawatt Solar Photovoltaics. In *Terawatt Solar Photovoltaics, roadblocks and Opportunities*. SpringerBriefs in Applied Sciences and Technology: 61–79. http://link.springer.com/10.1007/978-1-4471-5643-7_5 30 March 2019.

Thakur, T. 2016. Three Phase Faults Analysis of Power System. *Global Journal of Researches in Engineering (USA)*, 16(5): 13.

The University of Edinburgh. 2017. Renewable Energy | The Solar Spark. *The University of Edinburgh*. http://www.solarspark.chem.ed.ac.uk/science/renewable-energy 30 March 2019.

Times Media. 2015. *Eskom and SA Energy Crisis*. Cape Town: Times Media Books.

Wang, C. & Nehrir, M.H. 2006. Distributed Generation Applications of Fuel Cells. *2006 Power Systems Conference: Advanced Metering, Protection, COmmunication, and*

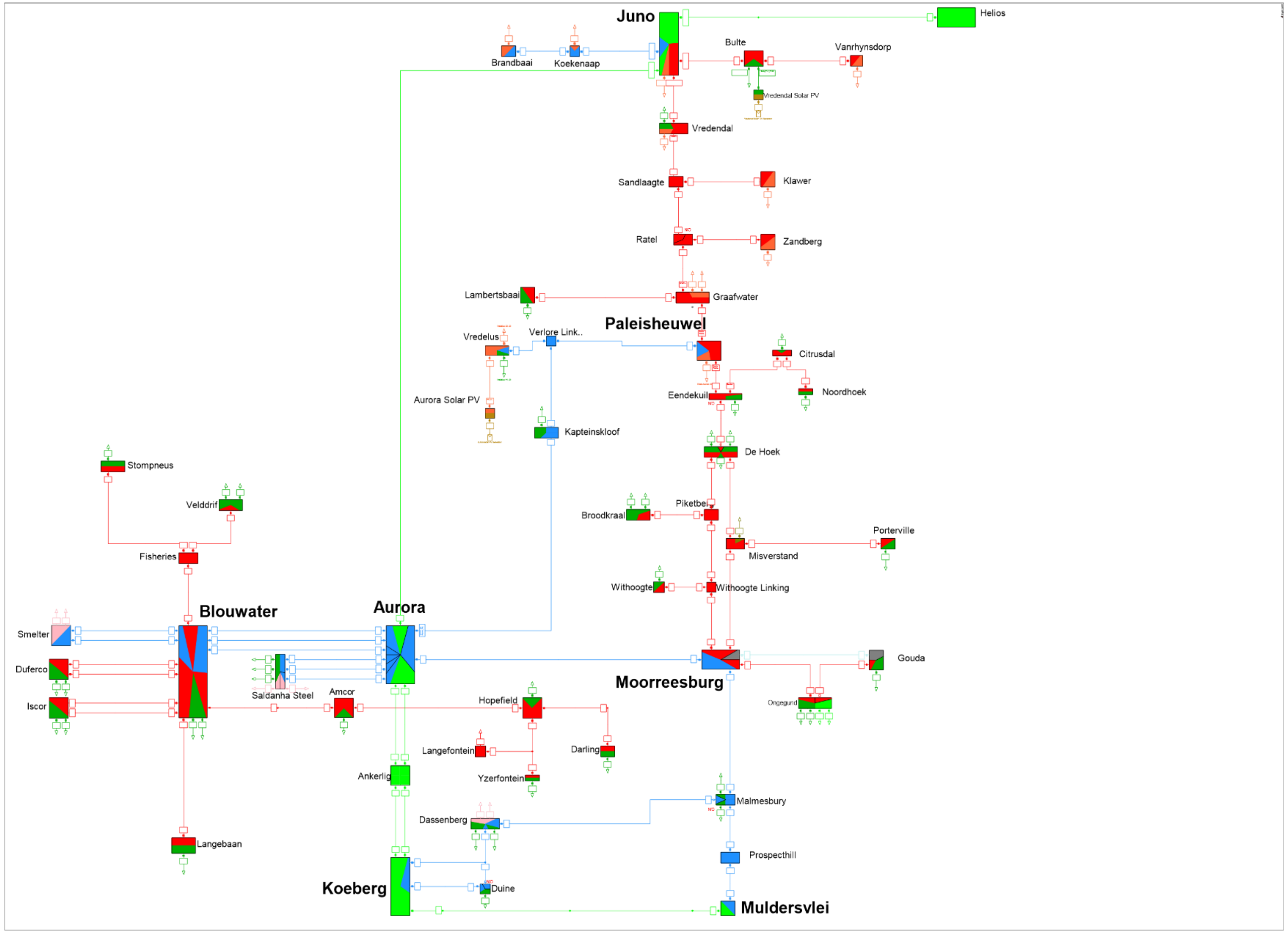
Distributed Resources (IEEE): 244–248. http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4064675&isnumber=4064642.

Wang, W., Pan, Z.C., Cong, W., Yu, C.G. & Gu, F. 2008. Impact of distributed generation on relay protection and its improved measures. *2008 China International Conference on Electricity Distribution, CICED 2008, IEEE*: 1–5.

Zeman, M. 2013. Photovoltaic systems. In *Delft University of Technology*. CD Delft, Neatherlands: Delft University of Technology: 1–17.

Zhang, J.F., Ding, S.M., Hang, Y.L. & Guang, H. 2009. Research on distributed generation source placement. *1st International Conference on Sustainable Power Generation and Supply, SUPERGEN '09*: 1–4.

Appendix A: West Coast Overview (South Africa)



Appendix B: Line Parameters

Name	Type	Length	Type of Phase Conductors	Type of Earth Conductors	Max.Sag, Phase Conductors	Max.Sag, Ground Wires	Irated(act.)	Irated	Z1	phiz1	R 1	X1	R 0	X0
	TypLne,TypTow,TypGeo, TypCabsys	km	TypCon	TypCon	m	m	kA	kA	Ohm	deg	Ohm	Ohm	Ohm	Ohm
Aurora-Juno 400_1	506A	163.41	2DINOSAUR50	S19 -(19/.104 19/2.65 19/2.7)	11.3	10.1	1.704	1.704	52.13013	85.72989	3.881535	51.98543	51.85101	179.3448
Brandbaai-Kookenaap 132_1	W05	49.8	ASH50	1.05E+52	5.1	4.1	0.648	0.648	23.78496	67.0266	9.283356	21.89848	30.42315	57.58682
Bulte Vredendal Solar 22 SC	11 kV 185mm2 Al PILC 3Cc	0.8			0	0	0.546	0.546	0.1097605	53.29715	0.0656	0.088	0.9972	0.0404
Bulte-Juno 66_1	W13	9	HARE50	6.20E+51	4.68	9.8	0.292	0.292	4.486667	56.70854	2.462723	3.750356	3.788079	14.6019
Bulte-Van Rhynsdorp 66_1	W13	21.84	HARE50		4.68	0	0.292	0.292	10.88764	56.70854	5.976209	9.100864	9.192404	35.43396
Helios-Juno 400_1 S1	506A	148.93	2DINOSAUR50	S19 -(19/.104 19/2.65 19/2.7)	11.3	10.1	1.704	1.704	47.5108	85.72989	3.537586	47.37892	47.25641	163.4528
Helios-Juno 400_1 S2	504	21.62	2DINOSAUR50	S19 -(19/.104 19/2.65 19/2.7)	13.1	11.8	1.704	1.704	7.059361	85.94205	0.4995584	7.041663	6.618077	23.6764
Juno-Koekenaap 132_1	W05	23.64	ASH50	1.05E+52	5.1	4.1	0.648	0.648	11.29069	67.0266	4.406797	10.39518	14.44183	27.3364
Juno-Vredendal 66_1	W13	16.32	HARE50		4.68	0	0.292	0.292	8.135822	56.70854	4.465738	6.800646	6.869049	26.47812
Klawer-Sandlaagte Switching 66_1	W13	14	HARE50		4.68	0	0.292	0.292	6.979259	56.70854	3.830903	5.833888	5.892567	22.71407
Ratel Switching-Sandlaagte Switchin 66_	W13	24.35	HARE50		4.68	0	0.292	0.292	12.13893	56.70854	6.663035	10.1468	10.24886	39.50626
Sandlaagte Switching-Vredendal 66_1	W13	19.2	RABBIT50		4.68	0	0.1860278	0.1860278	13.43799	39.13924	10.4227	8.482159	13.25012	31.63213

Appendix C: Busbar Voltages

Busbar	Area	Voltage
1	Helios	400kV
2	Aurora	400kV
3	Juno	400kV
4	Juno	132kV
5	Koekenaap	132kV
6	Skaapvlei	132kV
7	Juno	66kV
8	Vredendal	66kV
9	Butle	66kV
10	Vanrhysdorp	66kV
11	Vanrhysdorp	22kV
12	Bulte Solar PV	11kV

Appendix D: Transformer Specifications

Transformer	Power Rating	Qty	Rated Voltage	Z1	Z0
Juno	120MVA	2	400kV/132kV	11.89%	11.89%
Juno	80MVA	2	132kV/66kV	11.2%	11.1%
Bulte	10MVA	1	66kV/11kV	8.7%	8.7%
Vanrhysdorp	10MVA	1	66kV/11kV	8.7%	8.7%
Skaapvlei	80MVA	2	132kV/33kV	11.2%	11.2%
Skaapvlei	2.6MVA	1	0.69kV/33kV	6%	6%
Bulte PV Transformer	2.5MVA	1	0.4kV/11kV	6%	6%

Appendix E: General Loads

Load	Active Power	Reactive Power	Voltage (Per unit)
Helios	145.845 MW	86.775 MVar	1.0
Koekenaap	22.018 MW	7.143 MVar	1.0
Vredendal	8.005 MW	2.224 MVar	1.0
Bulte	3.83MW	0.96 MVar	1.0
Vanrhysdorp	3.8 MW	0.985MVar	1.0