Control and protection analysis for power distribution in a distributed generation system.

By

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Supervisor: Prof MTE KAHN

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DECLARATION

I, Abdolmonem Ibrahim Aljadid, declare that the content of this dissertation/thesis represents 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.

Signed **Date**

ABSTRACT

Distributed Generation systems based on renewable energy sources, such as wind or solar are mostly intermittent sources, due to their dependency on the weather, whereas those based on other primary energy sources are non-intermittent. All of them are specially designed to be integrated into distribution systems, in order to improve the power demand of consumers.

In the last few decades of the twentieth century, several different factors have played a key role in increasing interest in systems. Distributed Generation (DG) is gaining more and more attention worldwide as an alternative to large-scale central generating stations.

The aim of this research project is to investigate the contribution of distributed generation in fault current level in a power distribution system. The simulation results indicate that DG can have a positive or negative impact, on the fault current level in distribution network systems. The DG location and size affect the fault level. The second aim of this research was to suggest a model-based method for design, and implementation of a protection scheme for power distribution systems, by establish algorithms in a hardware environment. The overcurrent relay was chosen for the model development because it is considered a simple and popular protection scheme, and it is a common scheme in relaying applications. The proposed relay model was tested for fault conditions applied on a simple power system in different scenarios. The overcurrent relay model was implemented in MATLAB/Simulink, by using MATLAB programming languages and the SimPowerSystem (SPS) Tool.

MATLAB/SIMULINK software is applicable to the modelling of generation, transmission, distribution and industrial grids, and the analysis of the interactions of these grids. This software provides a library of standard electrical components or models such as transformers, machines, and transmission lines. Therefore, the modelling and simulations are executed using MATLAB/Simulink version 2014b.

Keywords: Renewable Energy systems, Renewable Energy Resources, MATLAB/Simulink, Electrical Distribution System, SimPowerSystem (SPS), Distributed Generation (DG).

ACKNOWLEDGEMENTS

In the name of ALLAH, the Most Gracious and the Most Merciful “Alhamdulillah”, all praises to omnipresent ALLAH for answering my prayers for granting me the strengths, patience and His blessing in finalizing this work.

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I would also to take this opportunity in order to express my deepest gratitude thank my parents, family and friends for their love, constant support and their precious advice through my life.

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DEDICATION

This research is dedicated to those who are dear to me, more particularly to my father's spirit Ibrahim Aljadid and to my mother Salma Abdulqader, of course my wife and my children.

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GLOSSARY

CO_2	Carbon Dioxide
PV	Photovoltaic
MW	Mega Watt
P_W	Power of wind energy
ρ	Air density
α	Wind turbine pitch angle
P	Active power
A	Area of wind turbine
V_1	Velocity of wind
P_t	Power extracted by the wind turbine
Q	Reactive power
λ	Tip speed ratio of the wind turbine
C_p	Wind turbine power coefficient
DC	Direct current
AC	Alternative current
U_{oc},	Open circuit voltage
n	Ideality factor
k	Boltzmann constant
T	Absolute temperature
q	Elementary charge
I_L	Light generated current
I_o	Dark saturation current
FF	Fill factor
U_{MPP},	Maximum voltage
I_{MPP}	The Maximum current
U_{oc}	Open circuit voltage
I_{sc}	Short circuit current
η	Efficiency of the solar cell
P_{in}	Total power in the light incident on the solar cell
PAFC	Phosphoric Acid Fuel Cell
AFC	Alkaline Fuel Cell
DMEF	Direct Methanol Fuel Cell

PEMFC	Proton Exchange Membrane Fuel Cell
MCFC	Molten Carbonate Fuel Cell
SOFC	Solid Oxide Fuel Cell
CIGRE	International Conference On Large High Voltage Electric Systems
DGs	Distributed Generations
FC	Fuel Cell
NPC	Neutral Point Clamped
CHB	Cascaded H-Bridge
FCs	flying Capacitors
$\boldsymbol{3V_P}$	Three phase voltage
$\boldsymbol{S_L}$	Apparent power absorbed by load
$\boldsymbol{P_L}$	Active power absorbed by load
$\boldsymbol{jQ_L}$	Complex power absorbed by load
$\boldsymbol{I_L}$	Line current and current absorbed by load
$\boldsymbol{I_S}$	Current of the utility source
$\boldsymbol{I_G}$	Current of Distributed Generation
$\boldsymbol{I_P}$	Phase current
$(\boldsymbol{Hz})$	Hertz
RMS	Root Mean Square Value of The Sinusoidal Voltage Wave
$\boldsymbol{m(t)}$	Modulation
$\boldsymbol{f_1}$	Fundamental power system frequency component
$\boldsymbol{U(t)}$	Voltage fluctuations
DPGS	Distributed Power Generation System
IDMT	Inverse Time Relays with Definite Minimum Time
MCCBs	Molded case circuit breakers
CT	Current Transformer
DRMS	Discrete Root Mean Square
SPS	Simpowersystem
B	Busbar
EDS	Electrical Distribution Network System

CHAPTER ONE

INTRODUCTION

1.1 Introduction

In the evolution of human civilization, different key factors are required in order to satisfy all the needs and to promote the development of this planet. One of these key factors is electrical power. This 21st century has seen electrical power becoming primordial in every sector of our life; it is almost impossible to talk about life without electrical power. From household needs to commercial and industrial applications, the electrical power is in action. The increasing consumption of electrical power has also led to an increased demand and many countries all over the world are facing big challenges in building new power plant infrastructures and long power transmission lines in order to meet the electrical power demand requirements of their countries. These new infrastructures are generally very costly and can lead to certain environmental concerns due principally to the use of fossil fuels which are the primary energy sources used to generate electric power.

Nature and humanity is threatened by global warming, caused by carbon dioxide emissions from fossil fuel. Vehicles and airplanes based on burning of gasoline, also contribute to large amounts of carbon dioxide being released into the atmosphere.However,CO_2 emissions from electricity production is listed as the major cause of carbon dioxide emission at an estimated rate of 57%global greenhouse gas emission. (Ashraf *et al*, 2006; Markham, 2009; Pal, 2009).

Figures 1.1 and 1.2 show global greenhouse gas emissions, which are broken down by the economic activities energy sources.

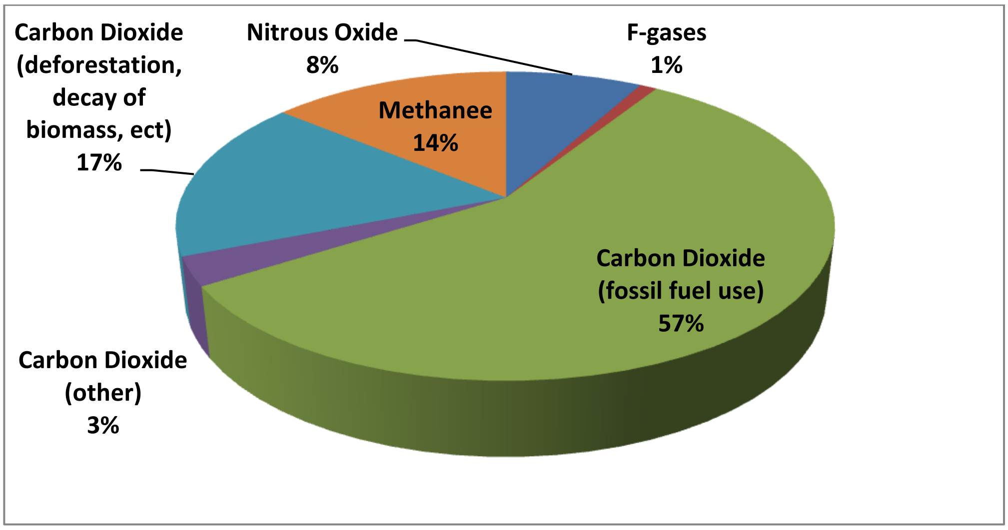


Figure 1.1: Global greenhouse gas emissions by gas (EPA, 2013)

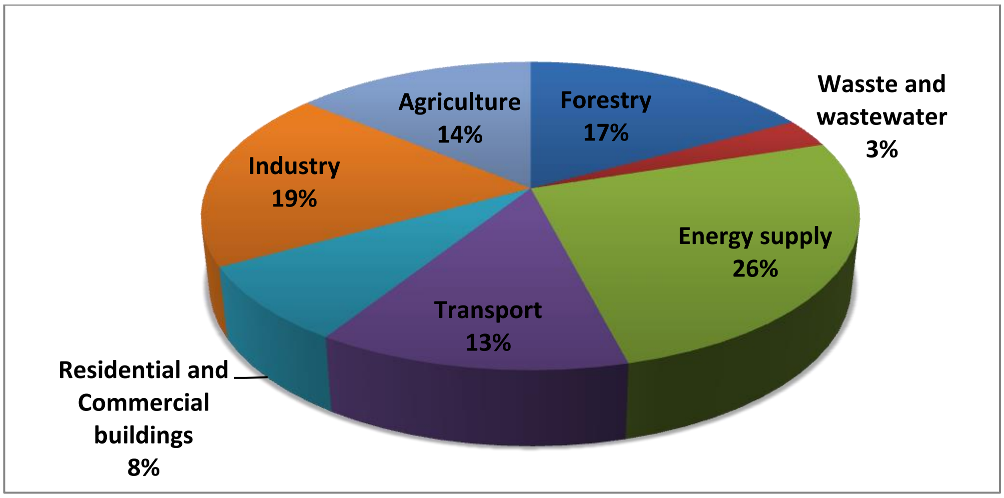


Figure 1.2: Global greenhouse gas emissions by economic activities (EPA, 2013)

Since the electricity demand is growing fast, while the building of new power plants as well as long power transmission lines is very challenging and costly, engineers have found alternative ways of generating electrical power and supplying it to the consumers. This is done by means of renewable energy sources such as solar, wind, biomass, etc. The use of renewable energy sources is encouraged all over the world, for their advantages of being less harmful to the environment, and their never-ending nature.

New power plants based on renewable energy sources can operate as standalone or grid connected systems, depending on whether the consumers are located in remote areas far away from the main power grid, or to supply power to both local consumers and the grid.

In grid connected applications, power plants based on renewable energy sources can be connected in the transmission or the distribution systems. When they are connected to the distribution system, they are referred to as Distributed Generation (DG). Distributed generation can also be based on some other primary energy sources which are not renewable.

Distributed Generation systems based on renewable energy sources, such as wind or solar are mostly intermittent sources due to their dependency on the weather, whereas those based on other primary energy sources are non-intermittent. All of them are specially designed for integration into distribution systems in order to improve the power demand of consumers.

However, problems still arise when distributed generation systems are integrated into the power distribution network, as the traditional distribution systems were designed to operate radially, without considering the integration of this new form of generation in the future. In radial systems, the power flows from upper terminal voltage levels down to customers situated along the radial feeders. Therefore, overcurrent protection in radial systems is quite straightforward as the fault current can only flow in one direction. With the increasing presence of distributed generation systems, distribution networks are becoming similar to transmission networks, where generation and load nodes are mixed (“mesh” system) and a more complex protection design is required. In this new configuration, design considerations regarding the number, size, location and technology of the DG connection, must be taken into account as the short circuit levels are affected and mis-coordination problems with protection devices may arise (Matcha et al, 2013).

Different types of events cause a negative impact on the reliability of the line. The magnitude of the impact is influenced by several factors, such as distance of the line to the nearest service centre, length of line, type of fault, time of day and protection scheme used. Many lines with poor reliability caused by temporary outages can be improved by installation of reclosers. The integration of distributed generators (DGs) into distribution systems, is being proposed as a solution, to meeting increasing load demands and to utilize more renewable energy. Existing overprotection schemes must be modified to address the new system characteristics of radial distribution systems with DGs. Minimum “off-the-shelf” overcurrent protection devices and distributed generators were added to the 123 Nodes Radial Test feeders. A commercial power systems analysis tool was used to determine the coordination issues that arise in the distribution system due to the integration of DGs (Butler-Purry & Funmilavo, 2009).

1.2 Background

Electrical power passes through three main stages before it can reach a customer point; the generation, transmission and distribution stages. The power is generated by power units which are not close to the consumers. Through these stages, the power system uses a huge passive distribution infrastructure, to deliver the power to the consumers, which includes multilevel voltage such as high voltage, medium voltage, and low voltage. Figure 1.3 shows the conventional theory of an electrical power system, in which the power flows from high level (generation) to low level (consumer). The voltage through these stages is transformed many times before it reaches the user. The voltage is either stepped up or stepped down by series transformers. The power generation facility at the utility generates three phases for which three wires are used to transmit power. Generating and distributing three phases is more economical than distributing the power using a single phase. The single phase power has only one (hot) wire.

Most power generation systems are based on fossil fuels, which are referred to as conventional primary energy sources for generation of electrical power. Figure 1.4 shows the world power production scenario in 2012, which comes from conventional sources such as coal, nuclear, gas, hydro and others. In general, the majority of power plants which use conventional sources have a negative impact on the environment.

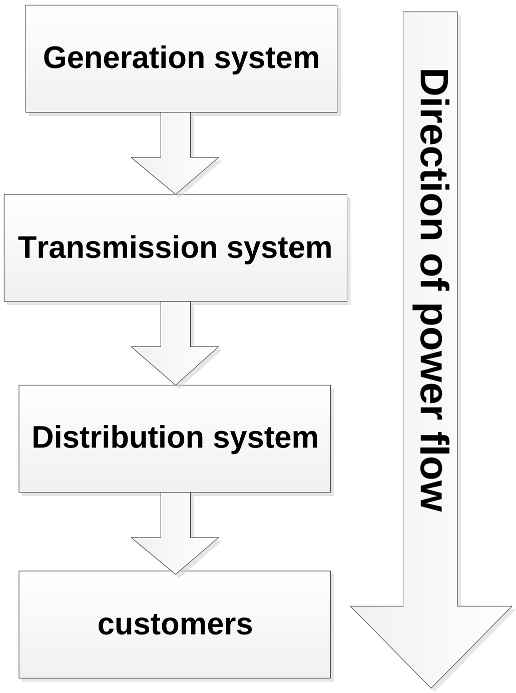


Figure 1.3: Direction of power flow in traditional power system

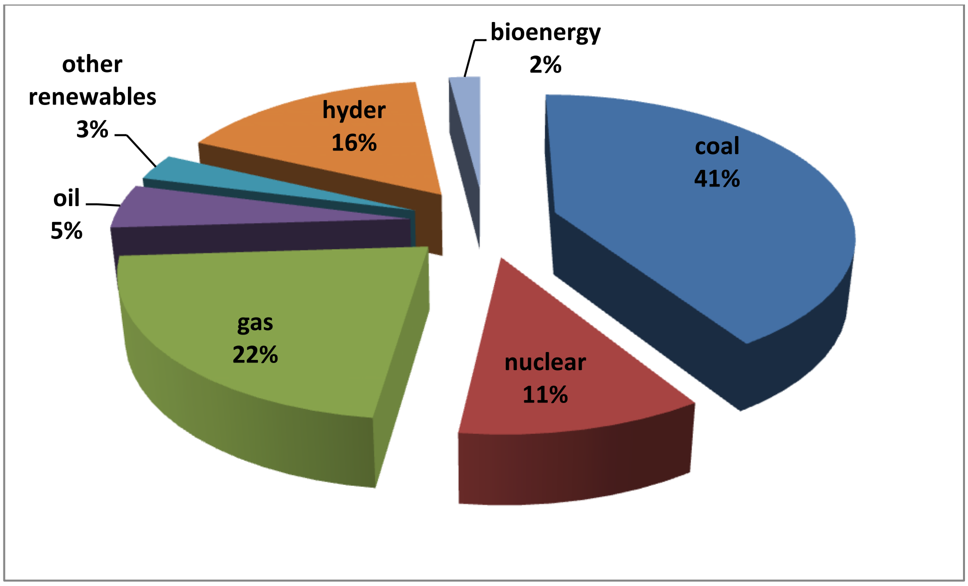


Figure 1.4: World power production scenario (IEA, 2014)

1.3 New concept of power system

The new configuration of a power system is shown in figure 1.5, and consists of the traditional power system which includes the generation, transmission and distribution systems, as well as new power generating units, which is known as Distributed Generation systems generally connected in the distribution systems. These new power generating units are mostly based on renewable energy sources, which have recently been considered as a key element in the electrical energy generation, in order to address global environmental problems, such as climate change and to increase the power generation capacity.

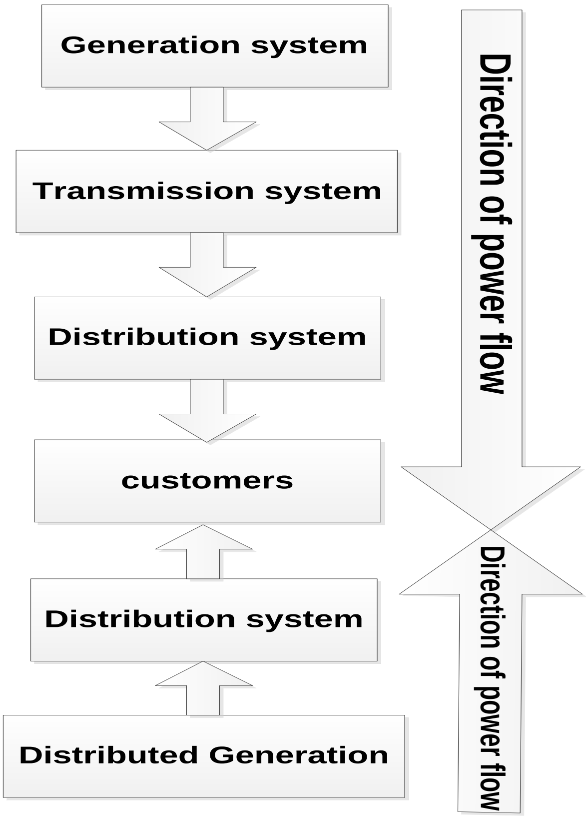


Figure 1.5: Bi-directional power flow due to distributed generation in a new power system concept.

In this new power system topology, distributed generation systems are connected to the distribution system close to the load. Therefore there is a change in the power flow concept of the power system, which has previously been designed to operate from the generation, transmission, distribution and finally to the consumers.

Traditional distribution systems have also been designed, based on the assumption that the primary substation is the only source of electrical power provider (El Safty et al., 2010). This fundamental basis is changed by distributed generation, by placing power sources onto the distribution system. Therefore, distributed generation interconnection results in operating situations, which do not occur in a conventional system, without generation directly located at the distribution networks. Careful engineering can effectively eliminate, the potentially adverse impacts which the penetration of distributed generation, could impress on the electrical supply system: the exposing system and customer equipment might be damaged; power quality and reliability can be affected negatively; extended time is required for restoration after outage; as well as prospective risks to public and worker safety (Walling et al., 2008).

This research will be focusing on, how to report some of the issues encountered when designing the over-voltage possibly, and inject harmonic into the grid, due to the increment of distributed generation into electrical distribution system, and the short circuit current levels and frequency change in the distribution system between protection devices, where a number of DG sources are connected to a radial distribution system.

1.4 Statement of the research problem

The main research target, is to model a radial distribution system and study the effect of distributed generation on the system, more particularly the effect of distributed generation penetration on short circuit currents of the distribution system, protective devices as well as the control frequency change in a distributed system due to the presence of renewable sources.

1.5 Thesis objectives and aim

1.5.1 **Objectives**

The main objective of this thesis, was to investigate and evaluate the effect that different configurations and integration levels of DG, may have on the fault current level in radial distribution systems.

The second objective was to develop possible solutions, for the increase of the fault current level into a distribution network system, in the presence of a significant number of DGs.

1.5.2 **Aim**

The main aim was to determine maximum and minimum fault currents due to the connection of distributed generations. This investigation is useful to the design engineer in selecting circuit breakers, for fault interruption, selecting relays for fault detection and determining the relay settings, which are referred to as relay coordination. The proper selection and setting of protective devices ensure minimum disruption of the electrical service and limits possible damage to the faulted equipment.

The proposed method aimed to ease the burden of decision making on the part of the system, operator by presenting a fast and accurate fault diagnosis method to classify, and identify the type of fault, which occurs on an overhead radial power distribution network.

Several methods for fault detection, and diagnosis in electric power distribution systems were investigated, and a method for the accurate detection and diagnosis of faults in distribution networks under various network operating conditions were modelled and simulated.

1.6 Research methodology

The research methodology involved a literature review, analysis of the existing methods, modelling and simulation of a radial distribution network in existing distributed generation and experimentation.

1.6.1 Literature review

This section is based on gathering theoretical information on electrical power system configurations, energy resources, the conventional generation method, nonconventional generation method, distributed generation technologies, and distribution systems in addition to the information related to the grid integration of renewable energy technologies and the impact of distributed generation on a power system.

1.6.2 Modeling

This section consists of modeling a radial distribution network including distributed generations using MATLAB/SIMULINK.

1.6.3 Simulation

In this section, simulation of different scenarios are performed. These simulations include different fault locations, connected and disconnected distributed generation at different line locations.

1.7 Scope and Limitations

This research study focused mainly on distribution systems in the presence of DG integration into low voltage distribution systems. Only the main technical issues with overcurrent protection systems of a distribution system were covered. Implementation of the established algorithms in some hardware environments was done. This work covered faults on distribution lines only. Therefore, fault detection and diagnosis on network equipment (generators, motors, transformers, etc.) was not covered. The DG technologies only considered the output of the power source as a fixed power supply to the grid from the customer’s side, for instance, synchronous generators and fixed speed wind turbines.

1.8 Outline of the Thesis

This thesis consists of five chapters and one appendix. It is organized as follows:

1.8.1 Chapter one

This chapter gives a brief introduction of this research project. The background of the problem, the problem statement, the objectives and research methodology are presented.

Additionally, the motivation that guides the research and all the assumptions made presented.

1.8.2 **Chapter Two**

This chapter covers the literature review. Firstly, conventional and nonconventional generation power plants are discussed, secondly power transmission and thirdly, power distribution systems. Thereafter, distributed generation technology and their advantages, disadvantages, types, capacity ranges and finally the interconnected interfaces of grid connection application.

1.8.3 **Chapter three**

This chapter deals with the issues of integration of distributed generation into distribution system, Impact of distributed generation on power systems are discussed.

1.8.4 **Chapter four**

This chapter is divided to two sections:

Section one is overcurrent protection scheme is implemented.

Section two deals with the investigation of distributed generation contribution in fault current level are performed. Simulation results with different DG configurations are presented at different line locations.

In This chapter, the explanation of the proposed system. A description of some of the important components of the system as well as their behaviour is presented.

1.8.5 **Chapter five**

This chapter presents the conclusions as well as the recommendations for this research project. The end of the chapter deals with references consulted in this research project.

1.9 Publications

Fault current contribution of distributed generation connected to the distribution network.

CHAPTER TWO

LITERATURE REVIEW

This chapter presents a general literature review on the structure of the electrical power system. It starts with a brief overview of power systems, and the concept of conventional and nonconventional generation methods. The chapter then focuses on the renewable energy technology. Lastly, a detailed explanation of prospective challenges related to the distribution system power quality, that may arise with the presence of DG is explored further.

2.1 Power system

The power system structure is shown in figure 2.1 below, and includes three different parts, namely, the generation, transmission and distribution systems. The generation system refers to the part of the power system where the electrical energy is generated. In most power systems, the generation part is located far away from cities and in order to supply electrical energy to the consumers, transmission lines are required. Than can be easily distributed.

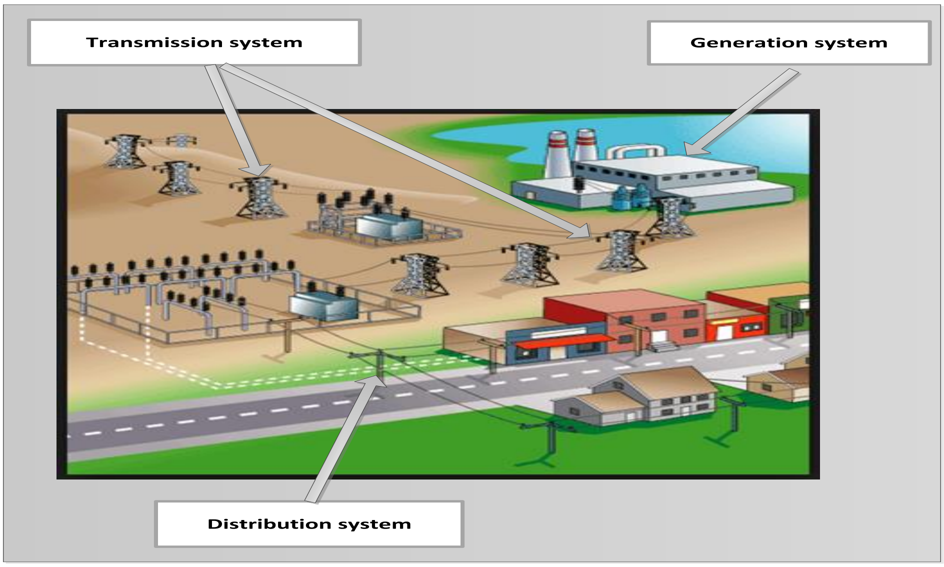


Figure 2.1: Electrical power system(ATE, 2014)

2.2 Generation system

The electrical generation system is divided into two main methods: firstly, nonconventional methods such as wind power, photovoltaic fundamentals and advanced energy technologies and secondly, conventional methods such as hydroelectric power generation, synchronous machinery, thermal generating plants and distributed utilities. Usually, the voltage levels of generation systems are around 11 kV and 33 KV due to technical problems such as, heating and insulation, which are stepped up with the aid of generating transformers in order to connect the generators and the transmission line (SINGH, 2008).

2.2.1 Conventional generating technologies

Conventional electricity generating technologies refer to the type of power plants that are mostly used and known since the beginning of electricity generation: These types of power plants are: thermal power plants, hydropower plants, nuclear power plants and some other technologies such as geothermal power, tidal power, wave power, etc. This section only focuses on the first three types of power plants mentioned above.

2.2.1.1 Thermal power plants

Thermal power generating technologies represent the most used type of power generation system in the world and this trend is not expected to change soon. The primary energy used is fossil fuels which include coal, gas and oil. This type of power plant always causes concerns about the future of the planet due to the fact that fossil fuels are cited as being responsible for emission of greenhouse gases which lead to climate change and global warming. Due to these concerns, many countries around the world are now focusing on alternative energy sources. A general layout of a thermal power plant is shown in Figure 2.2.

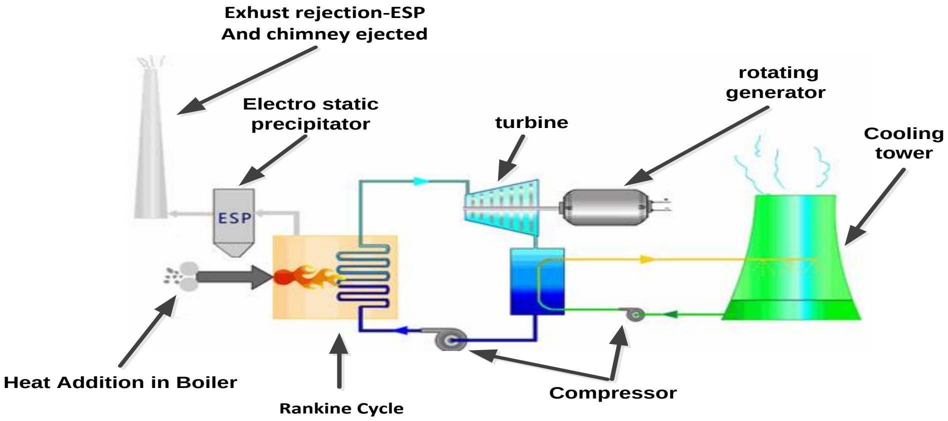


Figure 2.2: Thermal power plant (Learn Engineering, 2013)

2.2.1.2 Nuclear power plant

Nuclear power plants present the second most important type of power plants in the world. Compared to thermal power plants, this type does not generate carbon dioxide that contributes to global warming mentioned earlier. However, nuclear energy presents two main concerns which are firstly, the use of radioactive elements such as uranium which can lead to severe consequences in case of an accident by changing the biological structures in humans, animals and plant species.

The second concern about this type of power plant is related to the waste management which constitutes a serious problem for the environmentalists. A general layout of a nuclear power plant is shown in figure 2.3.

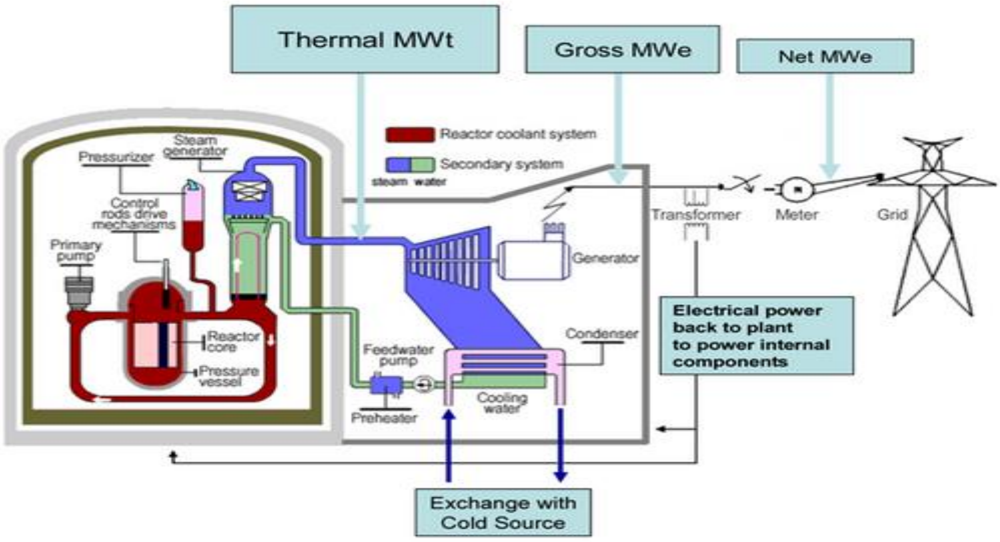


Figure 2.3: Nuclear power plants (Wilson, 2011)

2.2.1.3 **Hydropower plants**

Hydropower plants represent an alternative to thermal and nuclear power plants and are the most used power generating systems after thermal power plants. Unlike the first two power plants mentioned, this type of power plant presents some advantages, such as they do not have any negative impact on the environment and the water used as primary energy source is renewable. The main disadvantage is the fact that it is a bit difficult to supply the entire world with energy coming from hydropower systems because in some countries the available water is mostly used for other needs and also, this type of power plant requires long transmission lines in order to transport power from the generating area to the place where it will be used.

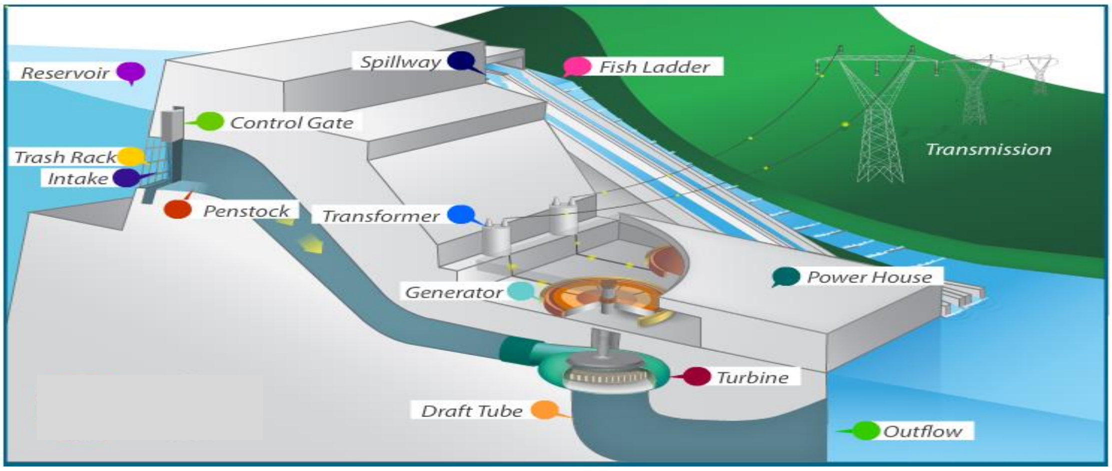


Figure 2.4: Hydropower plant layout (EERE, 2014)

Figure 2.4 shows a diagram of a hydropower plant connected to the transmission system.

2.2.2 Nonconventional generating technologies

Non-conventional power generation technologies are mainly based on renewable energy systems such as wind, solar, fuel cell biomass, hydro power, etc. Many countries around the world are focusing on developing these types of energy systems in order to fight against global warming and ozone depletion caused by some of the primary energy sources used in conventional power generation systems. For instance, in South Africa, the Department of Energy has set a renewable energy target of 10 000 GWh (0.8 Mtoe) by 2013, to be produced mainly from the renewable energy systems mentioned above. This section focuses on renewable energy systems.

2.2.2.1 Wind Power

Wind power represents one of the growing technologies in renewable energy systems. According to the Global Wind Energy Council, the installed wind energy capacity in 2014 reached 51,477 MW (Okere, By Roselina Okere) as shown in figure 2.5. As seen in figure 2.6, Africa and the Middle East region represent two regions where wind power is not developed.

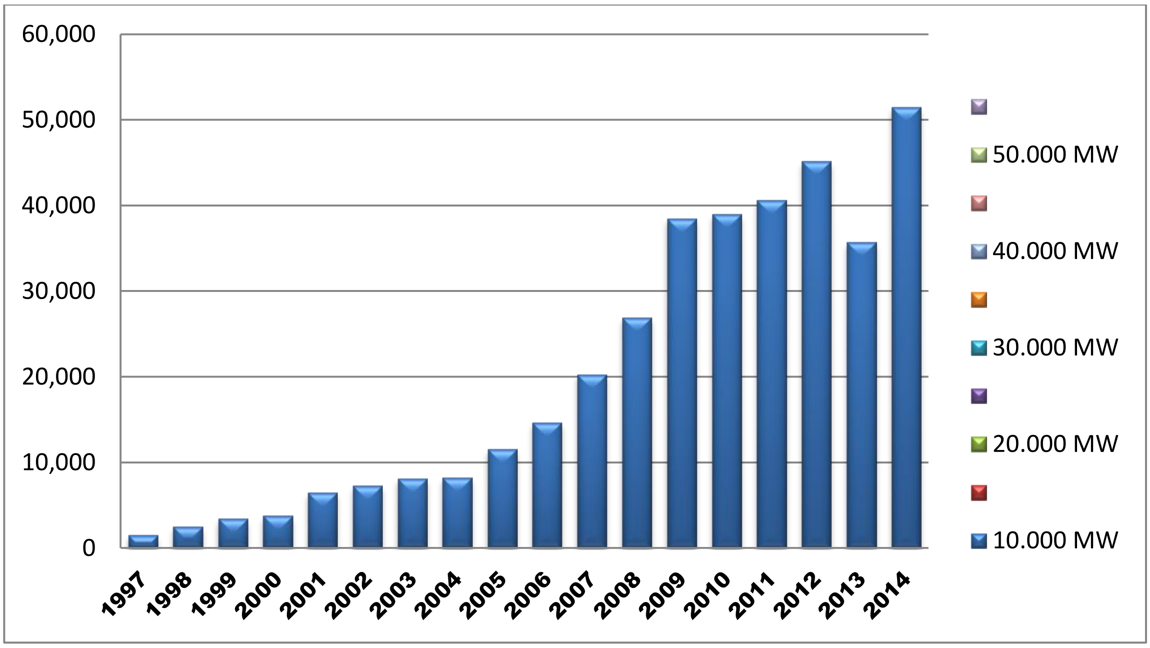


Figure 2.5: Global annual installed wind power capacity from 1997 to 2014 (Sawyer & Rave, 2014)

In July 2014 South Africa launched a 138-megawatt is called Jeffreys Bay wind farm, which was considered as one of Africa's biggest wind farms, This wind farm, comprising sixty 80-metre high turbines spread over 3 700 hectares, is provided enough green environmentally, renewable electricity to supplying more than 100 000 homes a year, helping South Africa to avoid production of 420 000 tonnes of carbon dioxide annually (Jeffreys, 2015; Mbendi, 2013; Roca, 2014; SAinfo, 2014).

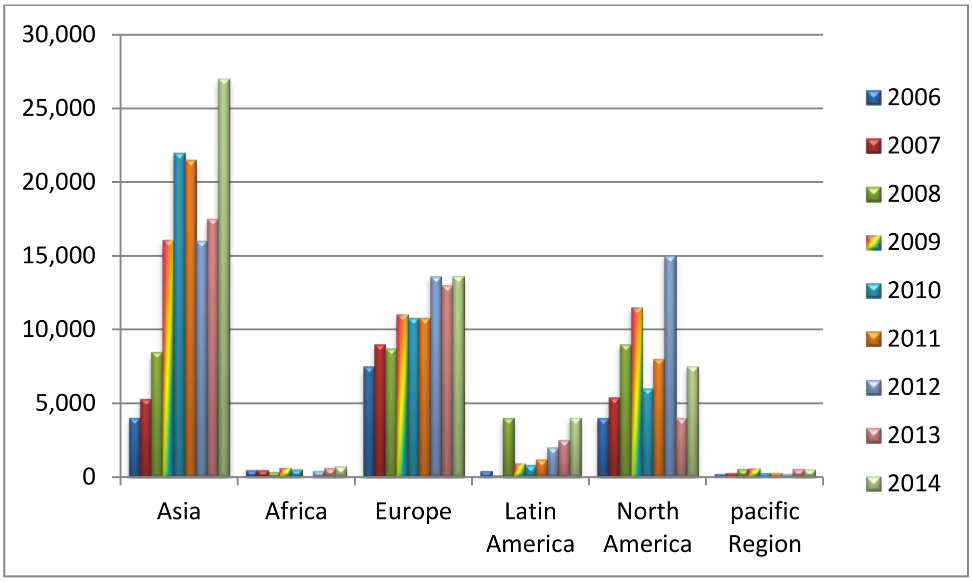


Figure 2.6: Annual installed capacity by region from 2006 to 2014 (Sawyer & Rave, 2014)

2.2.2.1.1 **Wind power advantages and disadvantages**

Wind power presents some advantages as well as disadvantages. The main advantages of wind power are:

- The wind is free, available and can be captured efficiently.
- The energy generated by a wind power generator does not cause greenhouse gases or other pollutants.
- Although wind turbines are very tall, only a small plot of land is used.
- Many people find wind farms an interesting feature of the landscape.
- Remote areas that are not connected to the electricity power grid can use wind turbines to produce their own supply.
- Wind turbines have a role to play in both the developed and third world.
- Wind turbines are available in a range of sizes which means a vast range of people and businesses can use them. Single households to small towns and villages can make good use of a range of wind turbines available today.

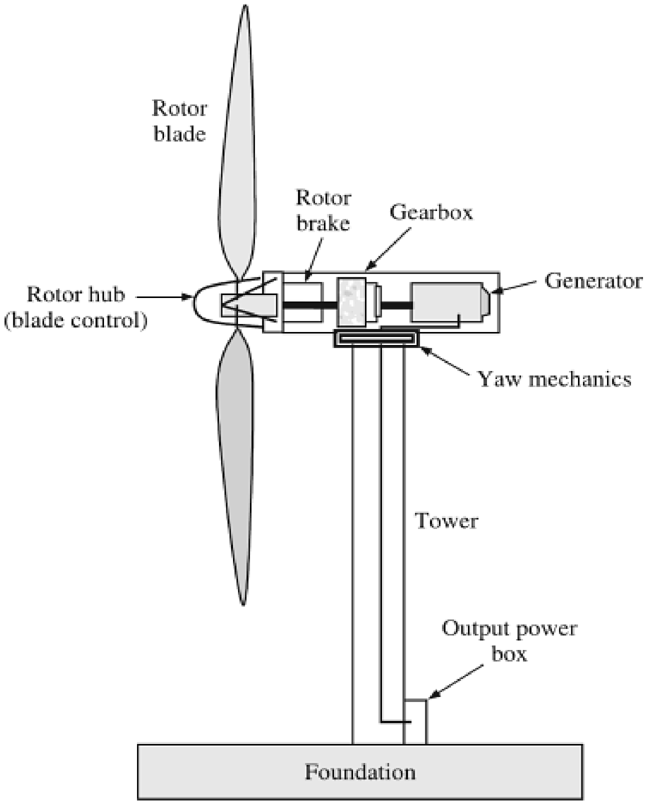


Figure 2.7: Different part of a wind power system(SOLANKI, 2008)

The major disadvantages of wind power are:

- The strength of the wind is not constant and it varies from zero to storm force. This means that wind turbines do not produce the same amount of electricity all the time. There will be times when they produce no electricity at all.
- Many people feel that the countryside should be left untouched, without these large structures being built. The landscape should be left in its natural form for everyone to enjoy.
- Wind turbines are noisy. Each one can generate the same level of noise as a family car travelling at 70 mph.
- Many people see large wind turbines as unsightly structures and not pleasant or interesting to look at. They disfigure the countryside and are generally ugly. When wind turbines are being manufactured some pollution is produced. Therefore wind power does produce some pollution.
- Large wind farms are needed to provide entire communities with enough electricity. For example, the largest single turbine available today can only provide enough electricity for 475 homes, when running at full capacity. How many would be needed for a town of 100 000 people?

2.2.2.1.2 **Different parts of a wind power system**

Wind power systems consist of four main parts, namely: the bases (foundation) which are made of concrete reinforced with steel bars; towers which are usually designed as a white steel cylinder and the Yaw mechanics are situated on the top, which is designed to control the turbine to turn according to the wind speed direction; the blades which are responsible for capturing the wind's energy; and finally the nacelle houses which contain the majority of the turbine’s components as shown in figure 2.9, such as a generator, gearbox and rotor. The spinning blades are attached to the generator through a series of gears. The gears increase the rotational speed of the blades to the generator speed of over 1,500 RPM. Figure 2.7 shows the construction of different parts of a wind power system (SOLANKI, 2008).

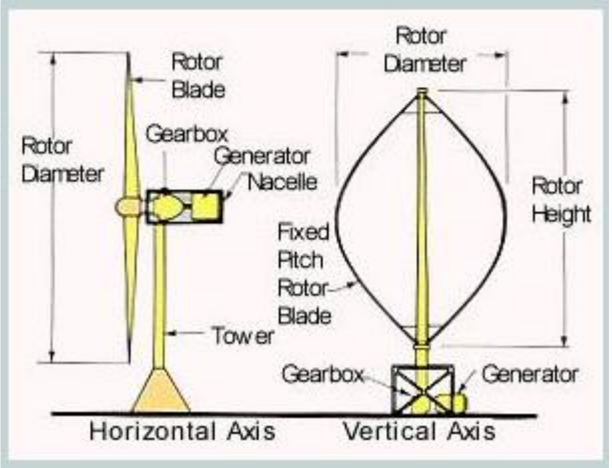


Figure 2.8: different types of wind-turbine configuration (WT, 2015)

Figure 2.8 illustrates the common horizontal axis wind-turbine include the gearbox mounted on the top of the tower, as well as the vertical axis wind turbine with gearbox at the ground level.

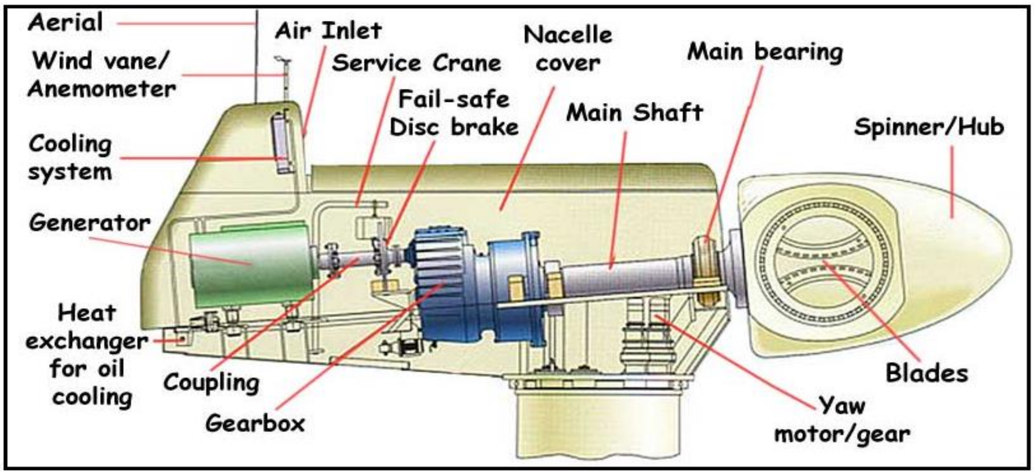


Figure 2.9: Nacelle houses (Fiddlers, 2015).

Figure 2.9 illustrates the Nacelle house includes the different mechanical component which operated kinetically in order to generate electrical power.

2.2.2.1.3 **Wind turbine operation**

The principle concept of wind turbine is to convert the kinetic energy of wind into mechanical energy of impellers shaft around the rotor. The rotor is connected to the main shaft which drives the generator. However, wind turbines are usually mounted on long tower to capture the most effective energy. In general, a pure wind power at 100 feet (30 meters) or more above ground, at that level blades of wind turbine can take advantage of faster and less turbulent wind (EERE, n.d; Tong, 2010).

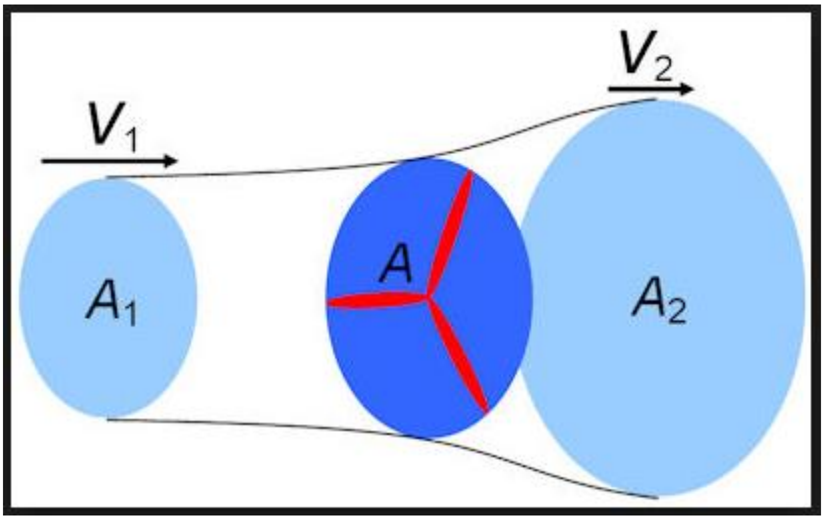


Figure 2.10: Power of the wind turbine (Energy Fundamentals, 2015).

2.2.2.1.4 **Power of the wind**

Wind power systems use wind energy to generate electrical power. The speed of the wind can be quite variable. Besides, some areas are not windy enough to extract a considerable amount of energy from the wind (Zobaa & Cecati, 2006). Considering the figure above (Figure 2.10), the power P_W contained in wind energy through an area A_1 with a velocity V_1 is given by the equation (Shepherd & Zhang, 2011):

$$P_w = \frac{1}{2}\rho A_1 V_1^3 \tag{2.1}$$

In this equation ρ is the air density proposed. The efficiency of wind energy is only 10-20% for propeller turbines and 35% for Darrieus turbines (Pal, 2009).

2.2.2.1.5 **Power of the wind turbine**

The power extracted by the wind turbine is given by the equation (Zobaa & Cecati, 2006):

$$P_t = \frac{1}{2}\rho A V_1^3 C_p(\lambda, \alpha) \tag{2.2}$$

In this equation $P_t, \rho, A, V_1, C_p(\lambda, \alpha)$ is the power extracted by the wind turbine, the air density, the area of the wind turbine, the velocity of wind and the power coefficient of the turbine, respectively.

The turbine power coefficient is defined as the fraction of power from the wind that the rotor can extract. It can also be defined as the ratio of the power of the wind turbine and the power of the wind.

2.2.2.1.6 **Tip ratio**

The power coefficient depends on the blade pitch angle α and the tip ratio which is given by the equation:

$$\lambda = \frac{\omega R}{V_1} \tag{2.3}$$

In this equation λ, ω, R, $V_1$are the tip ratio, the rotational speed of the turbine, the radius of the turbine and the wind velocity, respectively.

2.2.2.1.7 **Betz limit**

The maximum power coefficient of the wind turbine is defined by the Betz limit which states that no wind turbine can extract more than 59.3% of the wind power going through it. This is shown in figure 2.11 (Masters, 2013).

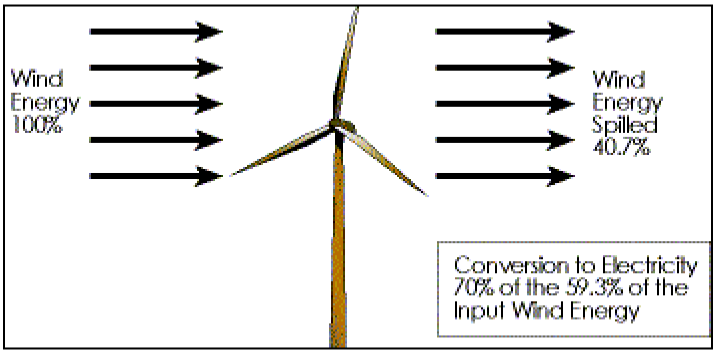


Figure 2.11: Horizontal wind turbine (Andres, 2014).

2.2.2.1.8 **Power curve of a wind turbine**

The power curve of a wind turbine is shown in figure 2.12 below. For different existing wind turbines, the power curve is given by the manufacturer. As shown in figure 2.12, this power curve is characterised by three different regions:

1. The cut-in region represents the minimum wind speed region where the wind turbine can produce a useful power.

2. The rated speed region refers to the region where the maximum power output of the electrical generator is obtained. In this region, the speed may vary from 13 to 16 m/s.

3. The cut-off region represents the region where we have the maximum wind speed that the wind turbine can handle. The typical values of cut-off speeds can vary from 25 to 30 m/s.

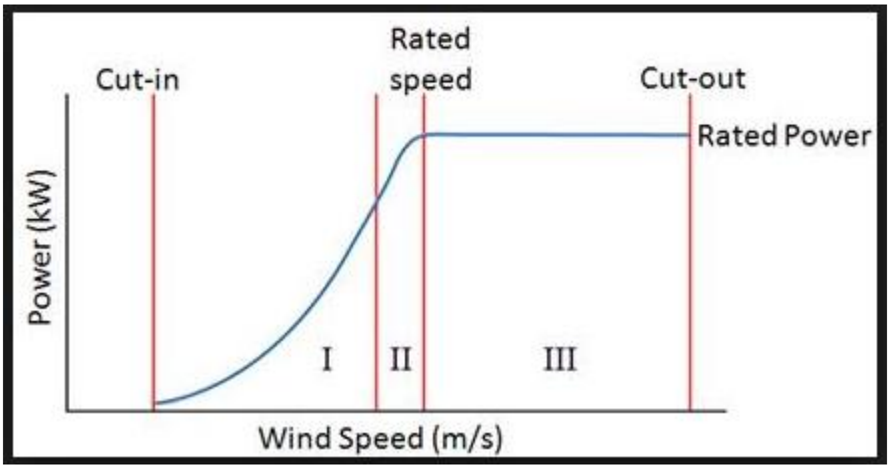


Figure 2.12: Wind turbine power curve(Ahmed & Siraj, 2010).

2.2.2.2 Solar power

Solar energy is the most important and available source of energy on earth and according to Ming et al., in 2014, Essentially 100% of the energy that fuels the earth comes from the sun, the 100 % incoming solar energy can be divided as following: 51 % absorbed by earth including the land and oceans, 20 % scattered and reflected by clouds, 19 % absorbed by atmosphere and clouds, 4 % reflected by earth's surface, 6 % scattered from atmosphere (SCC, 2011; BCS, 2013; Hall, 2013).

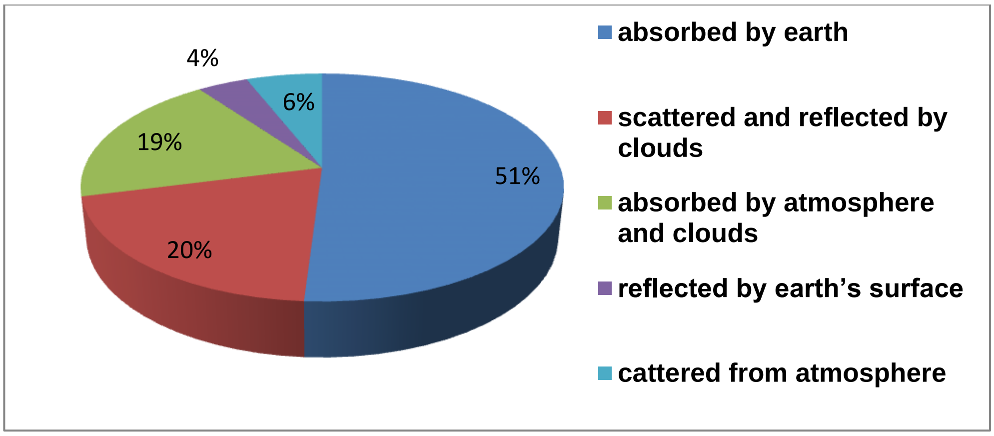


Figure 2.13: The 100 % incoming sun's energy balance

Figure 2.13 illustrates how the energy from the sun is absorbed, reflected, and emitted by the earth in percentage.

In order to use the 51 % of sun’s energy which is reached the earth surface there are two different solar power systems can be found; solar thermal and solar photovoltaic systems. Solar thermal power uses solar energy as source of heat which is concentrated and used to drive an electrical generator whereas solar photovoltaic power uses solar cells and captures solar energy and converts it directly to electricity.

2.2.2.2.1 **Advantages and disadvantages of solar power**

Solar power presents certain advantages, such as:

- Solar energy is free although there is a cost in the building of equipment required to convert solar energy into electricity or hot water;
- Solar energy does not cause pollution;
- Solar energy can be used in remote areas where it is too expensive to extend the electricity power grid;
- Many everyday items such as calculators and other low power consuming devices can be powered by solar energy effectively;
- Solar energy is infinite and will last forever.

Some of the disadvantages of solar power are:

- Solar energy can only be harnessed when it is daytime and sunny;
- Equipment used in solar power systems are very costly although prices are falling rapidly;
- Solar power stations are very expensive and they do not match the power output of similar sized conventional power stations;
- Solar power depends on the weather, cloudy skies reduce its effectiveness;
- Large areas of land are required to capture the sun’s energy;
- Solar power is used to charge batteries so that solar powered devices can be used at night. However, the batteries are large and heavy and need storage space. They also need replacing from time to time.

2.2.2.2.2 **Solar thermal power**

Solar thermal electrical energy generation uses the light from the sun to create heat. This light is concentrated and then used to heat a fluid in order to drive a heat engine and run an electrical generator. The fluid can be a liquid or a gas. Some of the fluids used in the solar thermal heating process are: water, oil, salts, air, nitrogen, helium, etc. (Nasri et al., 2011).

Four different technologies for solar thermal power generation systems based on four fluid heating processes can be found and are shown in figure (2.14). These technologies are (Hamilton, 2015): A Parabolic trough, Linear Fresnel, Heliostats and the Dish system (Nasri et al., 2011).

2.2.2.2.3 **Parabolic trough technology**

The parabolic trough technology consists of large curved mirrors used to collect the sunlight, which is concentrated into an absorber tube running along a focal line and producing temperatures of approximately 60^{o}C-400^{o}C. These large curved mirrors constitute collectors which are arranged in parallel rows of about 300–600 metres long and a multitude of parallel rows form the solar collector field. They then follow the path of the sun from east to west (Song et al., 2014; Anam, 2012).

The fluid running inside the absorber tube is heated up and goes to the heat exchanger at a temperature of about 390^{o}C. The steam generated is then used to drive a steam turbine in order to run an electrical generator (Song et al., 2014).

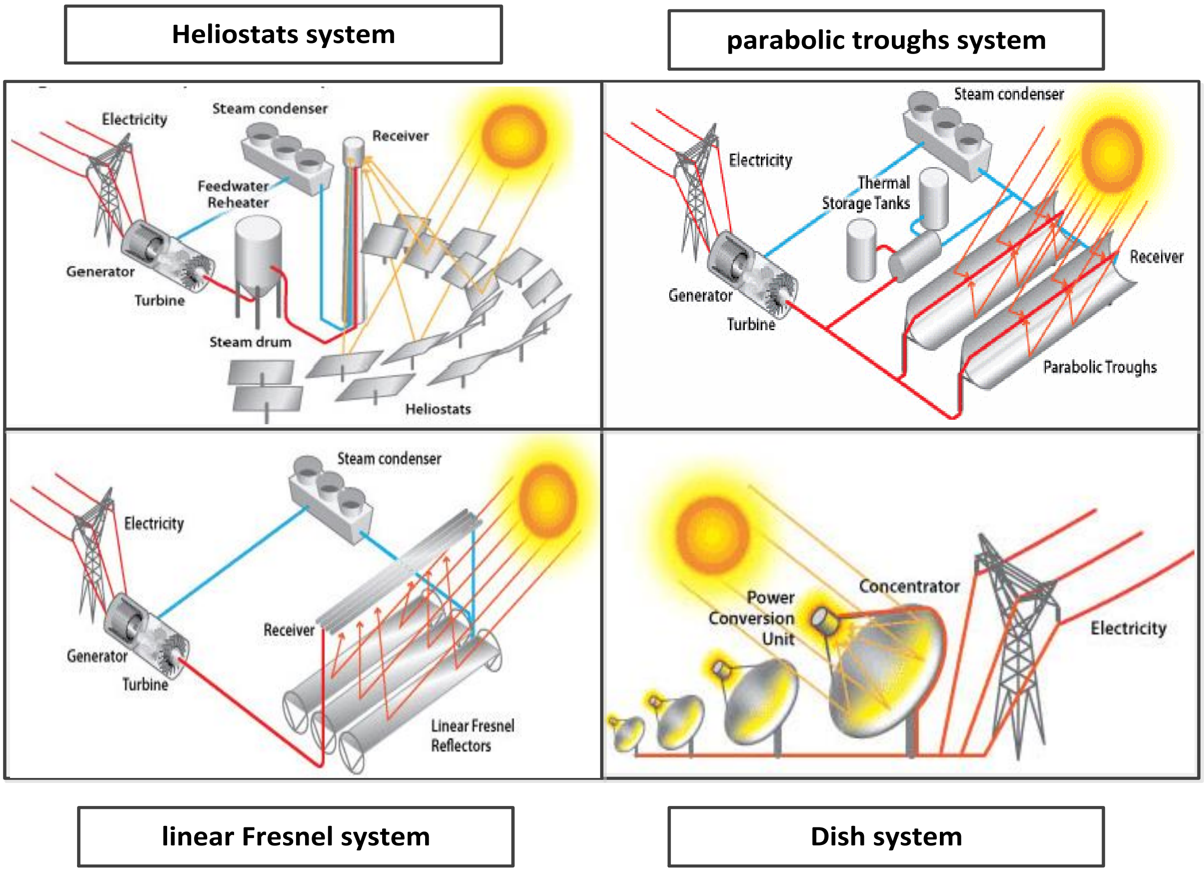


Figure 2.14: Solar thermal power generation technologies layout (Hamilton, 2015).

2.2.2.2.4 **Linear Fresnel technology**

This technology is almost similar to the Parabolic trough and is based on Fresnel linear reflectors which concentrate the sun into an absorber tube called a receiver. The temperature of the fluid in the heat exchanger is a bit lower compared to the parabolic trough technology.

2.2.2.2.5 **Heliostats technology**

Heliostats technology is based on mirrors which track the sun and reflect the sunlight onto a central receiver to produce a high temperature heat in order to run a steam turbine connected to a generator. This high temperature heat in the range of 540 to 840 ^{o}C is obtained by using hundreds of these large sun tracking mirrors. Generally power plants based on this technology can have capacities between 1 to 500 MW.

2.2.2.2.6 **Dish system technology**

The Dish system technology uses parabolic dishes of mirrors to direct and concentrate sunlight onto a central point called a receiver. A Dish system consists of two important elements which are the solar concentrator and the power conversion unit.

The solar concentrator collects the solar energy coming from the sun which is reflected onto a thermal receiver that collects the solar heat. The power conversion unit consists of a thermal receiver and a generator. The thermal receiver is used as an interface between the dish and the generator. It can be a bank of tubes with a cooling fluid, usually hydrogen or helium.

2.2.2.3 **Solar photovoltaic systems**

The Solar photovoltaic system is defined, as a system that performs direct conversion of sunlight into electricity, by using cells which are the principal elements of a photovoltaic system. A typical solar cell produces a power of less than 3 W at 0.5 V. In order to obtain enough power and voltage rating for large scale applications, solar cells are connected in series and parallel to form a module. Modules are connected in series and parallel to form a photovoltaic panel. Photovoltaic systems are classified as a standalone and grid connected system.

2.2.2.3.1 **Standalone photovoltaic systems**

A typical standalone photovoltaic system is shown in figure 2.15, and includes elements such as a solar photovoltaic panel (Photovoltaic module), DC-AC inverter, battery, solar charge controller and the load. This type of system is mostly used for isolated applications, especially in rural areas where there are no power lines.

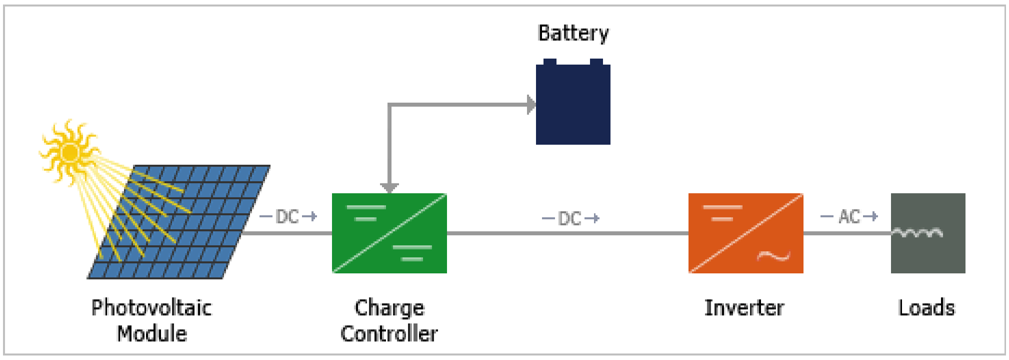


Figure 2.15: Photovoltaic system schematic representation(SYNERGY, 2014)

2.2.2.3.2 Grid connected photovoltaic systems

In grid connected applications, the DC power output from the photovoltaic system is converted to AC and injected into the utility grid. The AC voltage and frequency of the photovoltaic system must be synchronized with the utility grid. The grid connected photovoltaic system is shown in figure 2.16 and includes the photovoltaic panels (Photovoltaic module), charge controller, battery, DC to AC inverter, utility grid and the load. It should be mentioned that in photovoltaic grid connected applications, the batteries are included. The voltage simply can be fixed by the inverter at which the array operates; otherwise the maximum power point tracking function is usually used to identify the best operating voltage for the array. The inverter operates in phase with the grid as unity power factor, and generally delivers as much power as it can to the electric power grid given the available sunlight and temperature conditions (Eltawil & Zhao, 2010).

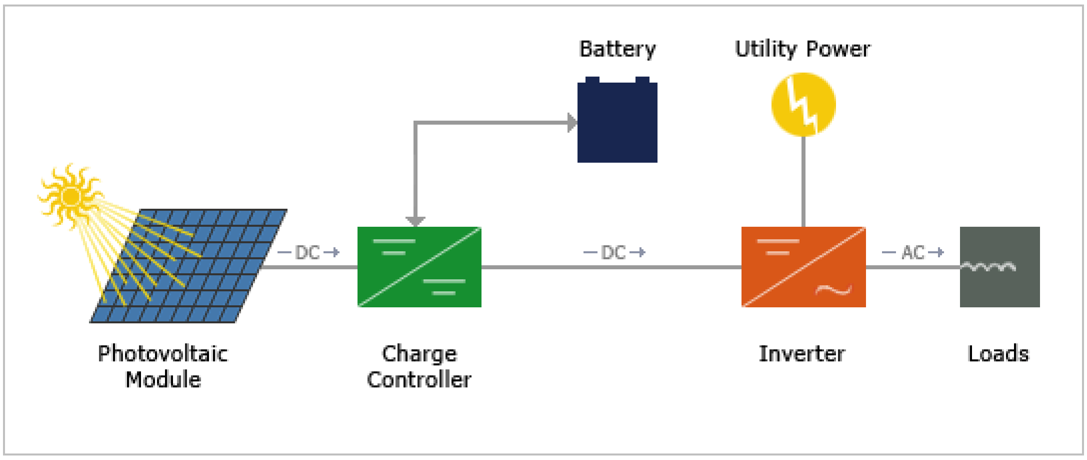


Figure 2.16: Grid connected photovoltaic system (SYNERGY, 2014)

2.2.2.3.3 Solar photovoltaic panel characteristics

The characteristics of photovoltaic panels are the same as the characteristics of solar cells. This section focuses mainly on the characteristics of solar cells.

The different variables used to characterise a solar cell are: the open circuit voltage, the short circuit current, the maximum power point and the fill factor.

2.2.2.3.4 **Open circuit voltage**

The open circuit voltage is defined as the maximum voltage of a solar cell when no load is connected to it. The open circuit voltage is shown in figure 2.17 and is expressed by the equation (Rau et al., 2011):

$$U_{oc} = \frac{nkT}{q} ln\left(\frac{I_L}{I_o} + 1\right) \tag{2.4}$$

In this equation U_{oc}, n, k, T, q, I_L, and I_o are the open circuit voltage, Ideality factor, Boltzmann constant, absolute temperature, elementary charge, light generated current and dark saturation current, respectively.

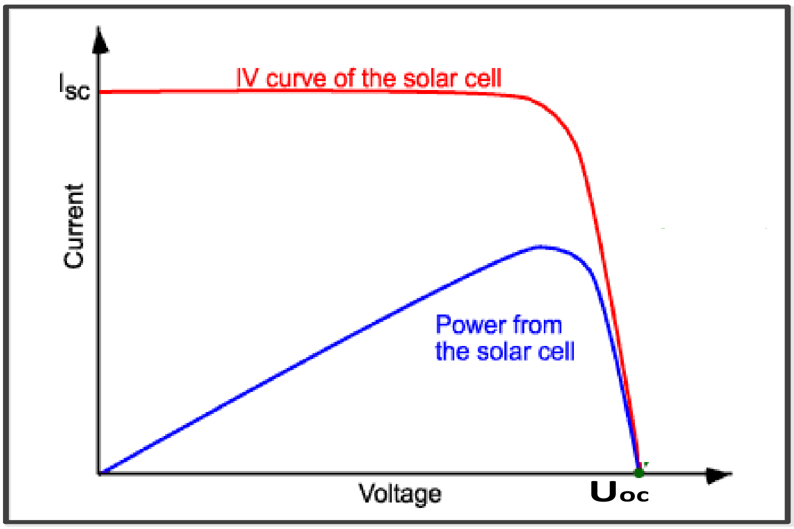


Figure 2.17: Voltage *versus* current characteristics of s PV cell (Education Org, 2015)

2.2.2.3.5 **Short circuit current**

A short circuit current I_{SC} is defined as the maximum current that can flow from a solar cell when the voltage across the solar cell is zero. The short circuit current is shown in figure 2.16.

2.2.2.3.6 **Maximum power point**

A maximum power point is the point where the solar cell supplies its maximum power. The voltage and current corresponding to the maximum power point are the maximum voltage U_{MPP} and the maximum current I_{MPP}.

2.2.2.3.7 Fill factor

The fill factor (FF) refers to the parameter used to determine the maximum power from a solar cell. It is defined as the ratio of the maximum power of the solar cell to the product of the open circuit voltage and short circuit current. It is given by the equation (Häberlin, 2012):

$$FF = \frac{U_{MPP} I_{MPP}}{U_{oc} I_{sc}} \tag{2.5}$$

Where U_{MPP}, I_{MPP}, U_{oc} and I_{sc} are the maximum voltage, the maximum current, the open circuit voltage and the short circuit current, respectively.

2.2.2.3.8 Efficiency of a solar cell

The efficiency of the solar cell is given by the equation (Wang & Wang, 2013; Balfour et al., 2011):

$$\eta = \frac{U_{oc} I_{sc} FF}{P_{in}} \tag{2.6}$$

Where U_{oc}, I_{sc}, FF and P_{in} are the open circuit voltage, short circuit current, fill factor and the total power in the light incident on the solar cell, respectively.

2.2.2.4 Fuel cell

A fuel cell is an electrochemical device producing electricity without any intermediate power conversion stage. The output of a fuel cell is a DC voltage which is be converted to an AC voltage by using an inverter which can then be either distributed locally or supplied to the utility grid. It is similar to a battery in many respects, such as components, but it can produce electricity over a longer period of time compared to a battery, due to the fact that it is continuously supplied with fuel and oxygen from an external source. The internal schematic of a fuel cell is shown in figure 2.18. The major advantage of a fuel cell is the low emission of greenhouse gases and high energy density which is 200Wh/l for a typical fuel cell. The electrical efficiency in fuel cell topology could be greater than 70% (Zobaa & Cecati, 2006).

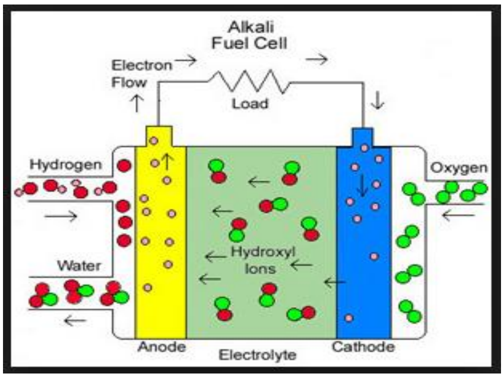
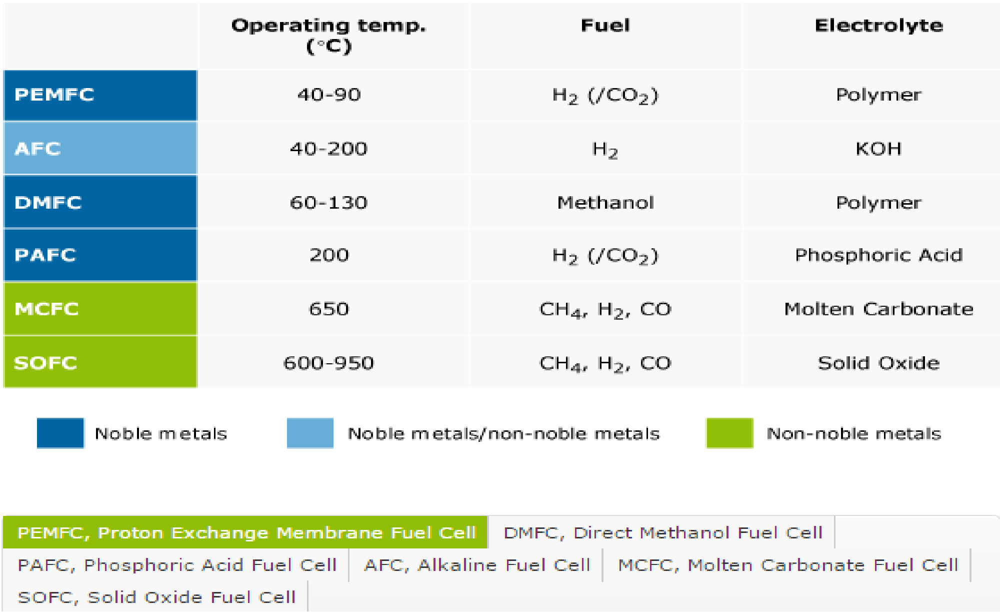


Figure 2.18: Fuel cell schematic (Smithsonian, 2008).

Six different types of fuel cells can be found and a summary of these fuel cells' characteristics are given in figure 2.19.



	Operating temp. (°C)	Fuel	Electrolyte
PEMFC	40-90	H_2 (/CO_2)	Polymer
AFC	40-200	H_2	KOH
DMFC	60-130	Methanol	Polymer
PAFC	200	H_2 (/CO_2)	Phosphoric Acid
MCFC	650	CH_4, H_2, CO	Molten Carbonate
SOFC	600-950	CH_4, H_2, CO	Solid Oxide

🟦 Noble metals 🟦 Noble metals/non-noble metals 🟩 Non-noble metals

PEMFC, Proton Exchange Membrane Fuel Cell
DMFC, Direct Methanol Fuel Cell
PAFC, Phosphoric Acid Fuel Cell
AFC, Alkaline Fuel Cell
MCFC, Molten Carbonate Fuel Cell
SOFC, Solid Oxide Fuel Cell

Figure 2.19: Different types of fuel cells (Nedstack, 2011)

Fuel cells are similar to photovoltaic cells by the fact that the power produced is in DC form; therefore, a DC to DC converter as well as an inverter is required.

2.2.2.5 **Biomass**

Biomass refers to a type of fuel derived from plant material, animal waste, food crops, grass, organic components and industrial waste, used generally as primary energy source to generate electricity. Biomass can also be used for some other forms of power. Several methods are used to generate electricity from biomass: The first method consists of burning biomass directly, heating water to steam and sending it through a steam turbine to drive an electric generator and generate electricity. In the second method used, a dry biomass goes through a gasification process with the absence of oxygen at a high temperature to produce a fuel gas which can be burnt to generate electricity. The last method consists of breaking down biomass which is in the form of bacterial organic material, in the absence of oxygen to produce biogas.

The use of biomass as source of electrical energy generation presents some advantages such as:

- It is easy to convert biomass to a high energy, portable such as alcohol or gas;
- It is economical compared to other sources;
- The use of biomass does not lead to any environmental concern;
- Biomass is abundant in nature.

2.2.3 Other non-conventional generating technologies

Besides the non-conventional generating technologies mentioned earlier, there are some other technologies known as storage systems but also used as generating technologies, as in the case of fly wheel storage, compressed air energy storage, super-conducting magnetic energy storage and battery storage. However, the focus in this research is not on these technologies (Bouzid et al., 2015).

2.3 Power transmission systems

After generation, the electrical energy needs to be transported to the consumers who are generally located far away from the generating area. This is done through long transmission lines. A transmission system can be made to transmit high voltage AC or DC power. In AC power, the transmission of power is made using a three phase system, whereas in DC it is made using two conductor DC systems. Most transmission systems are overhead lines. However, transmission systems using underground cables also exist. The level of voltage for a typical transmission system ranges from 132 kV up to 230 kV. Standard nominal transmission system voltages are: 69 kV, 115 kV, 138 kV, 161 kV and 230 kV, although, several transmission voltages may be at 23 kV to 69 kV, which are classified as primary distribution system voltages. A few transmission networks operate in the extra-high-voltage level (345 kV to 765 kV)(Campbell, 1990). Compared to DC, there are some advantages using AC systems. These advantages are:

- AC power can be stepped up or down;
- Maintenance is much easier than in DC systems;

However, AC voltage also has some disadvantages, such as: the volume of conductors is much higher than in DC, the reactance of the line affects the voltage regulation, the problem of corona, skin and proximity effects, the construction of an AC system is more challenging than for a DC system and an AC system requires synchronisation when connecting two transmission systems or more. Standard power transmission systems are 3-phase, 3-conductor and overhead lines with or without a ground conductor.

2.4 Power distribution system

The electrical distribution system is the portion of the power system starting from the distribution substation to the consumers. A typical distribution system is generally divided into six different parts, namely, the sub-transmission circuit, the distribution substation, the primary distribution, the distribution transformer, the secondary distribution and the consumers. The distribution system can be constructed in overhead or underground cables. The underground system is safer, more reliable and stable than overhead systems, because all conductors are gathered in one insulated cable and buried underground. Therefore, there is only a slight risk involved. In general, the underground system is used in areas where overhead construction is impractical or prohibited by the local laws. The underground system is more expensive due to the high cost of trenching conduits, cables, manholes and other particular equipment compared to the overhead distribution system.

2.4.1 Sub-transmission system

The level of voltage in sub-transmission systems range from (Grigsby, 2012): 69 to 138 kV depending on different countries. A typical sub-transmission system can be made in overhead or underground wires. The sub-transmission system refers to the part of the power system between the bulk transmission and primary distribution. The sub-transmission can be radially connected to the bulk transmission or in a loop or ring connection.

2.4.1.1 Distribution substation

The distribution substation is referred to as the part of the distribution system with the role of reducing the voltage of the distribution system to the distribution level. The standard voltage of distribution substations is between (Grigsby, 2012): (4-35) kV, and can be configured as 34.5 kV, 23.9 kV, 14.4 kV, 13.2 kV and 12.47 kV. The distribution substations are generally fed by the sub-transmission but in other cases they are fed by the transmission system. A typical distribution system consists of the components such as the transformer, the circuit breakers and switches (Robert A. Meyers, 2012).

2.4.1.2 Primary distribution

The primary distribution is the part of the substation fed either by the sub-transmission or by the transmission system. Generally, commercial and industrial customers are often directly connected to the distribution via the primary distribution.

2.4.1.3 Secondary distribution

The secondary distribution is the part of the distribution system where domestic customers are connected. The common level of voltage of a typical secondary distribution is 400/230 V, however, is configured as three phase four wire system (Bakshi & Bakshi, 2009).

2.4.2 Different configurations of distribution systems

A distribution system can be found in three different topologies, namely, radial topology, ring topology and loop topology.

2.4.2.1 Radial topology

A typical radial distribution topology is shown in figure 2.20 and consists of a distribution substation, radial feeders for energy delivery and a step down transformer to reduce the voltage to the distribution level. The main advantage of a radial distribution topology is its low initial cost compared to the other topologies. However, radial distribution topology has some disadvantages, such as, the customers depend only on one feeder; if there is any fault on the feeder, and all the customers will be without electricity. Another disadvantage is the fact that there is no loaded balance on the distributor due to the fact that the load at the end of the distributor is not equal to the nearest load close to the feeder.

The two disadvantages mentioned above make radial distribution topology suitable for use in short distance distribution systems only.

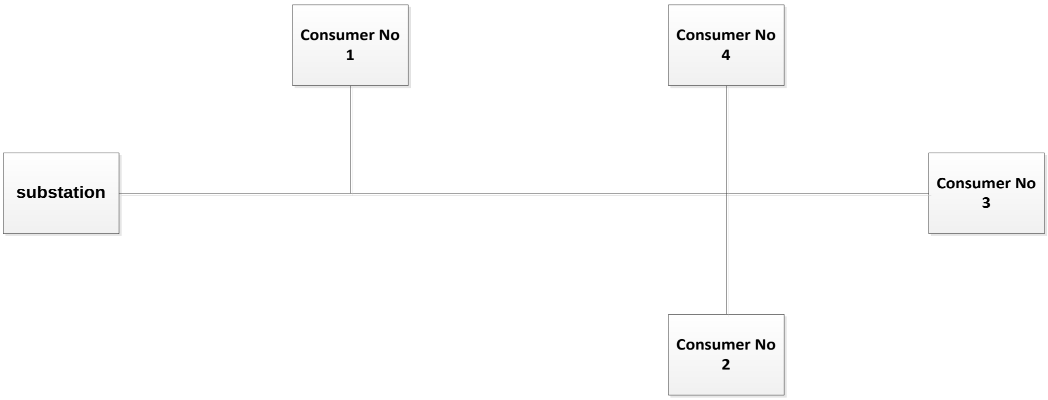


Figure 2.20: Schematic of a radial distribution system (Kiank & Fruth, 2012)

2.4.2.2 **Ring distribution topology**

The idea of a ring distribution topology relies on connecting the primary side of all distribution transformers together to form a loop or ring, it may have one or more feeding points. In particular, the essential concept of this system is the provision of electrical power to all transformers through two provided points in order to avoid a blackout of supplying the power to the consumer. In such system, the feeder covers the whole area of supply in ring fashion and finally terminated at the substation from where it is started. Figure 2.21 gives an illustration of a ring distribution topology. The feeder in this configuration is divided into number of sections for instance AB, BC, CD, DE etc., and then distributors are connected at these sections.

The ring distribution topology is more reliable than other topologies because in case of maintenance or a fault on any part of the network, it is easy to separate the faulty part and keep supplying power to the customers. In addition, the voltage vacillation is low compared to other distribution topologies, while at the furthest consumer; there is loaded balance on the feeder. Ring distribution topology usually used in heavily populated areas. Also it can provide a more continuous service than radial topology. Due to additional power lines and greater circuit complexity. However, this topology is more expensive (SINGH, 2008; Bakshi & Bakshi, 2009; Fardo & Patrick, 2009).

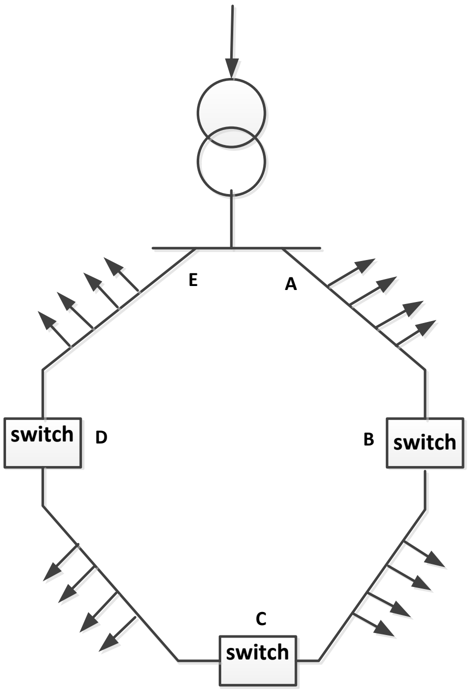


Figure 2.21: Ring distribution topology (RAY, 2006)

2.4.2.3 Network distribution topology

This topology is modified from the loop distribution topology to be an interconnected distribution system which has more than one source to supply electrical power into the network system. Figure 2.22 shows a diagram of a network distribution topology.

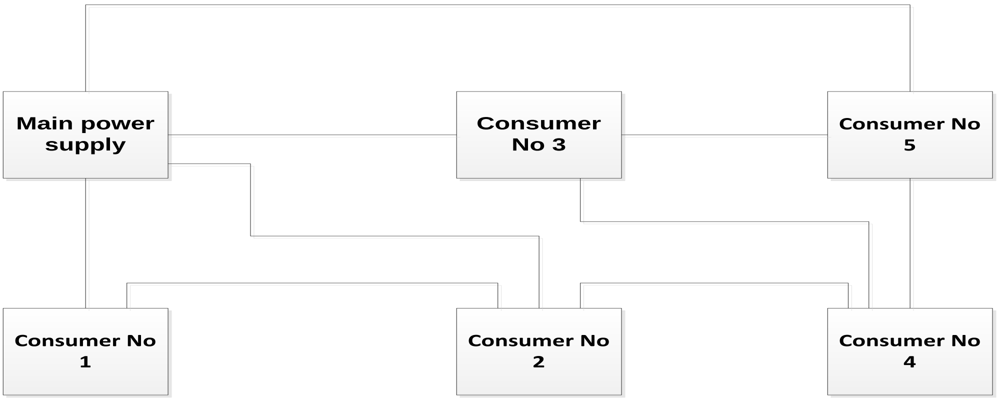


Figure 2.22: Network distribution topology (Fardo & Patrick, 2009)

2.5 Distributed Generations

The deregulation of the electricity market and the environmental concerns can be seen as two main drives making distributed generations gain popularity in recent years . We have seen an increasing interest in electricity suppliers in distributed generations seeking to provide acceptable power quality and reliability to the customers. Distributed generations refer to generating systems connected to a distribution network. Many different definitions of distributed generations have been proposed by some authors (Ackermann et al., 2001):

- The Electric Power Research Institute defines distributed generation as generation from a few kilowatts up to 50 MW;
- The Gas Research Institute, states that distributed generation is typically between 25 and 25 MW;
- Preston and Rastler define the size as ranging from a few kilowatts to over 100 MW;
- Cardell defines distributed generation as generation between 500 kW and 1 MW;
- The International Conference on Large High Voltage Electric Systems (CIGRE) defines DG as smaller than 50 –100 MW.

Distributed generation (DG) is known by several different names such as on-side generation, dispersed power, decentralized energy or decentralized generation, distributed energy resource or distributed resources and embedded generation (Yadav & Srivastava, 2014).

2.5.1 Advantages and disadvantages of distributed generation

2.5.1.1 Advantages of distributed generation

The use of distributed generations provides some advantages to electric power system operation such as (Kuang et al., 2011):

DG is a useful addition to a large power grid: as the implementation of networking, the emergence of AC/ DC hybrid transmission system and electricity market reforms, the reduced loss caused by major power system blackouts compliments a reasonable and feasible "Black Start" program. In DG, the hydro and gas turbine with easy start and fast recovery characteristics can be used as black start power supply.

DG can be used for military and humanitarian purposes due to the fact that electrical safety is an important component of national security in any country. Large power grids are vulnerable to the destruction of war or terrorism or catastrophe and it will seriously endanger national security. DG is an effective means to solve these electrical safety issues, from the support of isolated small villages to the support of entire large operational plans.

DG can make up for the deficiency of large power grids’ stability, especially when electric power systems fail. It can provide emergency power support, making use of local DG technology which can lead to gradual recovery of the important load of a local power grid in a short time then it will ensure the electricity supply of important users, but also prevent the system accident form expanding. It not only increases power grid flexibility, but also improves power quality and increases reliability.

DG does not require the presence of a power transformer and distribution station and reduces line loss which generally occurs in the transmission and distribution systems when the current is flowing. If DG is used to provide energy locally to the load, line loss can be reduced because of the decrease in current flow in some part of the network.

DG's environmental protection performance is excellent. It has high energy efficiency up to 65% to 95%. DG also makes the use of clean energy and renewable energy to generate electricity possible. Fuel cells, solar photovoltaic, solar thermal collectors and wind power will be effectively applied.

DG can break the power monopoly. In recent years, many countries have continued the electricity market reform with the intent to introduce competition, lower costs of power production and supply and optimize resource allocation. DG can contribute to the realization of these purposes. Because DG investment is small and construction time of installation is short, it is conducive to investment of independent power producers, which can realize the power industry market.

DG can promote the sustainable development of many countries' economies. In order to support sustainable development of economic growth, countries need to increase power capacity and expand power production. Using the traditional power generation mode, will pose a great threat to the energy supply. Another constraint that cannot be ignored is serious environmental pollution caused by the extensive fossil energy consumption and large amounts of greenhouse gas emissions. Active use of renewable energy and developing DG can ensure sustainable economic development.

DG can achieve load power demands in remote areas which are too far away from the existing power system where it requires too much investment to build transmission and distribution systems and because natural conditions are too harsh, making it impossible for the existing power system to set up the user's transmission line or where the attempt will often fail. Using DG mode such as small hydropower, wind power, solar photovoltaic and biomass power generation is an effective method to facilitate electricity supply in remote areas.

2.5.1.2 **Disadvantages of distributed generation**

Despite the fact that DG can present some advantages to the power system, DG also has some disadvantages such as (Kuang et al., 2011):

DG connected to the grid at the distribution side will have an effect on power system stability. When a large number of DGs is connected to the grid, it will seriously affect the distribution system design, control, operation and protection as well as reliability and security of the system.

The impact on system voltage:- DGs connected to the power system create a weak link in the network of Multi-distributed power. When there are large capacities of DG in a Power system, the introduction of DG will have a greater impact on system voltage, short circuit current, active and reactive power flow and other characteristics.

The impact on protection:- DGs change the radial passive distribution network into an active network of a small and medium power source, thereby changing the size of fault current and duration. The current no longer flows unilaterally from the substation bus into the load and the failure behavior of DG itself also has an impact on system operation and protection.

DGs use power electronic devices and the introduction of a large number of power electronic devices, capacitors and inductors will change the network topology of traditional power system, thus affecting power flow distribution and bringing uncertainty to the joint network stability.

The impact on grid planning:- A larger number of DGs connected to the grid make it more difficult for the distribution network planners to predict the growth of load, thus affecting planning.

2.5.1.3 **Objectives of distributed generation**

According to El-Khattam and Salama in 2004 the main aim of distributed generations is to provide part or all of a customer’s active power demand and/or as a standby supply. Therefore, referring to this definition, there is no need to supply reactive power from DG.

2.5.2 **Types of distributed generations**

Distributed generators comprise synchronous and induction electrical generators, also any type of electrical converter capable of generating power. An Interconnected Generation System is any generator or generation system that can either parallel or has the potential to be paralleled via design or normal operator control, in both cases momentarily or on a continuous basis, with the utility system. DG frequently utilizes the waste heat from the generation process as an additional form of energy for space or process heating, dehumidification, or for cooling through absorption refrigeration.

Different types of distributed generation can be found based on conventional and non-conventional generation systems. Figure 2.23 shows the diagram of the different distributed generation types.

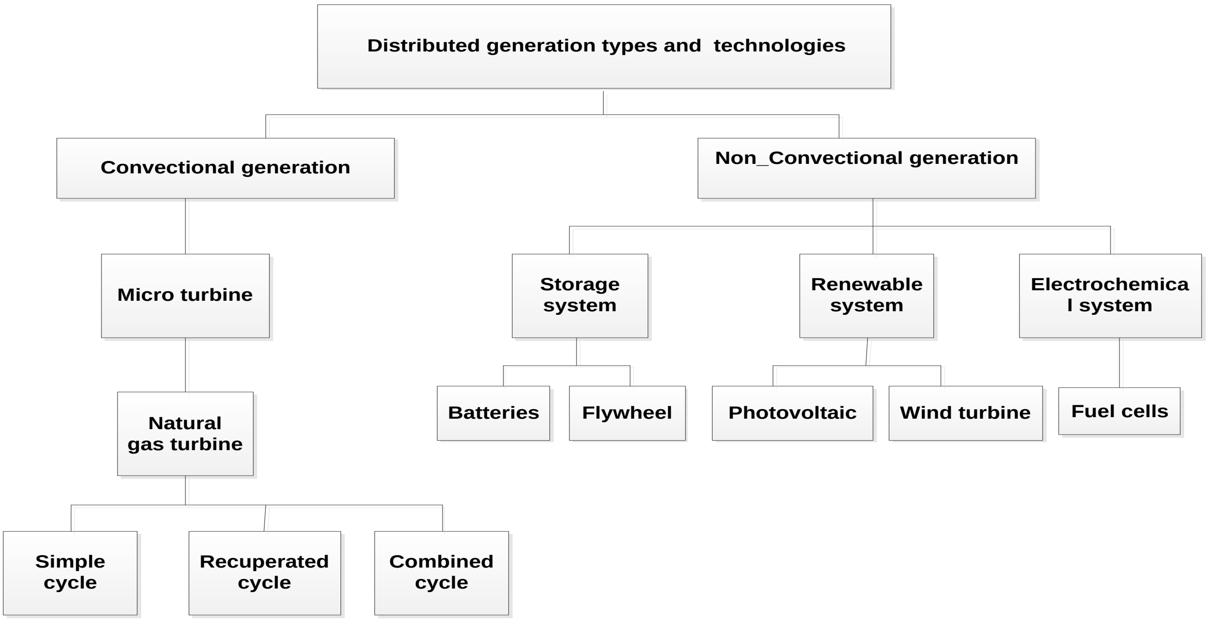


Figure 2.23: Distributed generation types and technologies (El-Khattam & Salama, 2004)

2.5.3 **Capacity range of Distributed generations**

Referring to their size, distributed generations can be classified as micro, small, medium and large capacities. Micro DGs have power capacities ranging from 1 W to 5 kW, small DGs have power capacities ranging from 5 kW to 5 MW, medium DGs have a power capacity ranging from 5 MW to 50 MW and large DGs have a power capacity range from 50 MW up to 300 MW (El-Khattam & Salama, 2004; Yadav & Srivastava, 2014). Individual wind turbines on wind farms (DGs) units are connected to the medium voltage network (generally 34.5kW (Morren et al., 2012; Pal, 2009). Typically, the large DGs capacity are directly connected to the closest substation through the tie line (Wang et al., 2012).

2.5.4 **Distributed generation interconnected interfaces and generator used**

The electric power produced by DG units is able to connect to the distributed system through three basic interconnection interfaces. Figure 2.24 shows different interfaces for the interconnections of DG units to the distribution network.

Interconnection interfaces are incorporated in three main stages: rectifier, converter or inverter, and lastly the protection, metering and control function units. Essentially, the interfaces processes are based on power electronic converters, which can be classified into three different groups: standard topologies, multilevel topologies and multiport topologies.

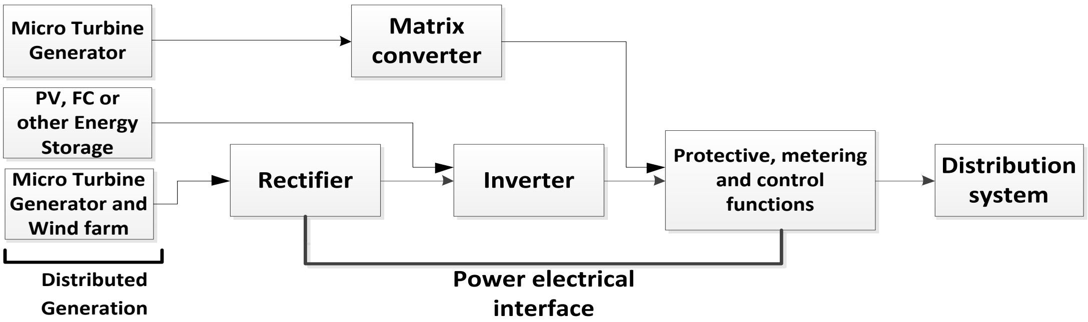


Figure 2.24: Three basic interconnection interfaces (Baghaee et al., 2008)

Firstly, standard topologies are known as two-port converters generally. They can be connected to the energy source by using its input port and the output port that connects to the load. There are two configurations of power converter, namely a single stage or double stage.

Figure 2.25 shows the single stage power converter, a unique power converter used to control the charge and discharge of the storage system and at the same time to connect to the AC grid. This configuration is used with multi energy sources such as PV, FC or Energy Storage (Fernão Pires et al., 2014; Baghaee et al., 2008).

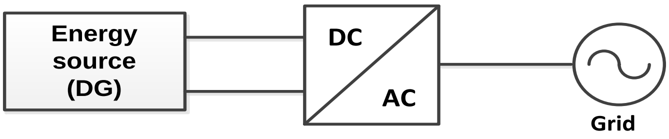


Figure 2.25: Single stage configuration of power converter.

Figure 2.26 shows the structure of a double stage interface converter for energy storage. In this configuration two power converters are used: a DC/DC converter to control the charge and discharge of the storage systems and a DC/AC converter to interface with the AC grid.

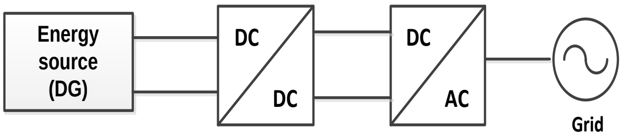


Figure 2.26: Block diagram of double stage power converter

In general, multilevel topologies are usually used for high voltage applications. These topologies allow synthesis of a desired AC voltage from several levels of DC voltages and reduce the voltage blocking of the power switches.

Lastly, the multiport topologies allow the processing of the energy from multiple energy sources or to a multiple load (Fernão Pires et al., 2014).

Inverters are used in power electrical interfaces as well, in order to convert or invert a low voltage, high DC potential into a low current high alternating voltage, which can then be connected to the utility grid. Three commercial topologies of multi-level voltage-source inverters are available: neutral point clamped (NPC), cascaded H-bridge (CHB), and flying capacitors (FCs). Beside these inverter topologies, Cascaded multilevel inverters are based on a series connection of several single-phase inverters (Malinowski et al., 2010).

The basic principle in using the inverter is to connect the output of the rectifier to the inverter input, which can then be converted to a low voltage, while DC to high voltage AC is to use up the stored high current inside a DC source and step it up to a high voltage. A Cascaded multilevel inverter reaches a higher output voltage and power levels (13.8 kV, 30 MVA) and has a higher reliability due to its modular topology. This structure is capable of reaching medium output voltage levels using only standard low-voltage mature technology components. Typically, it is necessary to connect three to ten inverters in series to reach the required output voltage. This configuration is used with different energy sources such as Micro Turbine Generators and Wind farms, which are essentially based on synchronous or induction generation (Baghaee et al., 2008; Majumdar, 2013; Malinowski et al., 2010).

In the event of interconnection synchronous or induction generation a rectifier must be used in order to convert an AC waveform into a DC waveform, otherwise the rectifier converts AC current or voltages into DC current or voltages (Baghaee et al., 2008; Anil, 2015).

2.6 Summary

This section covered the general structure of a power system: firstly, generation system, secondary power transmission system, lastly power distribution system; conventional and non-conventional methods; multi-distribution levels and configuration have been presented in terms of distribution systems; different types of distributed generation, their size and capacity, advantages and disadvantages are mentioned; as well as the energy resources used and the components which are part of a power distribution system. In addition, some of the interconnected interface methods and components used for grid connection application systems have been discussed.

CHAPTER THREE

Impact of Distributed Generations in Distribution systems.

3.1 Introduction

As stated in the first chapter, global warming, advancement in technologies, concern about the environmental impacts of fossil fuels and the growth of electrical power demand have directed attention towards integration of renewable energy based distributed generations in distribution networks. Distributed Generations have been interconnected to existing distribution networks providing various benefits to several entities such as the owner, utility and the final user. However, this integration has also significantly affected the flow of power and voltage conditions at customers and utility equipment. The impacts made by distributed generations can be either positive or negative depending on the distribution system operating and the Distributed Generations characteristics (Bhadoria et al., 2013; Kincaid et al., 2011; Maxwell & McAndrew, 2011; Kadir et al., 2012a; Arboleya et al., 2010). The conventional distribution networks have been designed to operate radially, without considering the integration of this new Distributed generation. The integration of Distributed Generations in an electrical power system affects the distribution system in several ways, such as, electric power losses, voltage profile, protection requirements, fault levels of the network and frequency**.** This chapter gives an overview of various issues in terms of Distributed Generations' integration in the distribution system.

3.2 Impact of distributed generation on power quality

Definitions of Power Quality: In the power system, the power quality is widely adopted to describe the electromagnetic phenomena. In IEEE Standard 1159, power quality is defined as "the concept of powering and grounding sensitive equipment in a manner that is suitable to the operation of that equipment". In IEEE 1159-1995, several aspects of power quality can be cataloged as transients, short duration variations, long duration variations, waveform distortion, voltage imbalance, voltage fluctuations and power frequency variations.

In a power distribution system, voltages are not always in their desired ranges due to variations of loads along the feeders, actions of tap-changers of the substation transformers and switching of capacitor banks or reactors. The small variation from its corresponding desired value is called voltage deviation or variance. The short duration variation category is used to refer to voltage sag, voltage swell and short interruption. Besides, the long duration variation category is used to refer to sustained interruption, under-voltage and over-voltage (Yang & Chen, 2012).

3.2.1 **Impact of Distributed Generation on Losses**

The electrical power distribution line has the highest total power losses. The installation of distributed generation (DG) is one of the methods used to reduce total system losses. Practically, the massive installation of DG systems can produce an important reduction of electrical losses both in transmission and distribution networks, while integration of a photovoltaic system to the grid is one of the most effective methods (Kongtonpisan & Chaitusaney, 2011; Arboleya et al., 2010).

There is a linear relation between power line losses and power efficiency of electrical power systems. An increment in line losses leads to poor efficiency of the system. Efficiency can be improved through decreasing line losses. When DG is used to provide energy locally to the load, line loss can be reduced because of the decrease in current flow in some part of the network. However, DG can increase or reduce losses, depending on several DG characteristics, such as: the location, capacity of DG and the relative size of load quantity, as well as the network configuration, etc.

One of the significant criteria that can affect the reliability of the system with low losses is DG location. Locating DG units to minimize losses is similar to locating capacitor banks to reduce losses (Bhadoria et al., 2013). The main difference between the above-mentioned situations is that DG contributes active power and reactive power $(P\ and\ Q)$ but capacitor banks contribute only reactive power flow . Generally, generators in the system operate with a power factor range between 0.85 lagging and unity, but the presence of inverters and synchronous generators provides a contribution to reactive power compensation (leading current) (Bhadoria et al., 2013).

In term of power flow analysis, generally, a single generator delivering the load $(P + j\,Q)$ through the transmission line with reactance(X) as shown in figure 3.1 below.

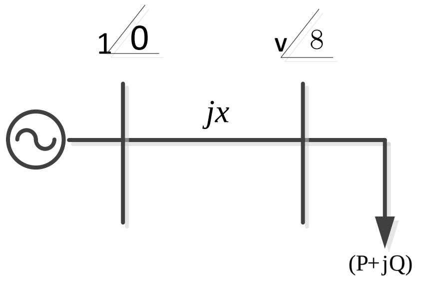


Figure 3.1: A simple diagram of power flow analysis (Chen, 2004)

Figure 3.2 depicts a simple radial distribution system before DG is installed, the load absorbed real power from one utility source and the current $I_L$is flow in line L_{Km} .

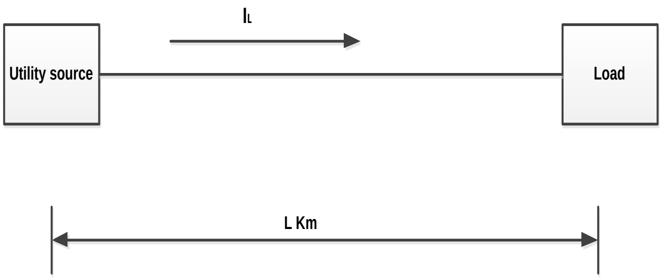


Figure 3.2: A simple radial distribution system without DG (Chiradeja, 2005)

The load complex power is (Chiradeja, 2005):

$$S_L = P_L + jQ_L \tag{3.1}$$

Therefore, the current absorbed by load is (Chiradeja, 2005):

$$I_L = \frac{(P_L - jQ_L)}{3V_P} \tag{3.2}$$

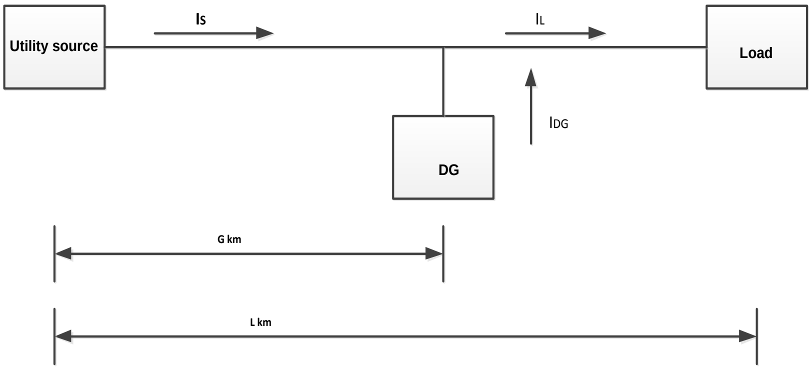


Figure 3.3: A radial distribution system in the presence of DG(Chiradeja, 2005)

As stated by Chiradeja in 2005 assumed that the load is Y-connected, as shown in Figure 3.3 a radial distribution system in presence of DG, and the line current is the same as phase current, $\boldsymbol{I_L = I_P}$, the load absorbs real power at some specified power Factor, DG produces real power at a lagging or leading or unity power factor, the line is short, and the voltage drop along the line is neglected.

$$I_G = \frac{(P_G - jQ_G)}{3V_P} \tag{3.3}$$

The line loss with the integration of DG is a combination of two parts:
Line loss from source to the location of DG, and Line loss from DG location to the location of load, which can be expressed as (Chiradeja, 2005):

$$I_S = I_L - I_G \tag{3.4}$$

3.2.2 Impact of Distributed Generation on Frequency.

Frequency variations in a power system are defined as the deviation of the power system fundamental frequency from it specified nominal value or standard frequency values (50, 60 Hz) (Dugan et al., 2012).

The growth of distributed generation, particularly photovoltaic was 878 MW in US by 2012 which is expanded in grid-connected application; the majority of the capacity increased in 2009 to 72%, but the distributed generation penetration growth of especially PV, when connected to the grid, may affect the reliability of the distribution network (Pourmousavi et al., 2012).

3.2.3 Impact of Distributed Generation on Voltage quality.

Voltage regulation in an electrical power system is one of the most significant objectives as demand and distributed generation can cause over voltages as well as under-voltages, depending on several factors including DG size and location, and method of voltage regulation.

As stated by Meena et al in 2009, power quality phenomena or power quality disturbances in voltage regulation depends on several factors, including sags, swells, under voltage, over voltage conditions, transients, harmonics, blackouts and flickers (Haig et al., 2006).

Voltage regulation can be affected by integration of distributed generation; voltage regulation in distribution system is designed on the basis of daily forecasts and seasonal changes in loading. Power injections from DG change the direction of flow of power. In case of minimum demand and maximum generation at the DG system, voltage level at the load centres may increase above the permissible limits. Due to this distribution system, voltage regulation devices, such as step voltage regulators, load tap changers, and switched capacitor banks may respond inappropriately (Bhadoria et al., 2013).

The influence of distributed generation on voltage regulation is shown in Figure 3.4 below which illustrates a small voltage swing on the feeder voltage less than 1.03 (pu).

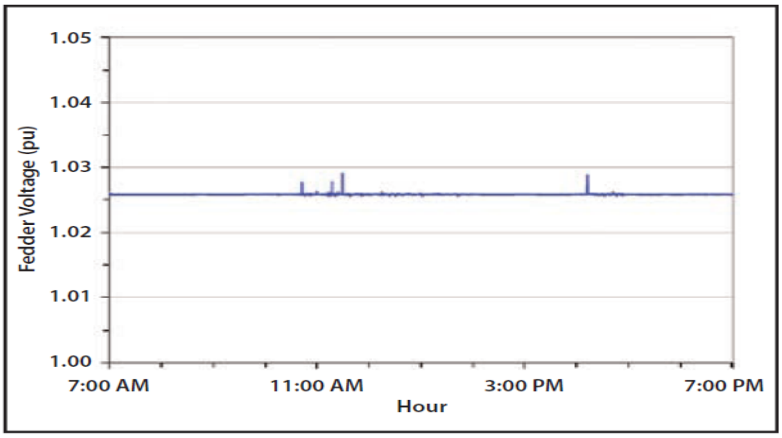


Figure 3.4: 14 kV Feeder's influence on voltage regulation without interconnecting of DG unit (Fadhel, 2015)

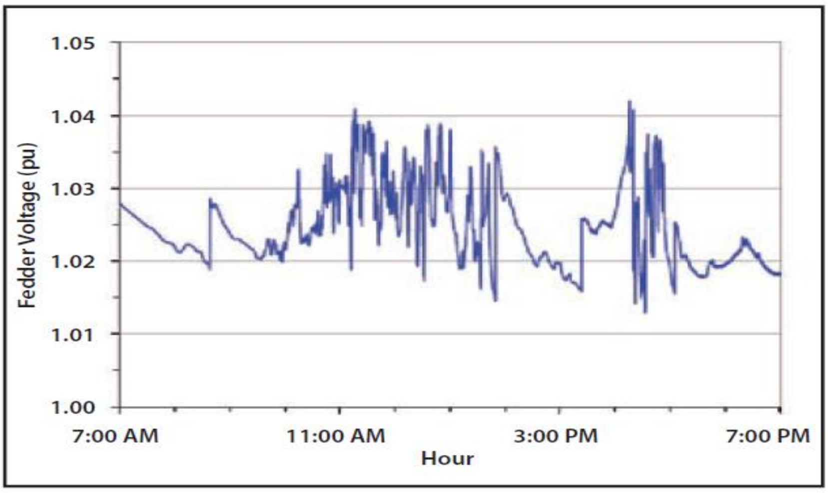


Figure 3.5: 14 kV Feeder's influence on voltage regulation with interconnecting of DG unit (Fadhel, 2015)

Figure 3.5 illustrates the contribution of distributed generation in voltage swing of voltage regulation on the feeder voltage more than 1.04 (pu).

3.2.3.1 **Voltage supply fluctuations**

Voltages fluctuations are generally described as repetitive or random variations of the voltage caused by loose or corroded connections at either the house or on the power lines, and are often noticed by flickering lights. Figure 3.6 shows the general overview of voltage fluctuation behaviour.

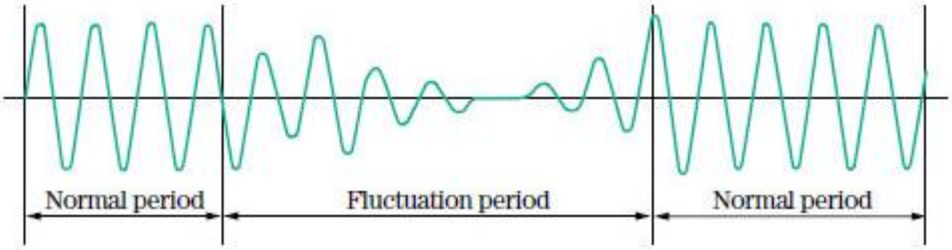


Figure 3.6: Voltage fluctuation behaviour (Yokagogawa, 2015)

Voltage fluctuation depends on several factors, such as load type and size and the power, and can be classified in three different types; Voltage swell, voltage sag and voltage surge. Figure 3.7 shows those three types of voltage fluctuations.

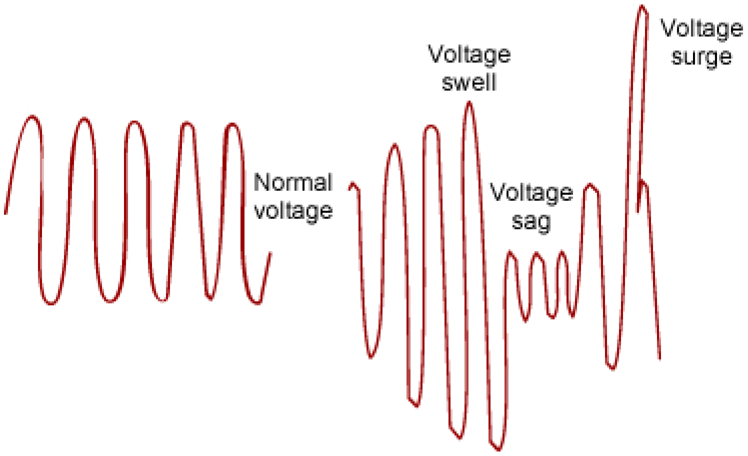


Figure 3.7: Different types of voltage fluctuation (Build, 2015)

1. Flicker

Flicker refers to small and fast variation visible to the naked eye and caused either by fluctuating load or production (Hariri & Faruque, 2014)(de Moura et al., 2008). Flicker is considered as one of the important power quality issues and it can cause noticeable variations in lighting and interrupt the operations of electronics. Furthermore, Flicker is typically caused by the use of large loads having rapidly fluctuating active and reactive power demands. In order to reduce the voltage flicker the output impedance of the Power Conditioning System must be reduced (Bhadoria et al., 2013).

2. Voltage fluctuation

Voltage fluctuation is defined as a severe voltage quality problem because it may lead to the light flicker phenomenon, which can occur due to fluctuating torque in the machinery loads, as well as the malfunction of the protective devices and process control equipment. Voltage fluctuation can transmit from high voltage levels in the system to low voltage levels and *vice versa* due to flow in the currents which originate from the non-linear varying loads such as arc furnaces, electric welders, and shredder or chipper motors (Elnady & Salama, 2007).

There is a slight different between voltage flicker and voltage fluctuation. Flicker can be described as stemming from fast changes in voltage magnitude, which is called voltage fluctuations, whereas voltage fluctuations can be represented as an amplitude modulation of the fundamental frequency voltage (Saidian et al., 2010):

$$U(t) = \sqrt{2}U[1 + m(t)]\cos(2\pi f_1 t) \tag{3.5}$$

Where U is the Root Mean Square (rms) value of the sinusoidal voltage wave, f_1 is the fundamental power system frequency component and $m(t)$ is the modulation.

Referring to Saidian et al. in 2010, the installation of DG to a distribution network has significant impact on voltage fluctuation, DG mitigates the voltage fluctuation of all buses of meshed distribution network and the voltage fluctuation of all buses improves by increasing the size of DG. Figure 3.8 shows the impact of different sizes of DG on voltage fluctuation done at different location.

3. Light flicker

The increase of the nonlinear loads can cause an instantaneous voltage drop in the adjacent buses, and mainly in the case of light loads, the voltage drop can cause light flickers, which is also called flicker, voltage flicker or voltage fluctuation.

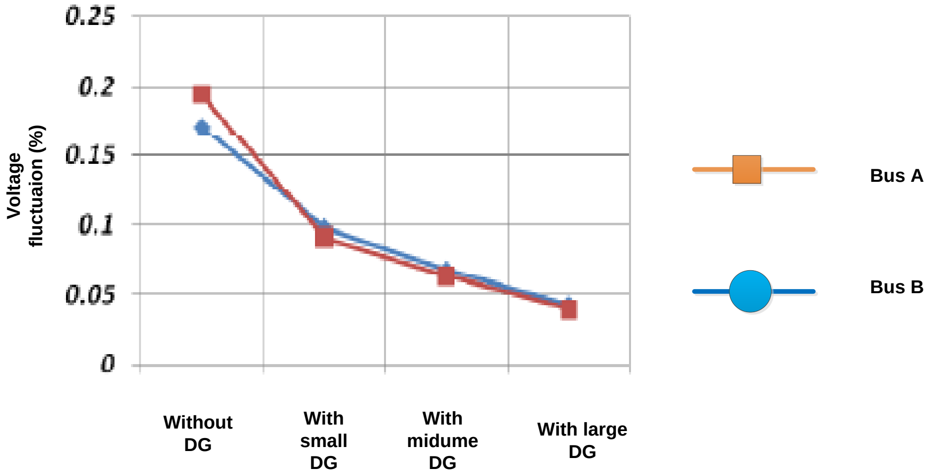


Figure 3.8: impact of different sizes of DG on voltage fluctuation (Saidian et al., 2010)

3.2.3.2 **Voltage sag**

The most common problem that can affect voltage stability is voltage sag, which is the impact of sensitive equipment that lack sufficient internal energy storage to ride through the sag.

According to Venmathi et al. in 2011, voltage sag is not a complete interruption of electrical power. It is just a temporary drop under 90 percent of the nominal classified voltage level. In normal cases most voltage sags do not go below 50 percent of the nominal standard voltage level, and they normally last from 3 to 10 cycles or 50 to 170 milliseconds.

The sag can also be considered as a decrease of short duration (half a cycle to 1 minute) in the supply voltage between 0.1 pu and 0.9 pu at the rated power frequency as defined by the International Electro-technical Commission (IEC) standard (Venmathi et al., 2011).

Voltage sag normally occurs due to a large amount of current drawn from the line, an event where the line Root Mean Square (RMS) voltage decreases from the nominal line voltage for a short period of time (A, Kusko, & M,T.Thompson, 2007). Figures 3.9 and 3.10 show voltage sage due to unbalanced fault condition and 80 % votage sag with duration of a few 60-Hz cycles.

Even if equipment does tolerate the sag, operation of under voltage relays, unbalanced relays or quick-acting relays in emergency off circuits, can often cause unnecessary shutdown of the entire system. The recovery of sag is at times misinterpreted as a power up, causing reset circuits to trip incorrectly (Meena et al., 2009) .

Fundamental reasons which cause the sag are:

- Large increase in current due to faults or large starting currents.
- Abrupt increase in system impedance (by loose connection).

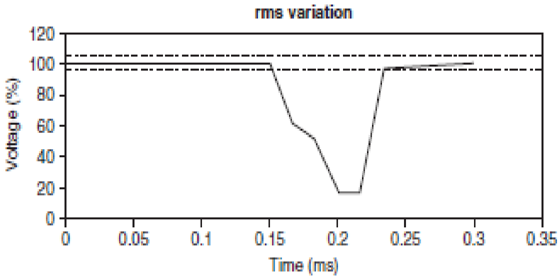


Figure 3.9: Voltage sag due to unbalanced fault condition (A, Kusko, & M.T.Thompson, 2007).

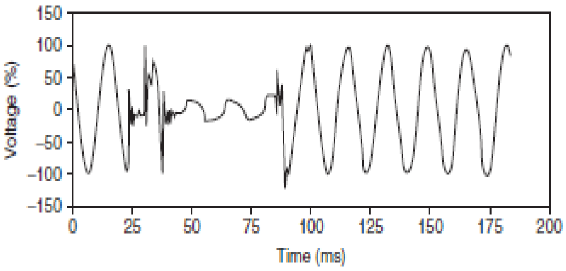


Figure 3.10: An 80 percent voltage sag with a duration of a few 60-Hz cycles (A, Kusko, & M.T.Thompson, 2007).

Voltage sags are currently a matter of great interest because they can pose a number of problems in the supplied equipment depending on their particular sensitivity. A three-phase short circuit or a large motor starting can produce symmetrical sags. Single-line-to-ground, phase-to-phase or two-phase-to-ground faults due to lightning, animals, accidents, etc. as well as energizing of large transformers can cause unsymmetrical sags. Load and transformer connections can modify the sag type experienced by a load.

There are many different processing tools for voltage measurement in power systems in order to improve power quality. Referring to Meena et al. in 2009 Root Mean Square (rms) is the most common method used to evaluate voltage sag.

The Root Mean Square value of a signal can be used effectively to detect voltage sags. For a discrete waveform, the (rms) magnitude of voltage can be calculated by using the equation (Meena et al., 2009):

$$U_{rms} = \sqrt{{}^{1}/_{N} \sum_{i=1}^{N} U(i)^2} \qquad (13)$$

Where N is the number of samples and $U(i)$ is the $(i)^{th}$ voltage sample.

Referring to Saidian et al. in 2010, the installation of DG to a distribution system has a significant effect on voltage sag, since DG mitigates the voltage sag of all buses of meshed distribution network and the voltage sag of all buses improves by increasing the size of DG, but increasing of DG size compensates more for the voltage sag of the bus close to the DG in comparison with other buses. Voltage sag and other power quality problems may arise when distributed generators are interconnected with the distribution network (Yadav & Srivastava, 2014). Figure 3.11 shows the impact of various sizes of DG on voltage sag, which had been implemented at different locations.

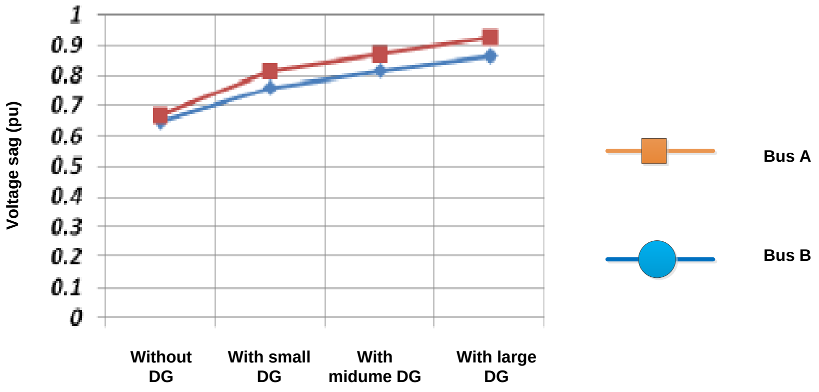


Figure 3.11: Impact of different sizes of DG on voltage sag Referring to (Saidian et al., 2010)

The integration of DG to a utility distribution system generally contributes to the mitigation of voltage sags due to the faults on distribution network feeders by increasing the fault level at distribution buses. Moreover, by constantly carrying on the voltage at its local bus and thereby feeding into the fault, the result is that the DG mitigates any sag due to faults in the rest of the network (Venmathi et al., 2011).

3.2.3.3 **Voltage swell**

A voltage swell is defined as the converse of the voltage sag, and is a brief increase in the rms line voltage (A, Kusko, & M,T.Thompson, 2007)**.** Referring to Meena (2009), voltage swell is also defined by the International Electrotechnical Commission as a short duration (few cycles to 1 minute) increase in the supply voltage between 1.1 pu and 1.8 pu at the rated power frequency. Voltage swell is also referred to as the voltage amplitude increase to 1.1 p.u (Deng et al., 2008).

In general, drawing a large amount of current due to a heavy load removal could be a reason for voltage swell. Figure 3.12 shows a voltage swell caused by a line-to-ground fault.

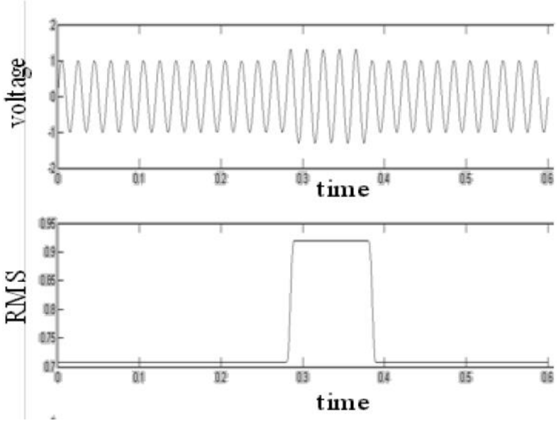


Figure 3.12: Voltage swell in the first graph is the instantaneous rms value of the voltage and the second graph is the line-voltage (Meena et al., 2009)

3.2.3.4 **Harmonics**

Harmonics is disfigurement of either voltage or current sinusoidal waveforms occurring due to the connection of non-linear loads to the distribution network. Distributed generations are considered as the biggest source of harmonics in a distribution system. Harmonics produced can be either from the generation unit itself (synchronous generator) or from the power electronic equipment such as inverters (Bhadoria et al., 2013; Hariri & Faruque, 2014).

Two types of DG can be distinguished; inverter based DG and non-inverter based DG. Distributed generation connected to a utility can be a source of harmonics. Therefore, it might also contribute to harmonic distortion in the system depending on the type of DG unit and the power converter technology employed. High levels of harmonics can be caused by a large amount of DGs which are installed on a distribution network. However, the DG units in turn contribute to levels of harmonic disturbance, although, the emission level of individual DG units comply with the current harmonic standards. Furthermore, the integration of a passive filter within these DG units also has a negative effect, thus the resonance phenomenon (Kadir et al., 2012b).

Power grids can suffer significant harmonic currents caused by these power electronic circuits, which are mostly used in nonlinear electronic loads and power electronic technology (Kang et al., 2012). Figure 3.13 shows Fundamental waveform with 3rd harmonic and result.

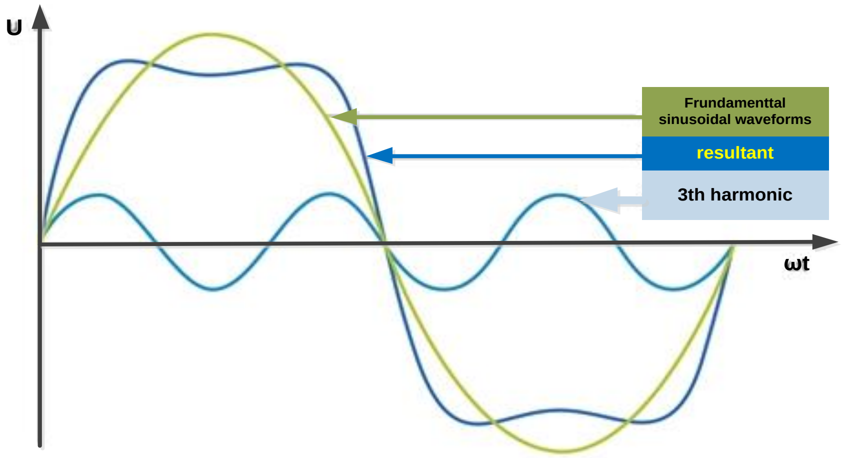


Figure 3.13: Fundamental waveform with 3rd harmonic and result (Colnago, 2012)

The total harmonic distortion (THD), is shown in Equation (11), and the individual harmonic distortion (IHD_h), in Equation (12) (Colnago, 2012):

$$THD = \sqrt{\frac{\sum_{n-2}^{nmax} U_n^2}{U_n}} [\%] \tag{3.6}$$

$$IHD_h = \frac{U_n}{U_1} [\%] \tag{3.7}$$

Where (U_n) is the voltage amplitude of order n component, (U_1) is the voltage amplitude of the fundamental component, and $(nmax)$ the highest component monitored.

3.2 Impact of distributed generation on distribution network protection

As stated earlier, the traditional distribution network was not designed to employ distributed generations, the insertion of DG into distribution networks must be accomplished with protection schemes modifications since conventional networks were previously planned as passive networks, carrying the power unidirectional from the central generation downstream to the loads (El Safty et al., 2010). The addition of distributed generations into distribution networks can produce bi-directional power flow and have other effects on the distribution system. This section is dedicated to discuss the impact of distributed generation systems in the distribution network.

3.2.1 Impact of Distributed generation on fault Levels.

The contribution of distributed generations on current fault level is one of the main concerns when distributed generations are connected into distribution networks. This fault current level depends upon three significant parameters which are: the initial symmetrical short-circuit current (I_K), the peak short-circuit current (I_P) and the steady state short-circuit current $(I_K^{''})$ (Morren et al., 2012). Figure 3.14 shows Typical short-circuit current which applied to fundamental waveform symmetrical current.

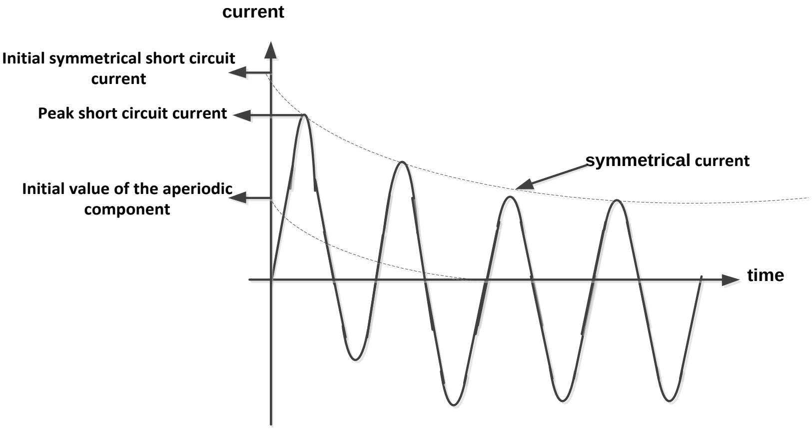


Figure 3.14: Typical short-circuit current (Morren et al., 2012)

Interconnections of distributed generation into the distribution network jeopardize the existing protection scheme. This effect relies upon the number of DGs, size, type and location. Furthermore, the configuration of the distribution system can be changed by the location of the distributed generation. In general, each branch of distribution network can be configured as a radial network configuration, in nature and overcurrent based protection schemes are set for uni-directional flow of current. However, integration of distributed generation power causes meshed configuration of the distribution system, therefore some branches have bidirectional current flow. Hence the protection schemes based on bidirectional flow of current no longer provide adequate protection in the presence of distributed generation integration (Singh et al., 2013).

The significance of an interconnected DG may result in the mal-operation of existing distribution networks by providing flows of fault currents which were not expected when protections were originally designed. In general, fault current increase is largely contingent on a number of factors, such as: capacity, penetration, technology, interface and connection point of DG. Furthermore, there are other parameters such as system voltage prior to the fault, etc. (Conti & Nicotra, 2009; Zayandehroodi et al., 2011a).

Security and the quality of distribution electricity supplies will be detrimentally affected because of the risk due to the possibility of interfering variables caused by distributed generation installation. Therefore, this process should be managed by a distribution network designer. Generally, electrical power flows from high voltage levels (power electrical sources) downward through different levels to the consumer point. The protection system is designed to detect abnormal operation which might occur on the network. In a fault condition in the traditional network, the current will normally flow directly to the fault zone. The fault current is increased in the traditional electrical network according to the current flowing from the main supply, connected generation and some of the motors on the consumer's side (Boljevic & Conlon, 2010).

Figure 3.15 shows Fault current level analysis of fault level due to a new plant connected to the network at different times.

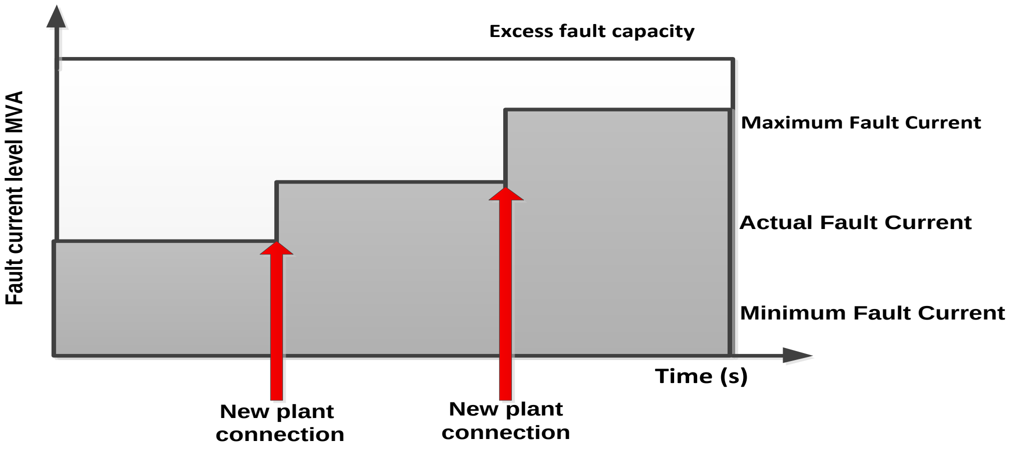


Figure 3.15: Fault level analysis for combined heat and power /CHP plant influence (Boljevic & Conlon, 2010)

The changes of fault level current as shown in figure 3.14 above will not be sensed by the present relay setting. This leads to mis-application of the relay scheme, which may be solved by using an adaptive relay but the adaptive relay must be regulated to a variable environment (George et al., 2013).

Figure 3.15 illustrates an example of various sizes of synchronous generator contributions in fault current levels which occurred in a distribution network. The short circuit level increases approximately 50 MVA when 9 MVA synchronous DG is installed. 50 MVA is about 5% of the circuit breaker breaking capacity. This means that 15% of the main transformer capacity has no impact on the short circuit level of the distribution system. A DG capacity less than 15% (simple rule) of the main transformer requires no specific technical calculations on bank level such as sending voltage variation and also short circuit level (Jung et al., 2012).

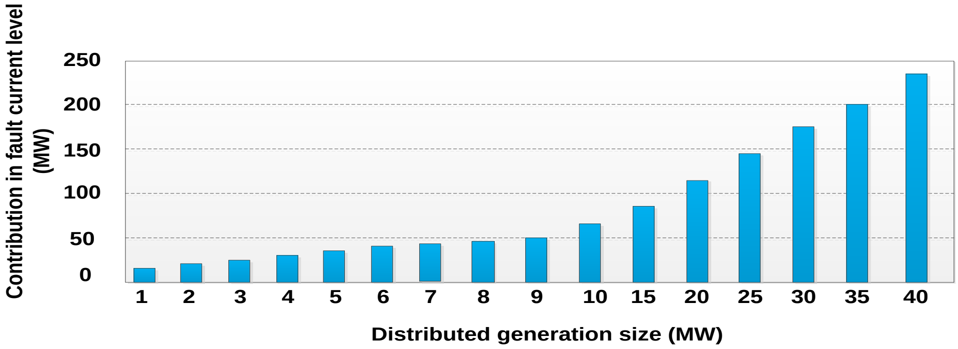


Figure 3.16: Different sizes of DG contribute to fault current level (Jung et al., 2012)

3.2.3.5 **Calculate the contribution of a DG unit**

Referring to Boljevic & Conlon in 2010 the initial symmetrical short circuit current $\boldsymbol{I_{SC}}$ is the R.M.S. value of the AC symmetrical component of a prospective short circuit current. The initial symmetrical SC power $\boldsymbol{S_{SC}}$ (or the fault level) is defined as (Das, 2011):

$$S_{SC} = \sqrt{3} I_{SC} * U_n \tag{3.8}$$

Where $\boldsymbol{U_n}$ is the nominal voltage (line) at the short circuit location**.**

The total short circuit resistance and reactance values are the sum of the respective network elements. The total short circuit impedance value $\boldsymbol{Z_T}$ is given by (Boljevic & Conlon, 2008):

$$Z_T = \sqrt{{R_r}^2 + {X_r}^2} \tag{3.9}$$

The three-phase symmetrical short circuit current is given by (Boljevic & Conlon, 2008):

$$I_{3\emptyset} = \frac{cU_n}{\sqrt{3} * Z_T} \tag{3.10}$$

The contribution of the upstream grid is calculated by (Boljevic & Conlon, 2008):

$$I_{SC} = \frac{cU_n}{\sqrt{3} * (Z_Q + Z_{SC})} \tag{3.11}$$

The SC current is (Boljevic & Conlon, 2008):

$$I_{SC} = \frac{c_{max} cU_n}{\sqrt{3} * (Z_G + Z_r + Z_L + Z_R)} \tag{3.12}$$

Where the impedance of the generator(Z_G), the transformer ((Z_{TRAN}) (if used), the interconnection line ((Z_L) to the substation and the reactor (Z_R) (if used) are included, all refer to the voltage at the SC location F. For a synchronous generator connected directly to the grid, the impedance and its correction factor are given by (Boljevic & Conlon, 2008):

$$Z_G = R_X + jX_d^n \tag{3.14}$$

Where jX_d^n is the sub-transient reactance of the synchronous machine.

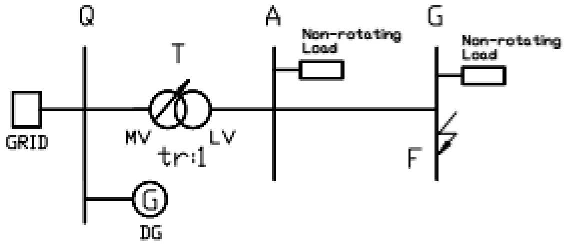


Figure 3.17: Connection of a conventional generator on MV bus (Boljevic & Conlon, 2009)

3.2.1.1 Effect of distributed generation on the feeder protection

Generally, power distribution utilities are a radial topology; each branch in the distribution network has one source supplying a distributor network of a downstream feeder. The protection system in the distribution involves fuses, recloser and overcurrent relays. However, the fundamental design of the protective devices assumes that the fault current is flowing in one direction, from the single source to the fault zone.

Several issues are raised in terms of feeder protection (Pan et al., 2013):

- Bi-directional fault current: installation of distributed generation results in the distribution network having various power supplies, which leads to a bi-directional fault current;
- Reduced or increased fault current is seen at relays: a coordinated relay in the protection system can be seen at relays due to increased or decreased fault current. Coordination may be upset;
- Changeable fault current levels: distributed generation such as a photovoltaic or wind turbine, are considered as intermittent sources. Fault current level can constantly change due to the integration of high variability of distributed generations.

Once DG is connected as shown in figure 3.18, downstream of the main feeder protection, and a fault occurs at the end of the feeder, the contribution of distributed generation in fault current level can be mitigated by the protection from the feeder and blind or delay its operation.

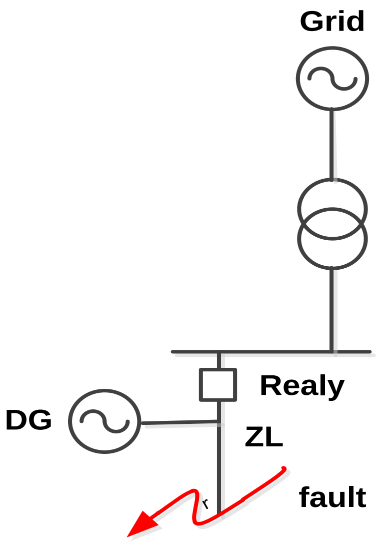


Figure 3.18: Short-circuit fault in MV network.

Where a direction element is not built on the other feeder as shown in figure 3.18, a fault on one feeder can trip the relay on others.

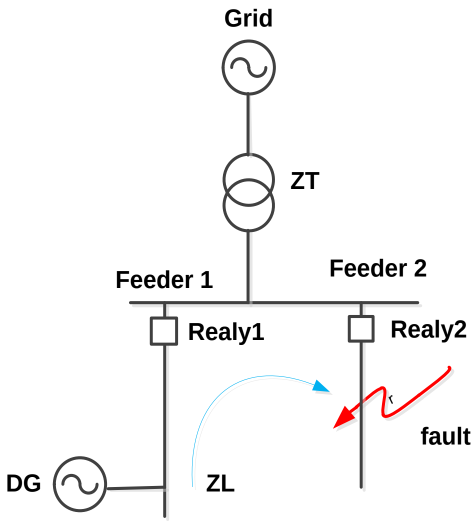


Figure 3.19: Principle of false tripping.

Figure 3.19 shows that there is in-coordination of previously coordinated relays. For time over current relays, they are coordinated up to a certain current level. The extreme fault at the substation can be increased by the distributed generation connected there which both relays R1 and R2 may experience and which may push them out of the current coordination range.

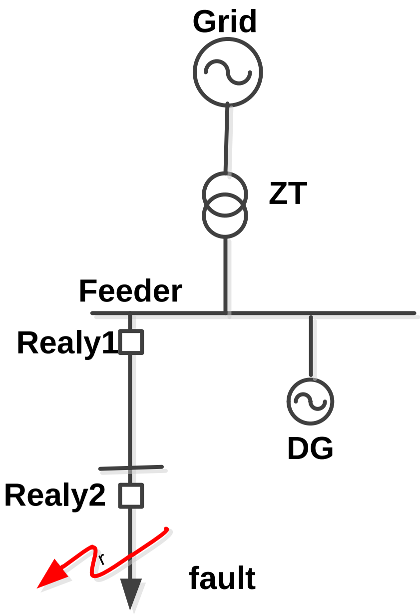


Figure 3.20: Mis-coordination of previously coordinated relays

Figure 3.20 shows a case where two faults occur on the distribution network. During fault F1, with DG connected, fault 1 should be cleared by fuse 2 before fuse 3 is operated and while fault 2 occurs it should be cleared by fuse 3 before fuse 2 works. The same fault current flows through both fuses. Although the two fuses are facing conflicting requirements on coordination with DG, there are also conflicting requirements on relay coordination.

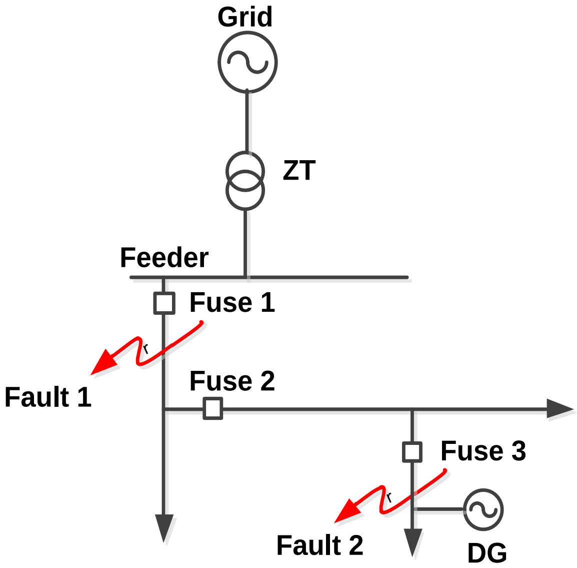


Figure 3.21: Conflicting requirements on relay coordination

3.2.1.2 Impact of Distributed generation on Coordination protection protective relays

Traditionally, in the protection scheme the current flows in one direction, but adding more power sources to the network results in network redistribution of branch currents. The impact of distributed generation on protective device coordination is based on several factors, such as sensitivity to distribution system configuration, DG's size and location. The fault current level increases progressively due to the penetration level of DG (Sa'ed et al., 2013). Figure 3.21 shows the conflicting requirements on relay coordination due to integration of distributed generation.

3.3 Other operating issues of distribution protection in the presence of distributed generation

The inclusion of distributed generation in a distribution system poses challenges to the power protection system. The impact of the distributed generation on the fault current on the power system protection will be higher. Introducing distribution generation units into a distribution grid affects its operation and negatively affects its protection schemes. Certain problematic scenarios occur due to this association with distribution generation, which are briefly described below (Darwish et al., 2013)**.**

3.3.1 Obstruction of automatic reclosing

In the case of a temporary fault occurring on the power line for a short duration, it is not compulsory to disconnect the power to the feeder by permanent line disconnection. The automatic re-closer disconnects the line for a short period of time to allow for arc extinguishing and then it re-connects again after a certain period. This process is repeated a specified number of times, after which the line is permanently disconnected if the fault still exists. However, with DG installed, the inverter may continue to energize the fault and the developed arc, which may convert the temporary fault to a permanent one even with the re-closer open. Hence, unnecessary line disconnection would occur. The problem of blocking automatic reclosing on permanent faults was investigated in the last decade (Radojevic et al., 2005; Darwish et al., 2013; Jamali & Parham, 2010).

3.3.2 Undesirable islanding

The maintenance processes or permanent faults are the two main factors that cause Islanding when a portion of the distribution system is electrically disconnected due to maintenance or a permanent fault. In this case, the remaining loads are powered only from the DG units when they are present. This raises concerns about the safety of system inspectors and restoration personnel due to the possibility of contact with live parts. Additionally, when these loads are only fed from DG units, the relatively lower power quality of such units may affect sensitive loads (Jennett et al., 2015; Darwish et al., 2013).

3.3.3 **Blinding of protection**

During a fault, it is possible that DG units could contribute to the fault current depending on the grid impedance and the DG power rating. The fault current will be shared between the grid and the installed DG. This leads to a lower grid current contribution to the fault than the specified value designed to trip the protection devices without DG installed, resulting in an undetected fault (Jennett et al., 2012; Coffele et al., 2012; Darwish et al., 2013).

3.3.4 **False tripping of feeders (sympathetic tripping)**

Protective device operation can cause sympathetic tripping when it works improperly. Obviously, the sympathetic trips are undesirable relay operations for unbalanced or high load conditions, which occur during or immediately following section faults. Sympathetic tripping is widely considered to represent a challenge for protection of networks with DGs. The severity of this problem is likely to increase as DG proliferates in the future (Mariappan et al., 2013; Jennett et al., 2015; Darwish et al., 2013).

3.3.5 **Temporary faults**

In radial systems, fault clearing requires the opening of only one device because there is only one source contributing current to the fault. In contrast, meshed transmission systems require breakers at both ends of a faulted line to open. Obviously, when DG is present, there are multiple power sources and opening only the utility breaker does not guarantee that the fault will clear quickly. Therefore, DG will be required to disconnect from the system when a fault is suspected, before the fast reclosing time has elapsed, so that the system reverts to a true radial system and the normal fault clearing process may proceed. Actually, there is the possibility that DG will disconnect either too quickly or too slowly with a detrimental impact on the distribution system. This creates numerous potential operating conflicts with respect to overcurrent protection and voltage restrictions. In this perspective DG seems to be rather incompatible especially with fast reclosing during temporary faults. This procedure may not allow the DG units to have enough time to be disconnected from the network. In this case DG units may sustain the voltage and fault arc, preventing successful reclosing in case of temporary faults. From the above consideration, it seems that the reliability of the power delivery system may be worsened due to the presence of DG, unless the anti-islanding philosophy and protection schemes are revised to ensure timely DG disconnection. However, changes in the present procedures will also be required to locate and isolate a fault, to determine whether it is sustained or not, and finally, to restore power to the customer (Conti & Nicotra, 2009; Zayandehroodi et al., 2011).

3.4 Control strategies for the distribution power system

In general, controlling a system consists of monitoring and collecting the necessary information in order to regulate its parameters according to the requirements. For a distribution system with distributed generations, the hierarchical control is classified into three different levels of control, namely, primary, secondary and tertiary levels as shown in figure 3.23. Each of these levels of control has objectives and methods which are designed and manipulated by different controllers.

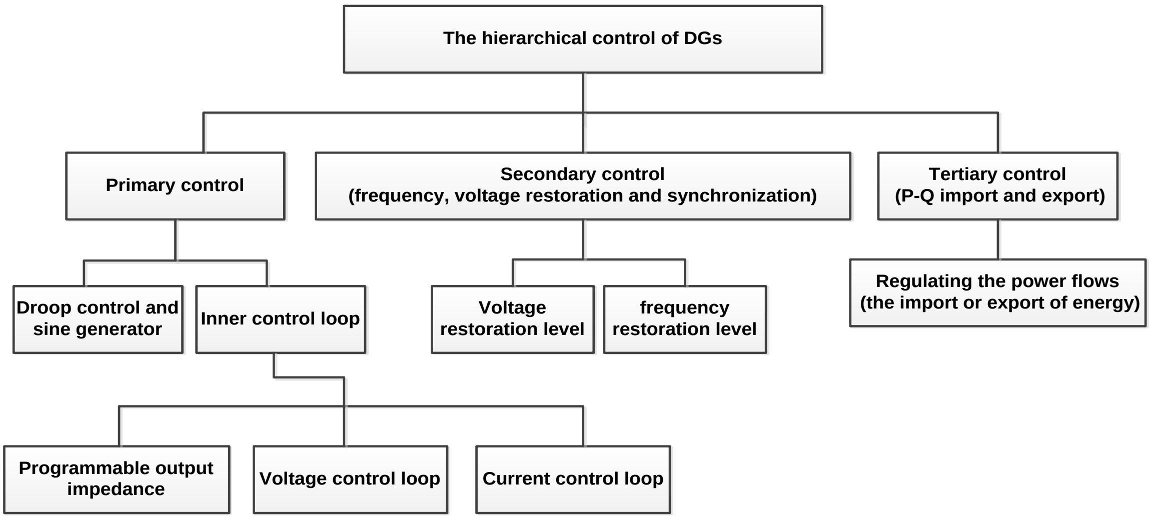


Figure 3.22: A hierarchical architecture of a DG control method (Bouzid et al., 2015)

3.4.1 The primary control (droop control)

The primary control is based only on local measurements and communication is often avoided for reliability reasons. These measurements are used to improve the system performance, stability and reliability. The primary control is used for the local voltage control, adjusting at the same time the frequency and the magnitude of the output voltage to get the reference of inner current and voltage control loops, and for ensuring a proper power sharing (active and reactive power among DG units).

3.4.2 Secondary control (frequency and voltage restoration and synchronization)

The secondary controller is responsible for restoring the frequency and amplitude deviations produced by the virtual inertias and output virtual impedances. Also, this control takes on the function of synchronizing the micro-grid with the main grid before per-forming the interconnection, the transition from islanded to grid-connected connected mode. The secondary control must measure the frequency and amplitude levels in the micro-grid, compare them with the references and send the errors to all the units to restore the output voltage. The phases between the grid and the micro-grid are measured and sent to all the modules to synchronize the micro-grid phase.

3.4.3 Tertiary control (P-Q import and export)

This level controls the power flow of the micro-grid imports exports energy. The set points of the micro-grid inverters can be adjusted. The tertiary control level is responsible for regulating the power flows of the import or export of energy between the grid and the micro-grid at the point of common coupling and to provide load balancing by using an optimal power flow solver. Thus, the active and reactive power flows can be exported or imported independently.

3.4.4. Classification of outer control loops for DPGS according to their role in micro-grids

The exchanged power between the distributed generation system and the grid is controlled by the power inverter, which is connected in parallel to the grid. The value of this power is more or less proportional to the desired power and the power inverter contributes to the formation of the grid voltage and frequency. The power inverters are classified in three classes: grid-forming, grid-supporting and grid-feeding. Figure 3.24 shows the classification of outer control loops for DPGS according to their role in micro-grids (Mastromauro, 2014).

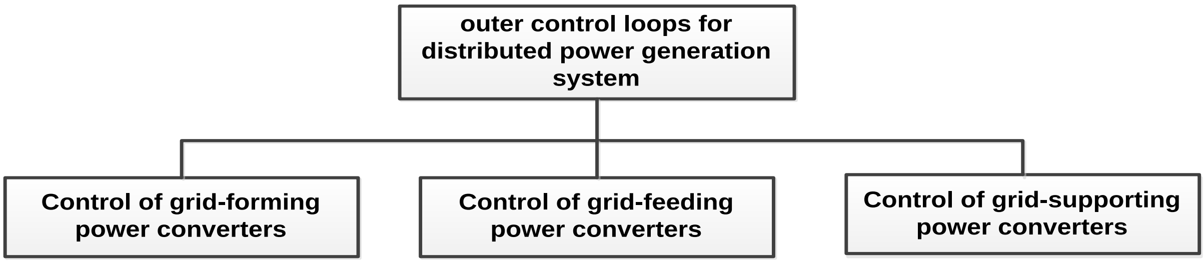


Figure 3.23: Classification of outer control loops for DPGS according to their role in microgrids (Bouzid et al., 2015)

3.4.5 Control of grid-forming power converters

The grid forming converters are power converters designed for autonomous operation and are considered as AC voltage sources with a low-output impedance setting with a fixed frequency, the voltage amplitude and the frequency of the local grid, by using a proper control loop and balancing the power generators and loads. However the voltage quality does not depend exclusively on the performance of the grid-forming converter since the connection of loads and other distributed power generation systems to the micro-grid distribution lines, which are usually weak low voltage lines, and this type of converter usually operates in islanded mode (Mastromauro, 2014).

Figure 3.25 shows the basic circuit diagram of the control of a grid forming power converter in three phases.

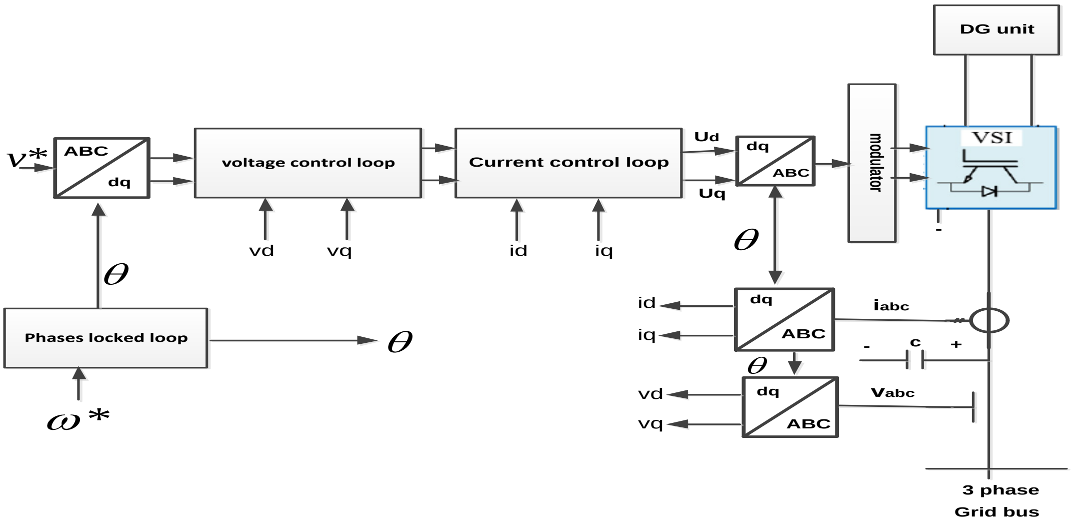


Figure 3.24: Control of grid forming power converter (Bouzid et al., 2015)

Where $\omega*$ is a fixed frequency, d_q peak transformation, i_d is the current that has control over the active component, i_q is the current that has control over the reactive component, v_d is the amplitude voltage which has a null value and v_q is the reference voltage.

3.4.5.1 Control of grid-feeding power converters

The grid-feeding power converters are designed to act as a current source, in order to provide (draw) a specified amount of converted, active and reactive power, either to or from the grid. However, the grid-feeding power converter cannot operate independently in island application. Essentially, grid-feeding power converters are usually located in distributed generation systems, operate in grid-feeding mode are connected to the grid in parallel and present high parallel output impedance. In addition, those components do not contribute to power balancing, for instance, PV or wind power systems (Mastromauro, 2014), since in the main grid the AC voltage is conventionally formed by synchronous generators (Bouzid et al., 2015).

The grid-feeding should be perfectly synchronized with the AC voltage at the connection point, in order to accurately regulate the active and reactive power exchanged with the grid. This is why we must use a phase locked loop. In this mode, the active and reactive power references are fixed (Arboleya et al., 2010).

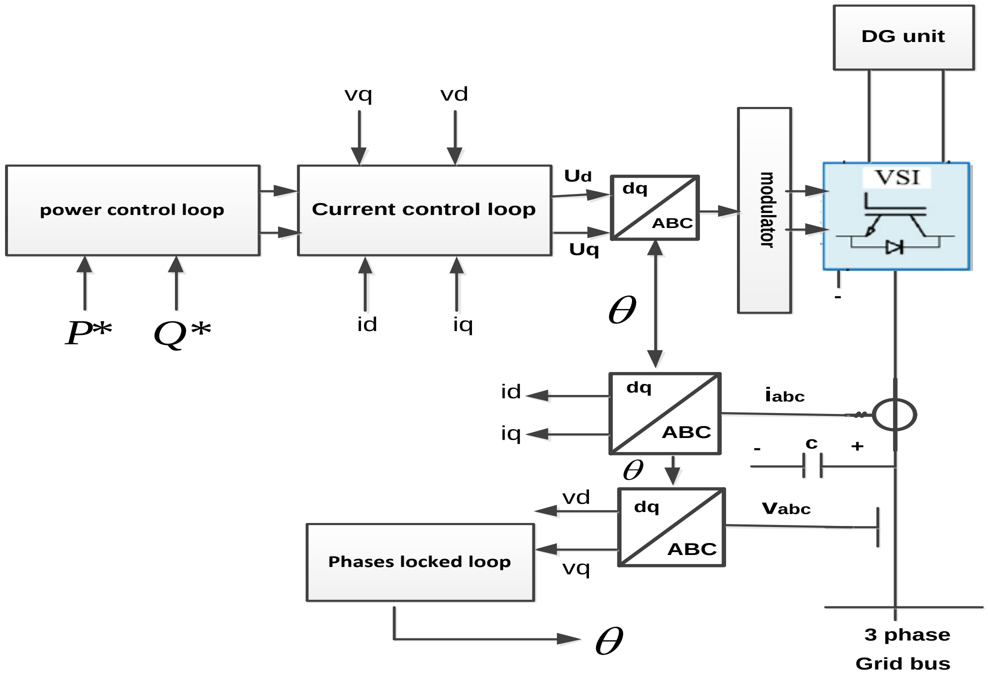


Figure 3.25: Basic control scheme of a grid-feeding voltage source inverter (Bouzid et al., 2015)

Figure 3.26 shows the control of the grid-feeding power converter, where P^* is delivered active power and Q^* is delivered reactive power.

3.4.5.2 Control of grid-supporting power converters

The grid–supporting power converters are authorised power sharing for power balancing either in interconnected grid application or island application, by controlling the quality of both the AC grid voltage amplitude E^* reactive power and frequency active power. They support the grid, either alone or with other grid-supporting inverters. The grid-supporting power converters have two main classifications: to control a voltage source with link impedance or to control a current source with parallel impedance. In grid-supporting inverters, the circulating currents between two parallel grid-forming inverters are avoided by introducing artificial droop coefficients in the inverter frequency and voltage control, equivalent to the droop of the generator in the primary frequency control of synchronous generators in the grid network (Bouzid et al., 2015).

In this mode the inverter operates as a grid-supporting source, because there are changes after the injected active and reactive power depending on the main grid voltage and frequency excursions from the nominal values (Arboleya et al., 2010).

3.4.5.3 Grid supporting power converter based on voltage source

This type of grid supporting power inverter is established on the control scheme of a grid supporting inverter, which is controlled for emulating the behaviour of an AC voltage source connected directly to the grid via link impedance which can be either a physical device connected between the voltage source inverter and the utility grid, or a virtual component, emulated within the current control loop. The amplitude and frequency of the grid voltage are regulated by the grid supporting power converter either in interconnected grid or stand-alone applications. Besides, frequencies are no longer fixed but obtained as a result of the droop equations as a function of active and reactive power components. In the case of a control system, the power converter delivers P and Q active and reactive power which are calculated by multiplying direct $i_d$and quadrature i_q current components by the direct U_d voltage grid component (Bouzid et al., 2015).

Figure 2.27 illustrates the basic structure of the control scheme of a grid-supporting power converter operating as voltage source.

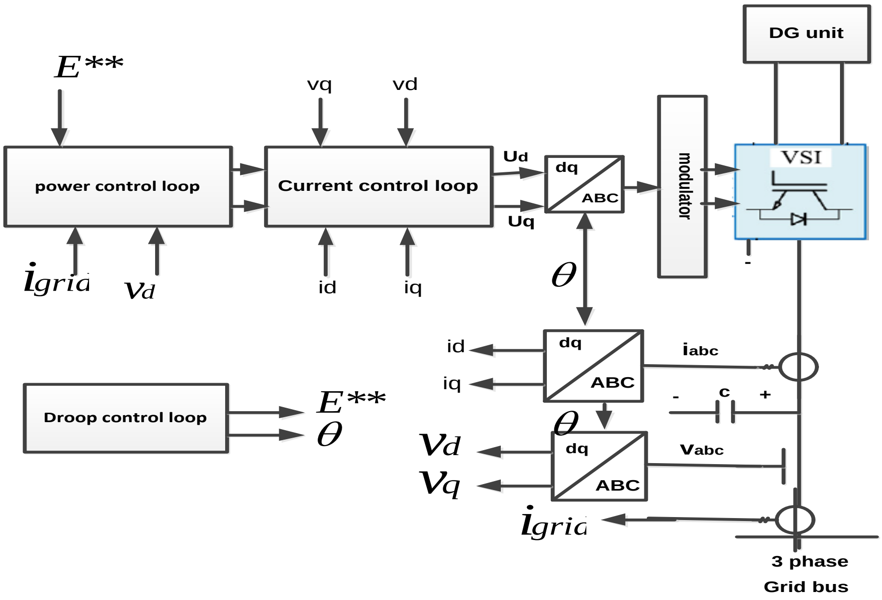


Figure 3.26: Basic control scheme of a grid-supporting voltage source inverter (Bouzid et al., 2015)

3.4.5.4 Grid supporting power converter based on current source

The control scheme of a grid-supporting power converter, which is based on current source control, is concentrated on operating as a current source. There is a small difference in the control scheme between a grid-feeding converter and grid-supporting power converter operating as a current source, as shown in figure 3.28 .The main objectives are to contribute to the regulation of the voltage amplitude and frequency of both the AC grid and the micro-grid and supply the load connected to the micro grid. In grid-connection modes the grid-supporting power converters regulate the exchange of active and reactive powers by using droop regulation techniques with the grid, thereby keeping the grid voltage frequency and amplitude under control. The main idea to support the droop control comes from mimicking the self-regulation capability of the synchronous generator in grid- connection mode, decreasing the delivered active power. Two reasons could explain this: the first reason is the analogy with the control of synchronous generators, the second reason being that droop characteristics for inverters were first implemented in UPS systems (Bouzid et al., 2015).

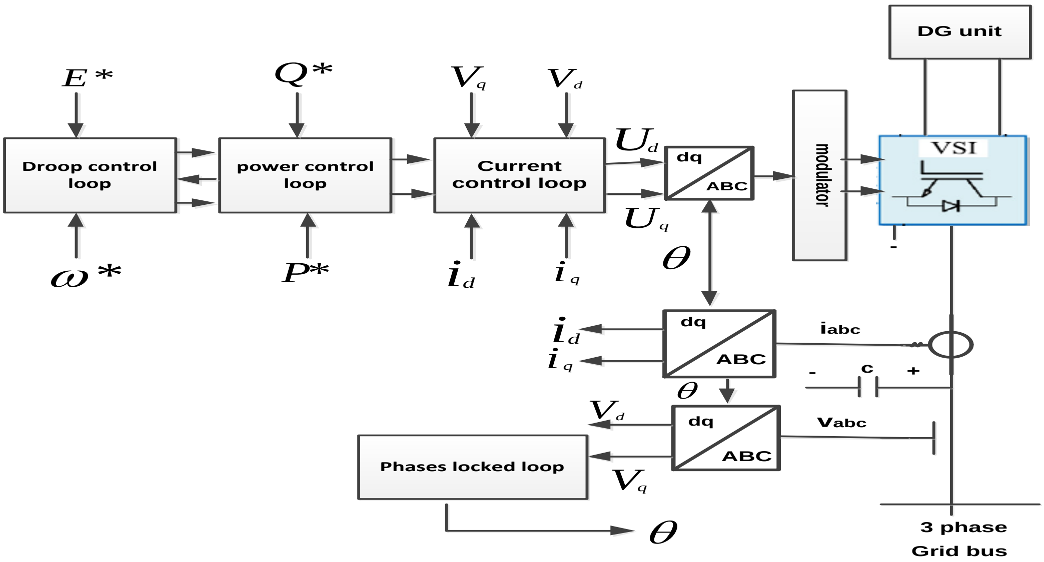


Figure 3.27: Basic control scheme of a grid-supporting current source inverter (Bouzid et al., 2015)

Referring to Bouzid et al. in 2015 the grid-supporting component is in fact a simplification, compared to others and grid-feeding and grid-forming components are two extremes, while having properties that lie between both extremes.

3.5 Protection system for a distribution network

A distribution system is designed to handle diverse types of faults. In general, faults result from high current levels which flow in electrical power systems which can occur due to various reasons, such as faults due to either permanent or temporary and both external or internal causes. The faults due to internal reasons, cause failure in system components and mainly short circuits. Consequently, it might lead to the following consequences:

- Thermal impact where a high fault current flow results in system equipment overheating, which may damage the insulation material and melt conductors;

• Electrodynamic impact: Electromagnetic effects of current cause electrodynamic forces observed in the network equipment;

• The voltage sags in the healthy network elements, which is often lower than the allowable load voltage;

• Switching surges: The switching of a current in an inductive circuit and critical situations such as resonance can cause over-voltages (switching surges) where the maximum peak value may reach two or three times the root mean square (rms) value of the nominal voltage;

• Over-voltages: An over-voltage occurs between the healthy phases and the earth when a phase - to - earth fault occurs. Likewise, it may result from an earth fault itself and its elimination.

Basically, the objective of a protection scheme is to keep the power system stable by isolating only the components that are under fault. The conventional types of protective devices are moulded-cases, thermo-magnetic switches, circuit breakers (MCCBs) and fuses. In addition there are overcurrent relays, which are the most common protection devices used to counteract excessive currents on electrical power systems.

The types of protection relays are mainly based on their characteristics, logic, actuating parameter and operation mechanism. Based on the operation mechanism, a protection relay can be categorized as an Electro Magnetic relay, Static relay and Mechanical relay. Actually a relay is nothing but a combination of one or more open or closed contacts. All these contacts or certain specific contacts of the relay change their state when actuating parameters are applied to the relay. That means open contacts become closed and closed contacts become open. In an electromagnetic relay the closing and opening of relay contacts are performed by electromagnetic action of a solenoid (Sallam, 2010; Association & Engineers, 1995).

In a mechanical relay the closing and opening of relay contacts is done by mechanical displacement of different gear level systems. In a static relay it is done mainly by semiconductor switches like a thyristor. In digital relays the on and off state can be referred to as 1 and 0 state (Association & Engineers, 1995).

- Based on characteristics, the protection relay can be categorized as:
  Inverse Time Relays with definite minimum time (IDMT), Instantaneous relays, IDMT with inset, stepped characteristic, Programmed switches and voltage restraint over current relay.

- Based on use of logic the protection relay can be categorized as:
  Differential unbalance, directional, restricted earth fault, over-fluxing, distance schemes, bus bar protection, reverse power relays, loss of excitation, negative phase sequence Relays, etc.

- Based on actuating parameters the protection relay can be categorized as:
  Current relays, voltage relays, frequency relays and power relays.

- Based on application the protection relay can be categorized as:
  Primary relay and back-up relay.

An overcurrent relay is an automatic device which senses an abnormal condition of an electrical circuit and closes its contacts. These contacts in turn close and complete the circuit breaker trip coil circuit, hence making the circuit breaker trip for disconnecting the faulty portion of the electrical circuit from the rest of the healthy circuit. However, relays need to be energized to operate. This energy can be provided by the monitored circuit itself or by using an energy storage system such as a capacitor trip device (Sallam, 2010)**.**

3.5.1 Different types of Overcurrent relay

An overcurrent relay is a device that operates only under fault conditions and it is run immediately when the load current exceeds a preset value. A Relay can be defined as a device able to sense any change in the signal level. In general, an overcurrent relay must have current setting multipliers ranging from 50 to 200% in steps of 25% which is referred to as plug setting. In addition, overcurrent relays should not be installed merely as a way to protect systems against high loading. The classifications of each relay which determine the plug setting are; the maximum current withdrawn by the load and the minimum fault current. Furthermore, relay settings are often selected taking both into account, over -load and overcurrent circumstances (Hussain et al., 2013).

The overcurrent relay can control the performance of a breaker through the repeated process of opening and closing based on the specifications of the relay characteristics. The main two types of relays are: instantaneous and time-delay. The time-current characteristic of an overcurrent relay consists of two sections: the first one is independent of the current, and the second one has an operating time that varies inversely with the current. Depending on the rate with which the relay operating time and current are related, the time overcurrent characteristic can be classified as inverse, very inverse and extremely inverse (Martínez-Velasco et al., 2010).

Regarding the operating scheme of relay characteristics, the classification of overcurrent relays can be divided into three main types: definite time, definite current and inverse time.

3.5.1.1 Definite current relay

The principle concept of this type of definite current relay is based on the current reaching or exceeding the setting threshold, after which the relay starts operating immediately. Figure 3.29 shows the operating current feature of this type of relay (Sallam, 2010; Gers & Holmes, 2004).

Figure 3.28: Overcurrent relay time – current operating characteristics.

In this type the relay scheme is adjusted based on its location in the distribution network. In the case of overcurrent, the relay is connected to the receiving end of a distribution feeder further away from the source, which will operate for a current lower than that connected to the sending end, particularly if the Distributor is too long and creates large impedance. In a case where the Distributor impedance is not too large compared with the upstream network impedance, interaction between the fault currents at both ends leads to poor discrimination in addition to little selectivity at high levels of short circuit current (Sallam, 2010; Gers & Holmes, 2004).

3.5.1.2 Definite Time Relay

In the protection scheme for this type of relay, the setting is adjusted to cope with different levels of current by using different operating times. The settings can be attuned in such a way that the relay, which is installed at the furthest substation away from the source, is tripped in the shortest time, and the remaining relays are tripped in sequence having longer time delays, moving back in the direction of the source. The difference between the tripping times for the same current is called the discrimination margin (Sallam, 2010; Gers & Holmes, 2004). Figure 3.29 shows Overcurrent relay time – current operating characteristics.

Figure 3.29: Overcurrent relay definite current characteristics.

3.5.1.3 Inverse Time Relays

Inverse time overcurrent relays are based on a quick operating scheme in order to sense the current increases. Figure 3.30 shows the characteristics of overcurrent relays and figure 2.31 shows the overcurrent relay inverse time with instantaneous unit characteristics. The categorization of an inverse time relay is dependent on time characteristics, such as with inverse, very inverse, and extremely inverse time characteristics to fit the requirements of the particular application (Sallam, 2010; Gers & Holmes, 2004).

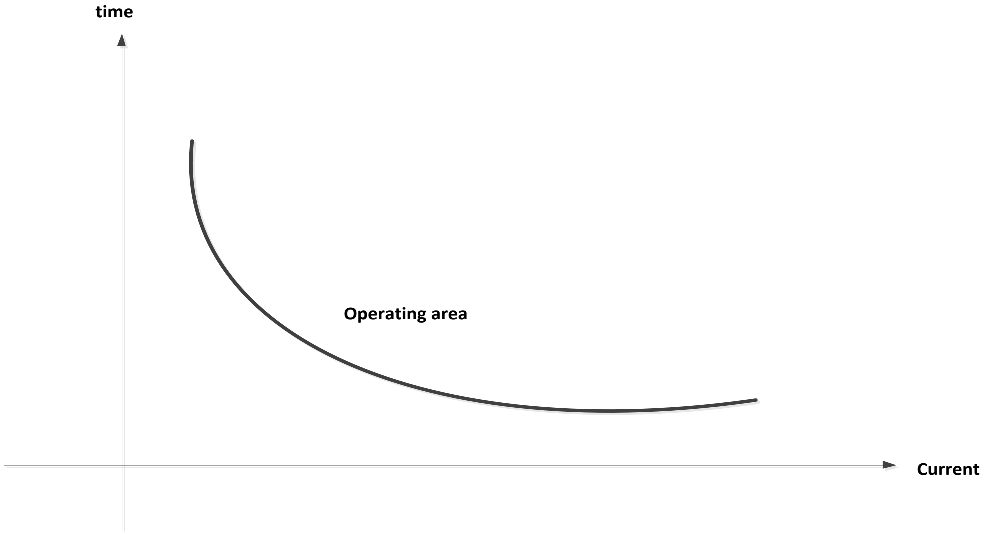


Figure 3.30: Overcurrent relay inverse time characteristics.

Figure 3.32 shows Overcurrent relay inverse time with instantaneous unit characteristics.

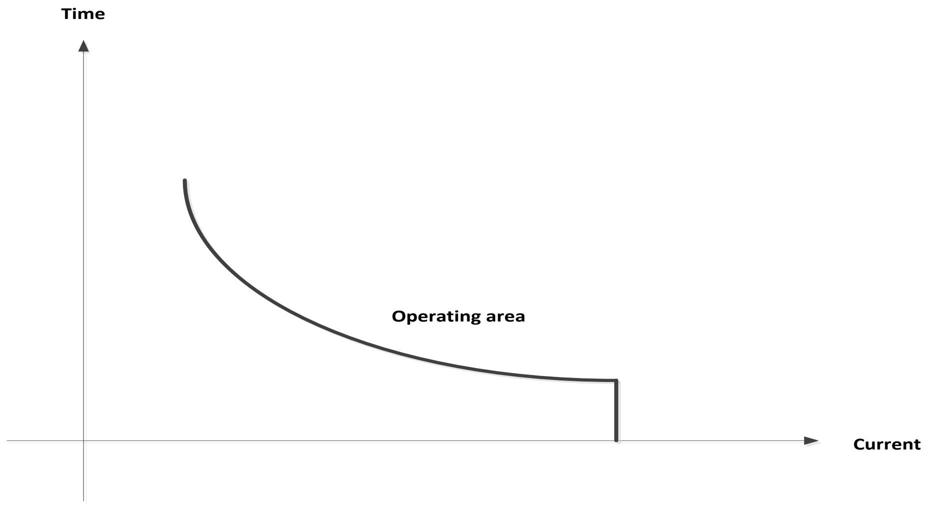


Figure 3.31: Overcurrent relay inverse time with instantaneous unit characteristics.

The coordination of this protective relay is set up during the process of the system design based on the fault current calculation.

In order to detect and clear faults properly and timeously, the relays have to be coordinated with other protective relays located at all the adjacent buses. In a protection system design coordination plays a key role in order to protect the system perfectly. The relay coordination problem is to determine the sequence of relay operations for each possible fault location so that the faulted section is isolated with sufficient margins and without excessive time delays (Hussain et al., 2013).

In general, protective elements, such as fault detection, fault clearing and minimization of the outage times are adversely affected by distributed generation which demands the need for changes in fault localization methods and equipment used. The conventional protection schemes such as overcurrent protection systems used in distribution networks in the presence of distributed generation, depend on how significant the impact from the distributed generation is during faults. In power distribution networks with distributed generation, protection coordination is complicated, as a conflict exists between adjustments of settings required to avoid blinding and sympathetic tripping (Marvik et al., 2007; Tiwari et al., 2014).

3.6 Summary

This section was dedicated to the impact of distributed generation in a distribution system, where different issues can arise due to the integration of distributed generation in the power system networks mentioned. Other operating issues of distribution protection in the presence of distributed generation, control strategies for distribution power generation, and a protection system for a distribution system has been presented.

CHAPTER FOUR

Modelling and simulation

4.1 Introduction

The aim in this chapter is to investigate some of the matters which are raised due to the impact of distributed generation. A description of the different components which are part of the system under study is provided. Different components of the system are described. Some of the main circuit parameters were assumed on the basis of system ratings, while others were determined. This chapter begins with the system configuration where the distributed generation, loads and conventional generator are all connected to the grid. Moreover MATLAB/SIMULINK software is deployed for the investigations on a model.

MATLAB/SIMULINK software is applicable to the modelling of generation, transmission, distribution and industrial grids, and the analysis of these grids' interactions. This software provides a library of standard electrical components or models such as transformers, machines, and transmission lines. Therefore, the modelling and simulations are executed using MATLAB/Simulink version 2014b.

This chapter is divided into two sections: the first section models overcurrent relay and the second section investigate the impact of distributed generation on fault current level.

Section one

Modelling and simulation of an Overcurrent Relay

4.2 General concept of an Overcurrent Relay

The fundamental concept of an overcurrent relay is based on the premise that withdrawing current in the system leads to consequent change in the current level, and in general, the normal fault condition which is based on a very simple premise that in most instances of a fault, there are different levels of current, because the current dramatically increases from the pre-fault value. If one establishes a threshold well above the nominal load current, as soon as the current exceeds the threshold, it may be assumed that a fault has occurred and a trip signal may be issued.

An instantaneous overcurrent relay is based on this fundamental principle. However, the best feature of this kind of protection scheme is a quick reaction time. Therefore, it is the most popular kind used at all voltage levels to protect different equipment such as distribution lines, transformers, generators, and motors. (Phadke & Thorp, 1988; Aman et al., 2012).

The overcurrent protection system is shown in Figure 4.1 with the placement of protection components such as current transformer (CT), circuit breaker, and a relay for distribution line protection. As shown in figure 4.1, it is located between the current transformer and the circuit breaker. The input signals are received by relay from the secondary winding of the current transformer and treated according to the relay setting, before sending a control command to the circuit breaker in order to operate either the opening or closing, respectively. The current transformer is a very important element in the electrical power system, because it reduces the high magnitude currents of the power system to more manageable levels which can be easily controlled.

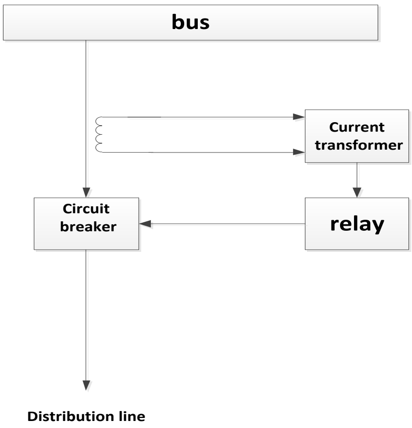


Figure 4.1: Overcurrent protection scheme

In an overcurrent relay a definite current characteristic is normal protection scheme selectivity which is done in this study by using the modeling tools in MATLAB/Simulink. Moreover, it has to be considered that when a distribution system is accommodated in distributed generation, the protection scheme has to be changed because of the bidirectional current which is flows due to the additional power source, and also fault currents can circulate in both directions throughout a system device. Therefore, overcurrent relays should be used to guarantee a safe operation scenario.

4.3 Description of the relay model

In the modeling part, MATLAB/Simulink is used as simulation tool to model an overcurrent relay. The current is measured in three phases at one bus and then the current measurements are sent to an instantaneous overcurrent relay model. However, current signals from the power system must be converted to digital form to be adapted for processing which can then be used to operate the breaker (Zhang et al., 2007). Figure 4.2 shows the overcurrent protection components which are used for modeling an instantaneous overcurrent relay in this work.

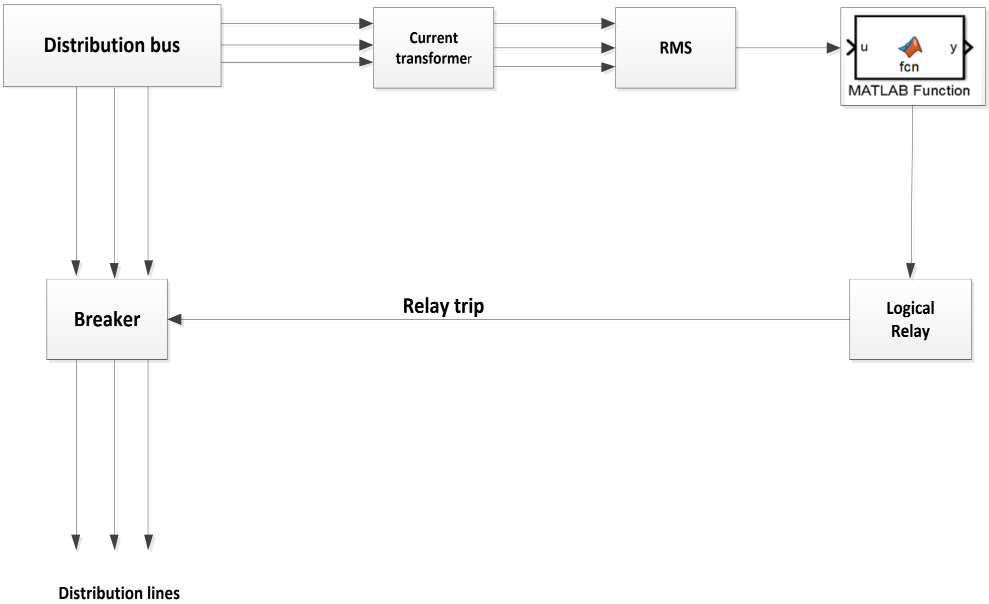


Figure 4.2: Block diagram of protection scheme using overcurrent relay

4.4 System components

4.4.1 Digital relay model

In an instantaneous overcurrent relay, the input to the model is in analog form extracted from current signals by the current transformer. The signals will be converted to Root Mean Square (RMS) signals. This adaptation is done by using RMS filter Converter.

MATLAB/Simulink library has many different types of RMS blocks: the Discrete Root Mean Square (DRMS) block for a signal to compute its discrete-time and cumulative root mean square value. It is used in conjunction with the Signal Constraint block to optimize the signal energy. Furthermore, the R.M.S value gives a measure of the average energy in the signal (Mathworks, 2015a).

The discrete-time, cumulative root mean square value of a signal $u(t_i)$ is defined as (Mathworks, 2015a):

$$\boldsymbol{R.M.S} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\|u(t_i)\|^2} \tag{4.1}$$

The RMS filter is a very important component of an overcurrent relay. The behavior of digital relays is directly dependent on the output of the RMS filter and these signals must be converted and controlled as digital signals through a MATLAB function in order to be converted to digital form as mentioned previously. This function is a computer language description of a Simulink block written either in MATLAB, C, C++, Ada, or Fortran. The most public use is to create a custom block which can dynamically interact with other blocks in a Simulink environment. The users can employ MATLAB function for a variety of applications, for instance describing a system as a set of mathematical equations, incorporating existing C/C++ code into a simulation, and adding a block that represent a hardware device driver (Luo & Kezunovic, 2005). However, in our model, The MATLAB function is written in C++ programming language as mentioned and finally this signal can control the breaker in order to open or close.

The moment that the output of the RMS signal is produced, this signal is fed into the relay protection algorithm block based on certain conditions. This block compares the current value with the pickup value. If the measurement current is greater than the pickup value a command will be sent to the relay in order to start the trip, taking into account the characteristic curve, either long Inverse or Extremely Inverse, Standard Inverse and Very Inverse, before the start of the trip. It then sends a trip signal once the operation time has elapsed.

Figure 4.3 shows the protection algorithm implemented in MATLAB by using C++ programming languages. The overcurrent model is attached to a single subsystem (block) and a graphical user interface is provided where the user can select the specification of the overcurrent relay.

The overcurrent relay must be operated immediately in order to detect the fault conditions and to avoid sending a false tripping command to the relay there are steps involved that guarantee the safe, reliable and fast operation of overcurrent relays.

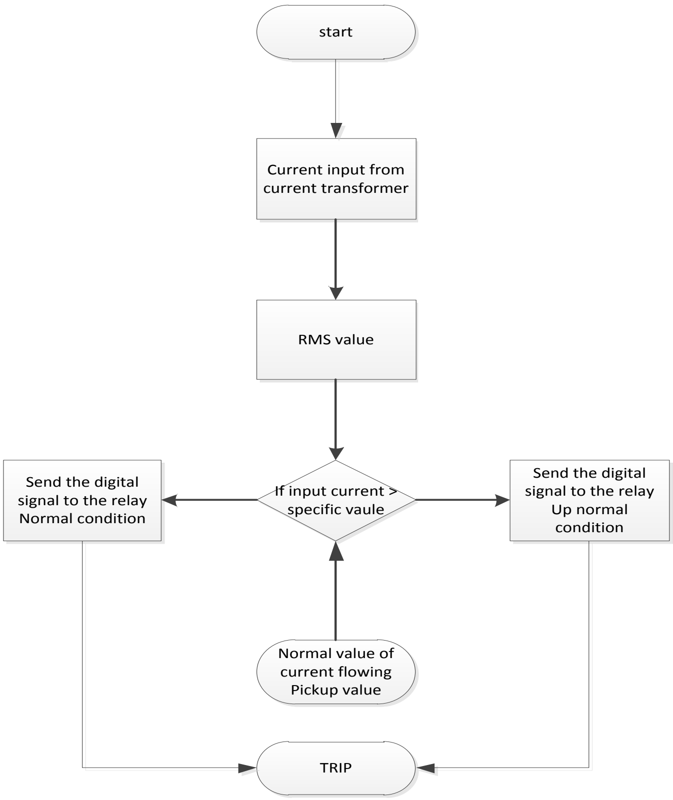


Figure 4.3: Protection Algorithm implemented in the overcurrent relay

Generally, there are certain steps which are followed in choosing the pickup value of the overcurrent relay as displayed in figure 4.4. Following these steps, fault analysis of the test system was conducted (Almas et al., 2012).

Firstly full load current must be estimated, the short circuit current must be expected, and other important thing must be taken in the account the turn ration of the current transformer, which can be defined as the number of turns on its secondary divided by the number of turns on its primary. Therefore, the current ratio of an ideal transformer is inversely related to the turns ratio (Liptak, 2003):

$$\frac{I_P}{I_S} = \frac{N_S}{N_P} \tag{4.2}$$

Where I_S secondary current, I_P primary current, N_S number of turns in the secondary winding and N_P number of turns in the primary winding.

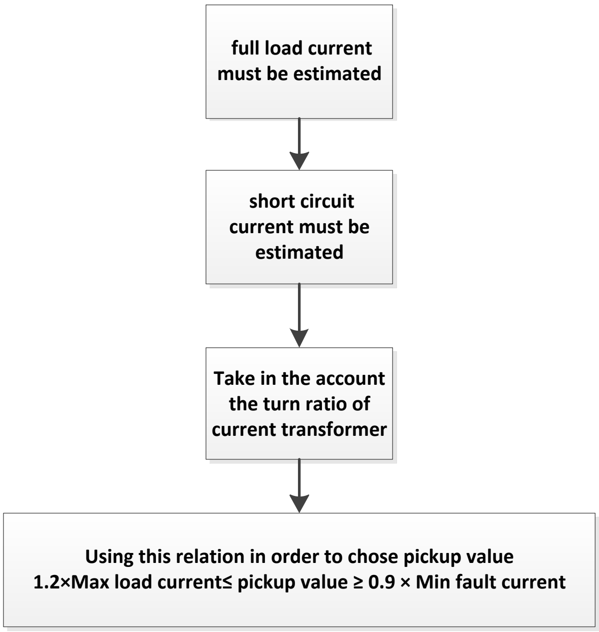


Figure 4.4: Choosing pickup values for overcurrent relay calculation

4.4.2 ON and OFF modes operation

The MATLAB function presented in Figure 4.5 produces an output Y which is smaller than the input U. The working principle is contained in switching on and off the function for a certain period of time. This function works according to the current flow in the line as the actual converter, which has two modes of function: the ON mode and OFF mode. Both modes are presented in figure 4.5.

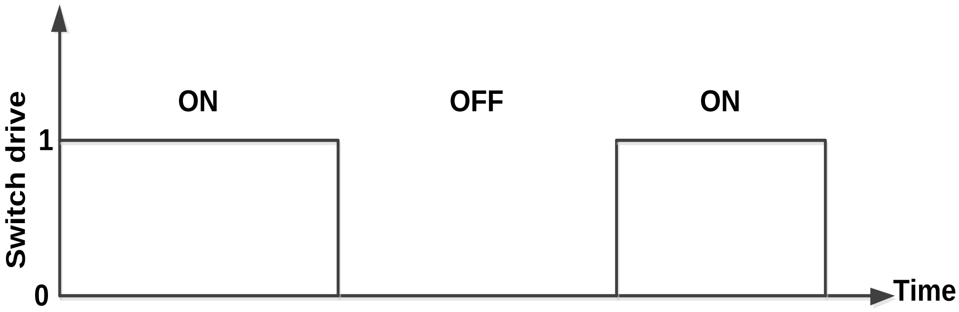


Figure 4.5: ON and OFF modes' characteristic operation.

4.5 Overcurrent relay model in SimPowerSystems (SPS)

Overcurrent relay can be modelled in SPS, because SPS libraries are provided with many diverse components and analysis tools for modelling and simulating electrical power systems. The libraries provide numerous models of electrical power components, including three-phase machines, electric drives, and components for applications such as flexible AC transmission systems and renewable energy systems. Harmonic analysis, calculation of total harmonic distortion, load flow, and other key electrical power system analyses are automated (Mathworks, 2015).

In this study we used SPS components and MATLAB programming languages in order to implement a control scheme and simulate its performance.

4.6 Description of network

The modelling and design in SPS for coupling the overcurrent relay model and for investigating its characteristics when subjected to faults, is displayed in figure 4.6. The major components of the test case are:

- The source is three phase voltage, 50 Hz, 25 kV phase voltage.
- Three phase transformer (two windings) 500 VA,25/0.400 KV.
- Distribution line (7r-section), 1 km
- Three phase fault block to introduce three phase fault to ground.
- Circuit breaker to disconnect the faulted branch with external control trip signals from the overcurrent relay model.
- RLC three phase load in series connected1 MW.
- Simulation time step = µ 70 sec.

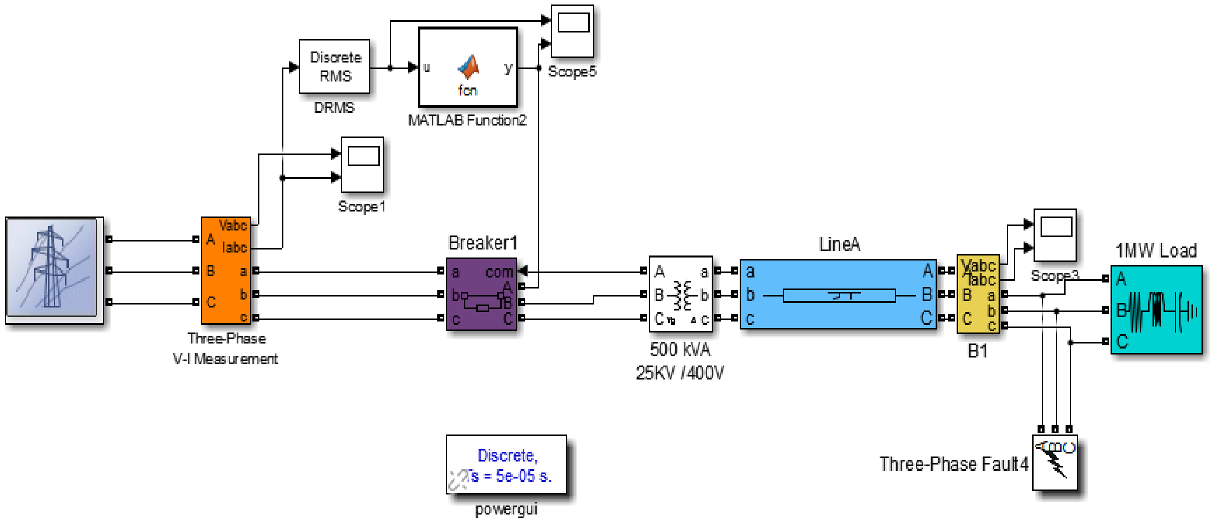


Figure 4.6: Over current relay model in SimPowerSystems.

4.7 Simulation result

After the signal is processed by the RMS discrete block which is displayed in figure 4.6, the MATLAB function compares the absolute value of the relay input signal with the pickup setting to check the status of the power system. In the case of the fault existing in the protection zone of the system, the absolute value of the relay input signal is greater than the pickup setting; otherwise it is smaller than the pickup value. The output of the comparator in Matlab function 2 (Figure 4.6) is the Trip signal for the circuit breaker, which is represented as a digital signal as shown in figure 4.7, if the fault exists within the zone of protection.

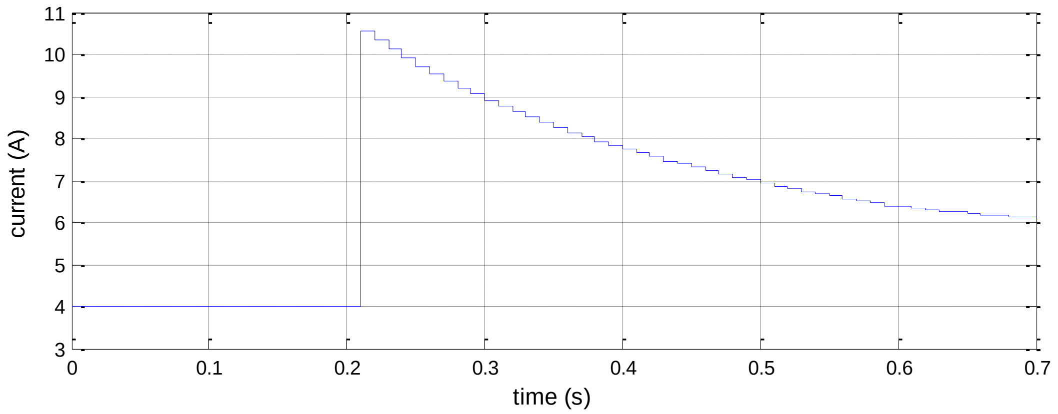


Figure 4.7: Output signal of RMS measure block.

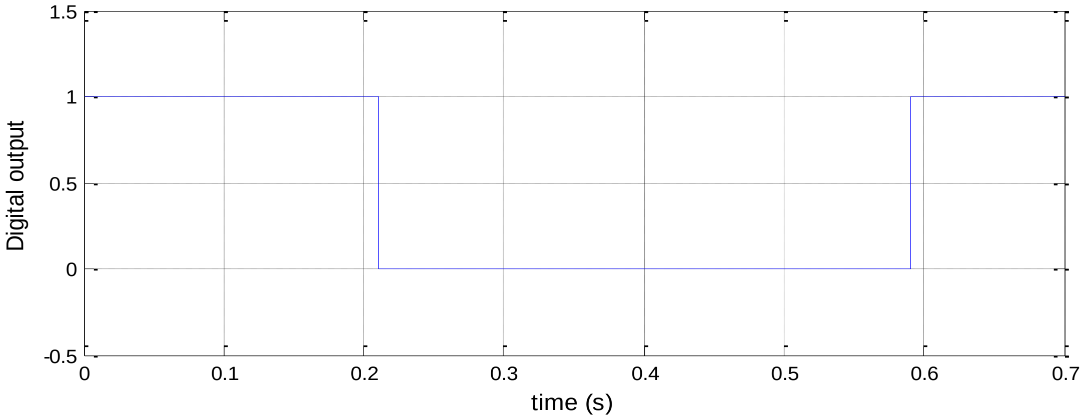


Figure 4.8: Trip signals as a digital output from MATLAB function.

Figure 4.8 illustrates the trip signal output of the relay logic block for a test case in which the digital signal starts closing and opening the breaker trip. Figures 4.9, 4.10 and 4.11 show the current wave behavior for phase A, phase B and phase C during the test condition. The results show that there is switching off at t = 0.2 s till t = 0.6 which means the fault current level went over the steady state current condition. Obviously, once the relay detects the value of the fault currents, a trip signal is sent to the circuit breaker and the three-phase currents become zero.

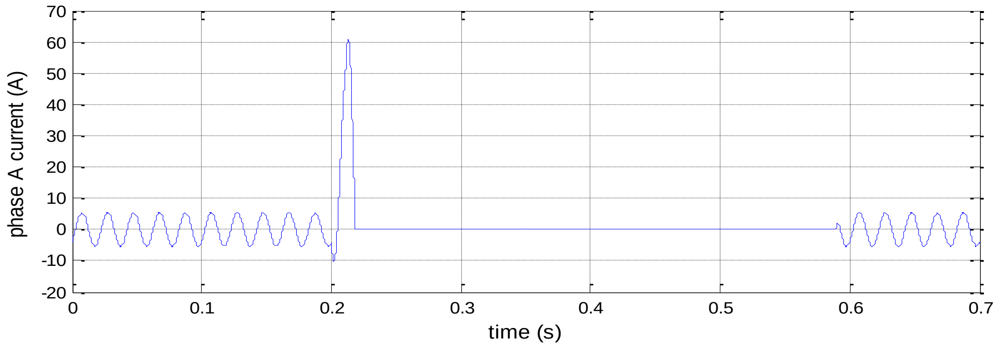


Figure 4.9: The current behaviour for phase A from MATLAB/Simulink simulation

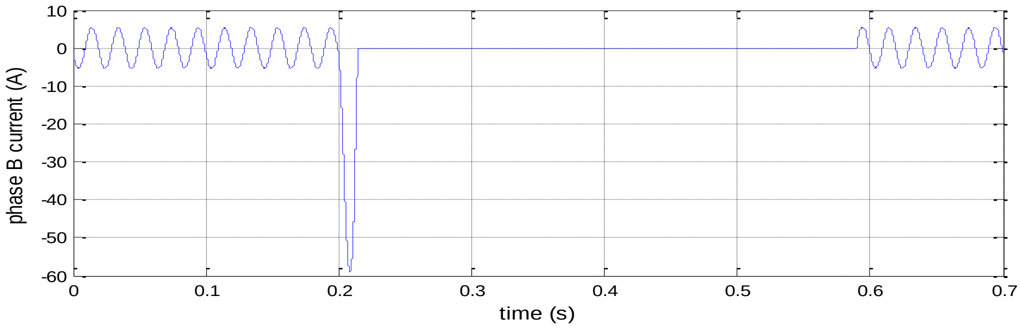


Figure 4.10: The current behaviour for phaseB from MATLAB/Simulink simulation

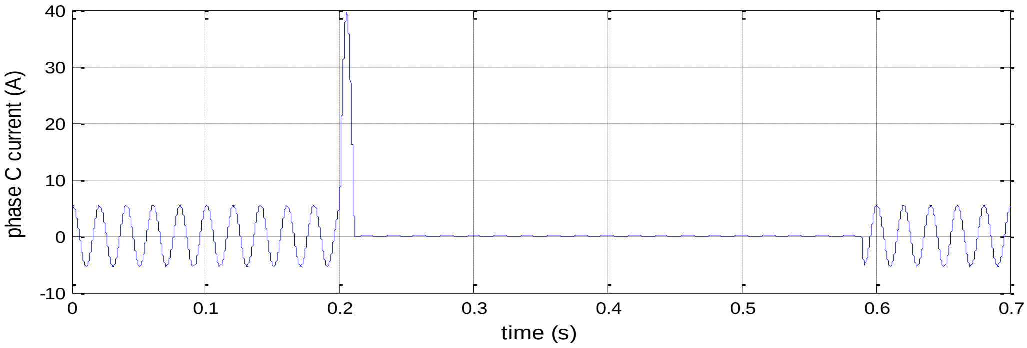


Figure 4.11: The current behaviour for phase C from MATLAB/Simulink simulation.

Figure 4.12 shows the output of the relay trip and the current measurement in phase A combined in one scope.

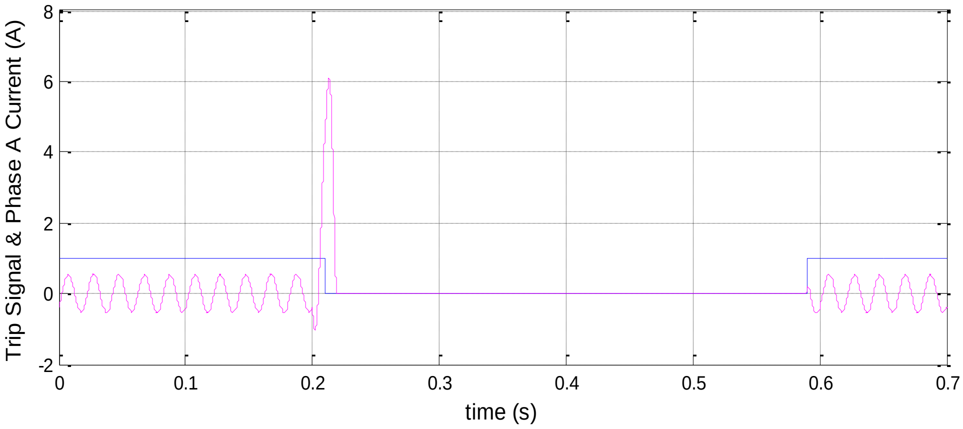


Figure 4.12: Overcurrent relay Trip Signal where Fault occurred in phase A.

4.8 Summary

Finally in this section, a simple approach to simulation of an interactive protection system for power distribution system, however the reasons for choosing to model an instantaneous overcurrent relay are: Firstly, it is considered as the simplest protection scheme in protection engineering and it is a common scheme in relay application. Secondly, an overcurrent relay provides protection against overcurrent as the name states. However, the simple operating principle of this relay is that it uses current input from a breaker and compares the measured current values with the present values.

This study used a MATLAB function for collecting the data and issuing the tripping signal. The model was implemented and investigated using the commanding MATLAB code, and Simulink blocks, the programming is done in C++ language, and the first-time user can spend a long time with setting everything under proper control. Power system configuration, fault detection, fault calculation, discrimination, and classification were achieved with the MATLAB/Simulink program.

Section Two

Investigation of fault current contribution scenarios for power distribution in the presence of distributed generation system

4.9 Introduction

Distributed generation (DG) grid-connected applications are developing for to multiple reasons, such as, environmental concern, global warming and the very high cost of building transmission lines, etc. Many different reasons contribute to the implementation of this unit in modern distribution grids. However, this corresponds to an increase in the amount of power delivered by these units. The connection of DG resources is a necessary requirement to the network, besides voltage regulation and power quality constraints, the total fault current level which is mainly obtained by the short-circuit contribution of both the upstream grid and the DG, should remain below the network design value. This issue is frequently the major limitation for the interconnection of DG units to the grids (Baghaee et al., 2008).

The DG's contribution in fault current level during transient faults must be strictly estimated since it may have major impacts on the protection system of feeders, and could raise the short circuit level enough to cause protective devices malfunction. Furthermore, it might cause a failure to mechanical and thermal stresses on feeder's circuit breakers that lead to exceed breaker permissible limits (El Safty et al., 2010).

In this section investigation of fault current contribution scenarios for power distribution in a distributed generation system will be achieved. We will give an overview of distribution network components used in these simulations, and some simulation results will be discussed**.** Lastly, some of the main circuit parameters were assumed on the basis of system ratings, while others were determined.

4.10 Description of network

The system for application of a radial distribution system with distributed generation also has a three phase fault implemented. Figure 4.13 shows the overall view of the proposed system which consists of various distributed generation systems connected to the secondary radial distribution of a utility grid through a distribution system.

A 47 MW conventional power plant is considered as grid side provider, 500 kVA power transformer (25/0.400 kV), two 300kW and 700 Kw distributed generation is installed successively on five different buses, B1, B2, B3, B4 and B5. The distance created between B1, B2, B3, B4 is 0.5 km by using a conductor overhead distribution line (7r-section). Their protection system is represented in three overcurrent relays R1, R2 and R3 installed on each bus. There are two static loads (4.10 kw, 4.99 Kvar) connected to B1, B2 and 7.10 Kw, and 7.99 Kw is connected to B3.

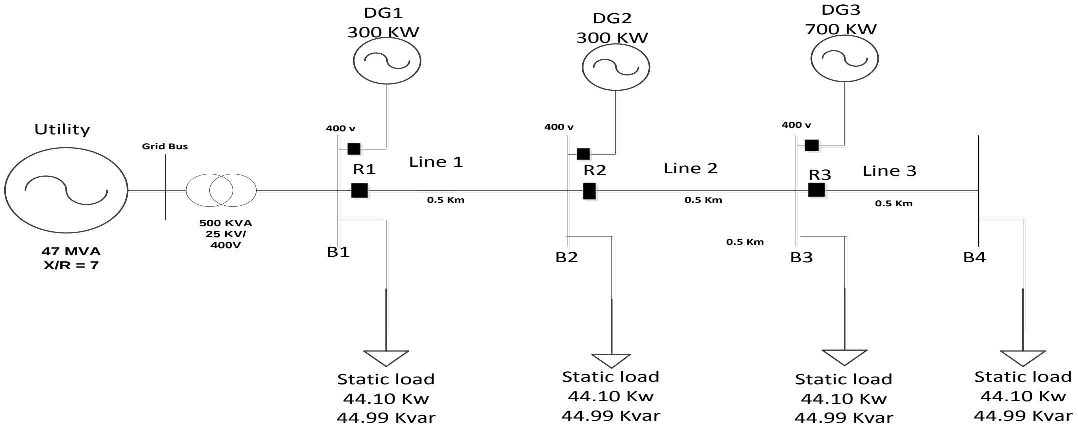


Figure 4.13: One line diagram of a system design.

Figure 4.1 illustrates $I_{R1}, I_{R2}\ and\ I_{R3}$ which are respectively the currents seen by relay1 (R_1), relay 2 (R_2) and relay 3 (R_3).

In addition $I_{DG1}, I_{DG2}\ and\ I_{DG3}$ are respectively the current contributed by DG1, DG2 and DG3.

Figure 4.14 shows a MATLAB/Simulink model of several distributed units integrated into the electrical distribution network. Depending on the placement of the DGs in the feeder, different protection scenarios will arise, as designated in Figure 4.13.

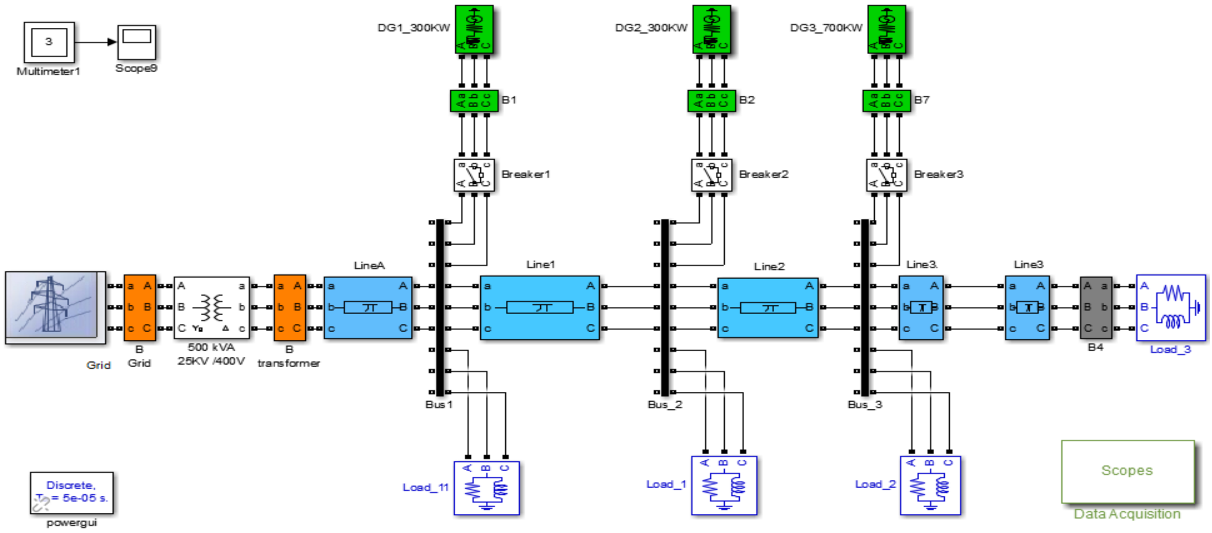


Figure 4.14: MATLAB/Simulink model of distributed generation integrated into the electrical distribution system

Table 4.1: Radial distribution network model simulation data

Main power supply (Grid)	
Power (w)	47 *10^6
$V_{Phase\ to\ Phase}$ (V)	25 000
Frequency (Hz)	50
Distributed generation	
Power (w)	500*10^3
$V_{Phase\ to\ Phase}$ (V)	415
Frequency (Hz)	50
X/R ratio	7
Generation type	swing
Three-phase Transformer	
Power (w)	500*10^3
$V_{Phase\ to\ Phase}$ (V) primary side	25 000
$V_{Phase\ to\ Phase}$ (V) secondary side	415
Frequency (Hz)	50
Distribution line (7r-section)	
Frequency (Hz)	50
Positive-and-zero-sequence resistances (Ohms/km)	[0.01273 0.3864]
Positive-and-zero-sequence inductances (H/km)	[0.9337e-3 4.1264e-3]
Positive-and-zero-sequence capacitances (F/km)	[12.74e-9 7.751e-9]
Line length (km)	0.5
Load	
Power (w)	1*10^6
$V_{Phase\ to\ Phase}$ (V)	400
Frequency (Hz)	50
Inductive reactive power QL (positive var)	100
capacitive reactive power Qc (positive var)	100
Load type	Constant PQ
Fault	
Fault resistance Ron (Ohm)	0.00001
Ground resistance Rg (Ohm)	0.00001
Snubber resistance Rs (Ohm)	1*10^6
Initial status	0

4.11 Implementing of a simulation electrical distribution system (EDS) using (SPS) tools

In this study we used SPS components in order to implement EDS and simulate it. However, the investigation of the current behaviour will be done under different conditions.

This part will be divided into three main scenarios which are classified according to fault location, where it will be located on line 1, line 2 and line three. Each scenario will have different cases according to connection or disconnection of the distributed generation and all models are simulated on a three seconds period range.

4.12 Scenario 1

4.12.1 Case 1(Only DG1 is connected)

Simulation of three phases to ground fault at line 3 of the electrical distribution system (EDS) with no DG is carried out and the simulation result is integrated in figure 4.15 with the result of the connection of DG1.

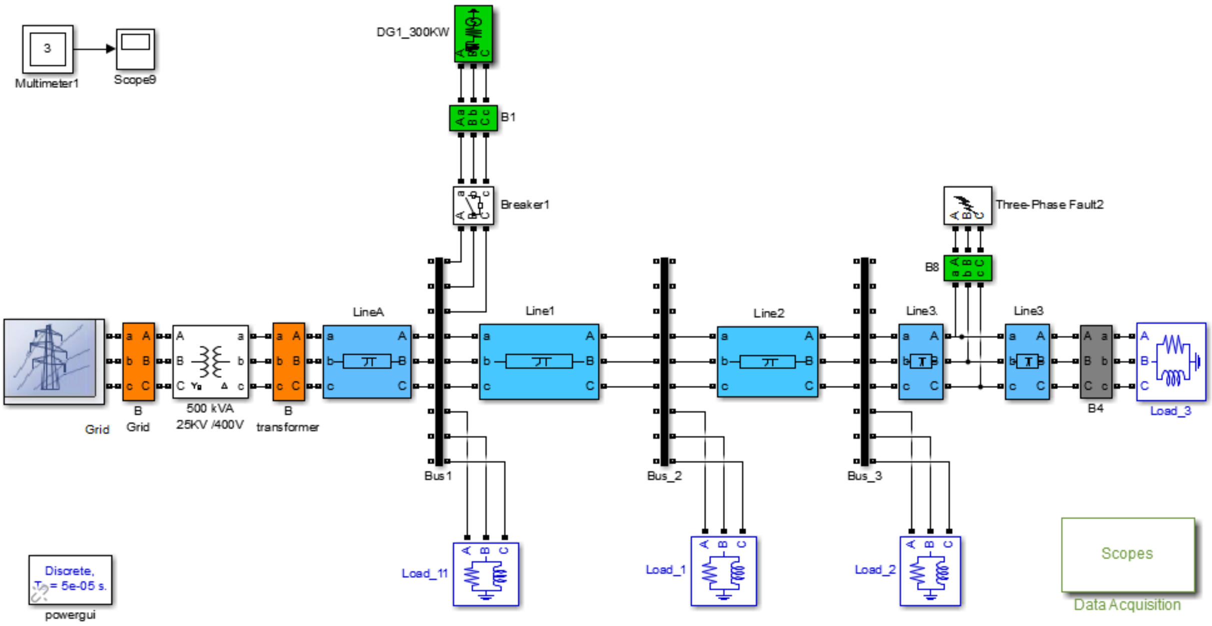


Figure 4.15: Simulink model of symmetrical fault occurred on line 3 of EDS with and without connection of DG1.

In Case 1, no DG is installed in the model of the distribution system. Figure 3.16 shows that a three phase fault (symmetrical) occurs at the middle of the line between bus 3 and bus 4 at voltage level of (400 V), while the current measurements are done in bus 1. The purpose of Case 1 is to compare the fault response of the system with other cases.

We assumed that the fault is not detected by the protective devices at any bus in the system either when DG is connected or not. Figures 4.16 displays the current measured when the fault occurred. The tripe spike at t = 0.1 s on the vertical axis is the current fault measurement without DG1 connected, which is approximately between 750:-750(A) as illustrated on the horizontal axis, and at t = 2 s DG1 is connected and the fault current level was slightly lower between 725:-725 (A).

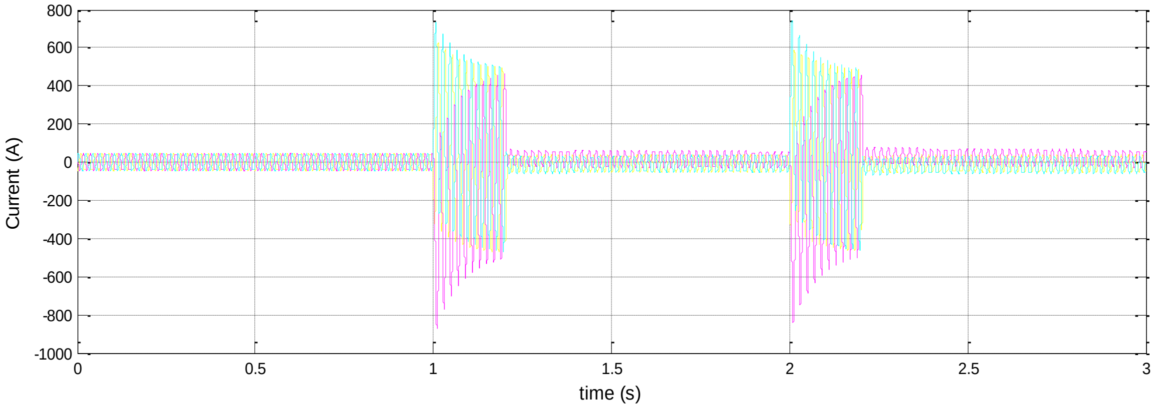


Figure 4.16: Simulation result of current measurement at B1 when the fault occurred at line 3 on EDS of 1 MW full load, with and without connection of DG1

Figure 4.17 illustrates the EDS simulation result of the measured voltage at bus 1, which is implemented in a two way connection and disconnection of DG1. It is shown that the voltage has a transient nadir/base current which is much lower than the steady state voltage and the voltage threshold of 400 V.

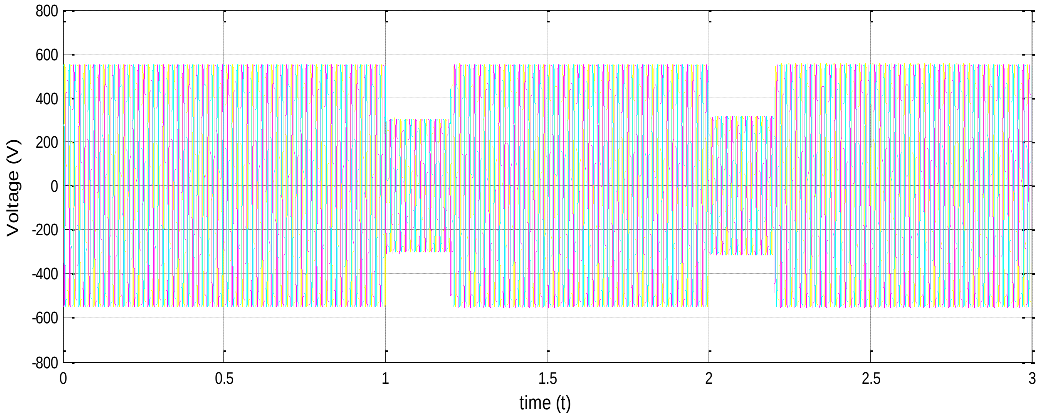


Figure 4.17: Fault voltage line 3 at the fault point, with and without DG in the system.

Figures 4.18 and 4.19 show the current measured during the fault, at bus 2 and bus 3. The upper envelope signal at t = 1 s on the vertical axis is the highest fault current level, which is measured without connection of DG1. This fault current is approximately in the range between 700:-820(A) as is illustrated on the horizontal axis, and at t = 2 s, DG1 is connected and the fault current level is almost between 720:-900 (A) at bus 1. Although, the current levels at bus 3 are more than the current levels at bus 2 which are shown in figure 4.19, because bus 3 is nearby the fault zone and therefore it is more effective than the other bus.

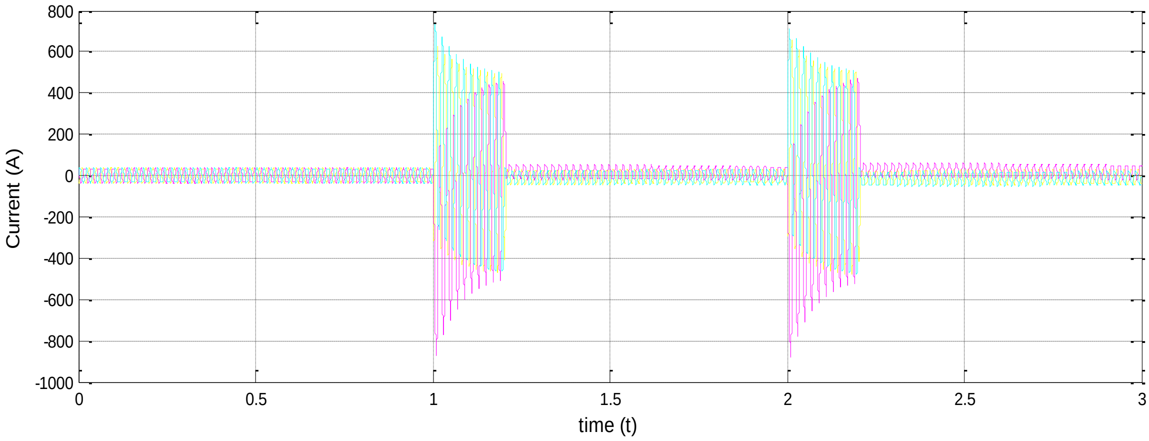


Figure 4.18: Three phase symmetrical fault current peak in the bottom at bus 2.

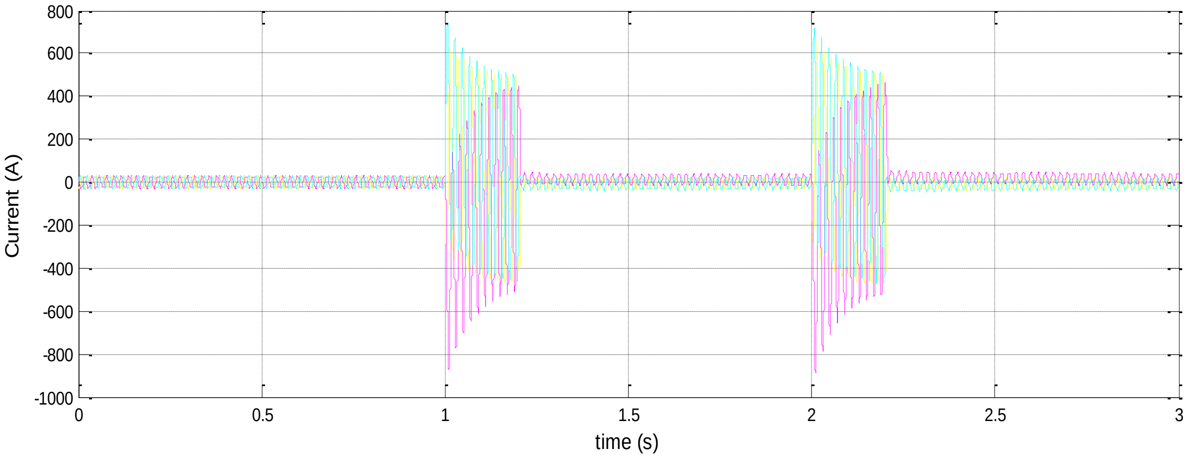


Figure 4.19: Three phase symmetrical fault current peak in the bottom at bus 3

4.12.2 **Case 2 (Only DG2 is connected)**

In this case a short circuit is located on the same distribution line 3. However considering that only DG 2 is installed on the EDS, as shown in Figure 4.20. The model is thus simulated without any connection and disconnection of DG 3.

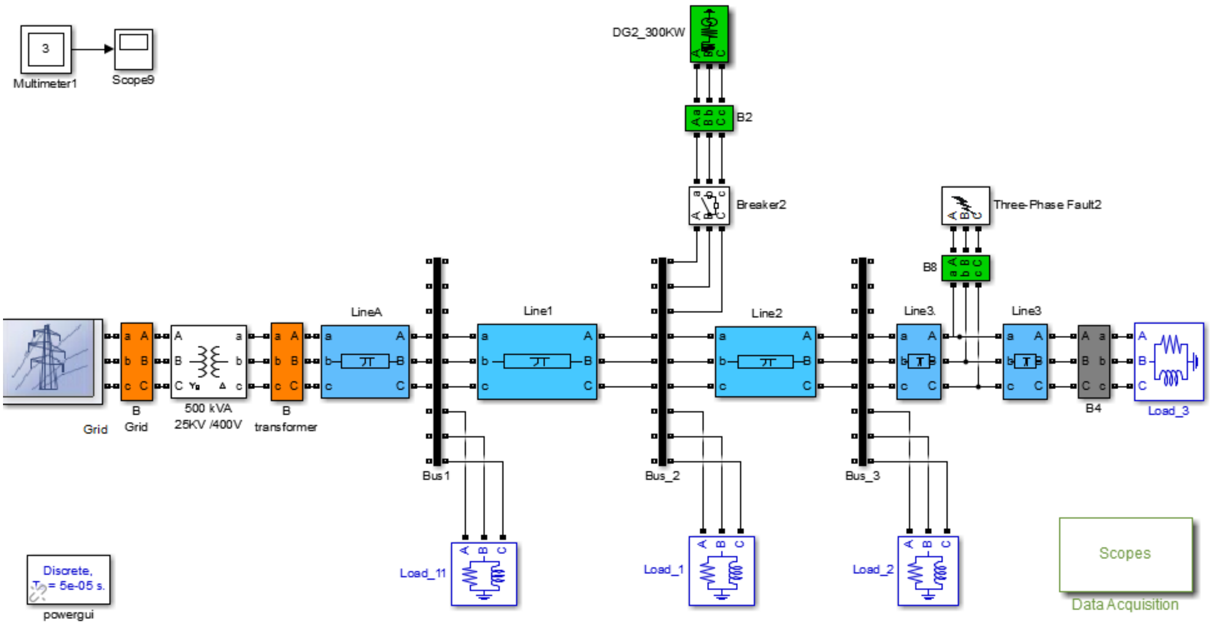


Figure 4.20: EDS with connection of DG at bus 2 and symmetrical fault occurred in line3.

The fault is recorded as a symmetrical fault at bus 1. As shown in Figure 4.21. A temporary fault was simulated at t = 1 s without connection of DG 2, and also at t = 2 s with connection of DG 2. The figure below shows the fault current waveform. In the fault condition it can be seen that the current became very high compared with the nominal value.

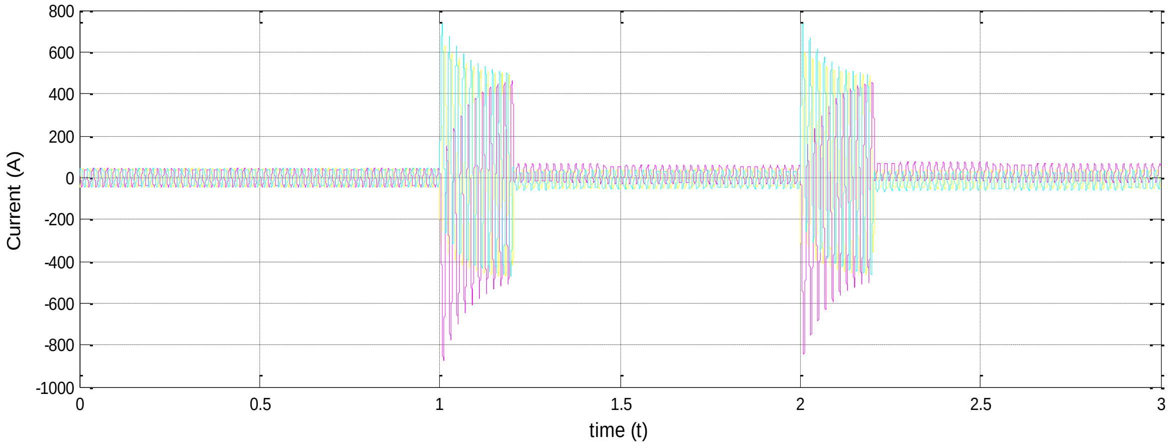


Figure 4.21: Asymmetrical fault and current measurements during both cases of connection and disconnection of DG 2.

Figures 4.22 and 4.23 show the increment of the current due to an asymmetrical fault which occurred at 1 s while the system is fed by the main source only and at t = 2 s the system is powered by both the main source and the distributed generation as well. There are slight changes in the fault current behavior at bus 2, which can be seen in figure 4.22. The fault goes beyond (+700 : - 840) A. Although, when the DG2 is connected, it is about (+740 : 880) A , which means that the fault level increased marginally when the DG 2 was disconnected. In bus 3, in figure 4.23, when the fault current flowed through, the contribution of DG 2 may be recognized by the difference in the current level before and after the connection of the DG 2.

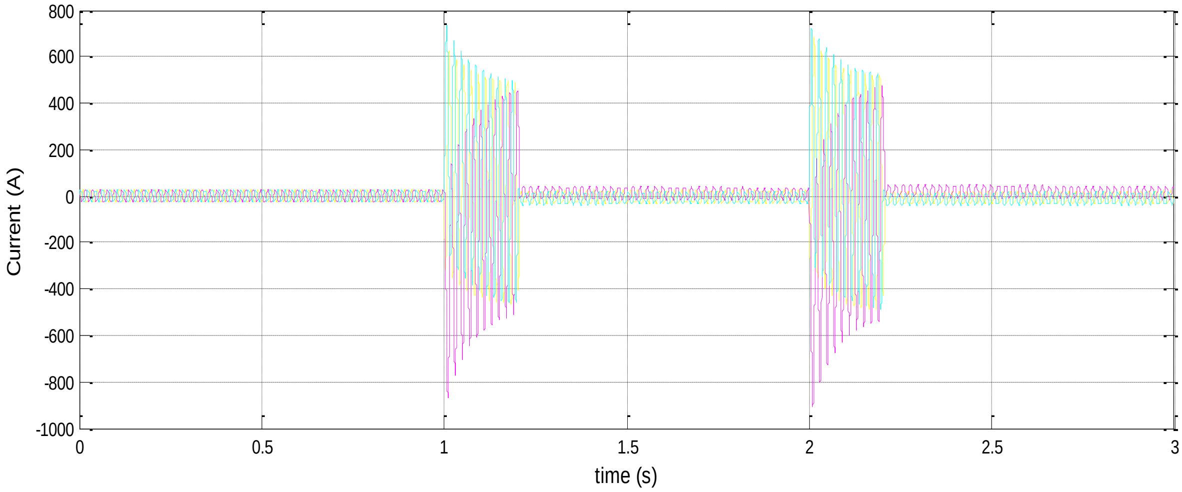


Figure 4.22: Current measurement at B 2 with and without connection of DG 2, in event of fault applied in line 3.

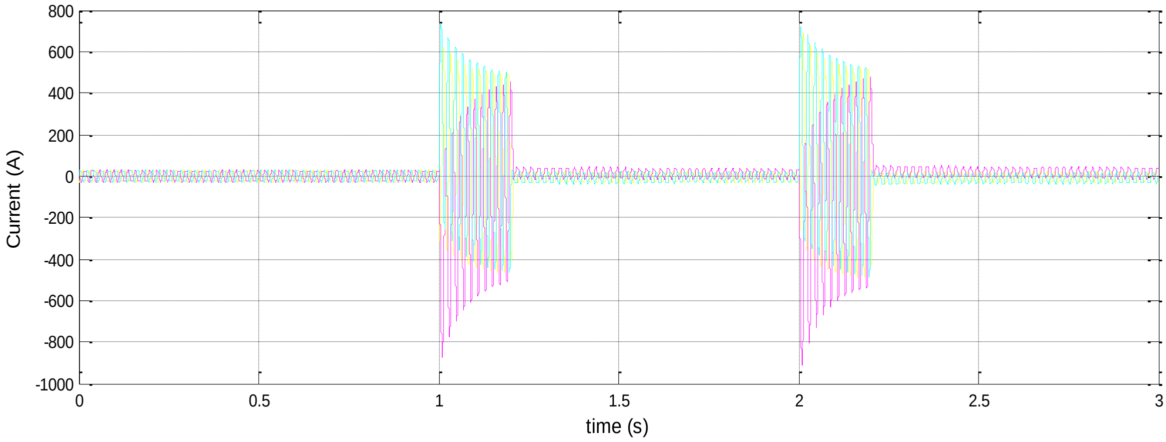


Figure 4.23: Current measurement at B 3 with and without connection of DG 2, in event of fault applied in line 3.

Figure 4.24 displays the increment in fault level at t = 2 s due to connection of DG 2, which is comparatively higher than the fault level at t = 1 s before the connection of DG 2.

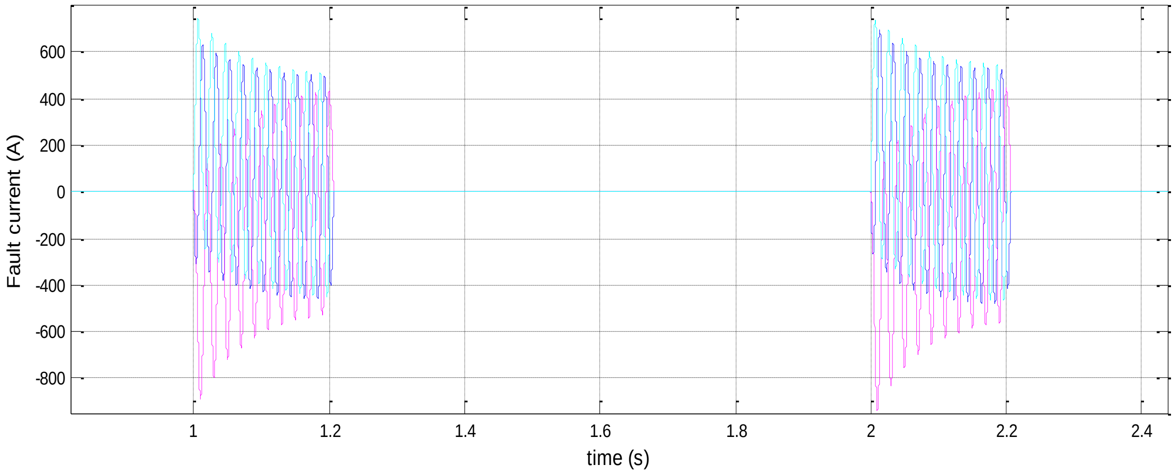


Figure 4.24: Fault current measurement at the fault location.

4.12.3 Case 3 (Only DG3 is connected)

The model in Figure 4.25 represents the operation of a three phase fault implemented in line 3 with and without the presence of DG 3. A fault temporarily occurred at the middle of line 3.

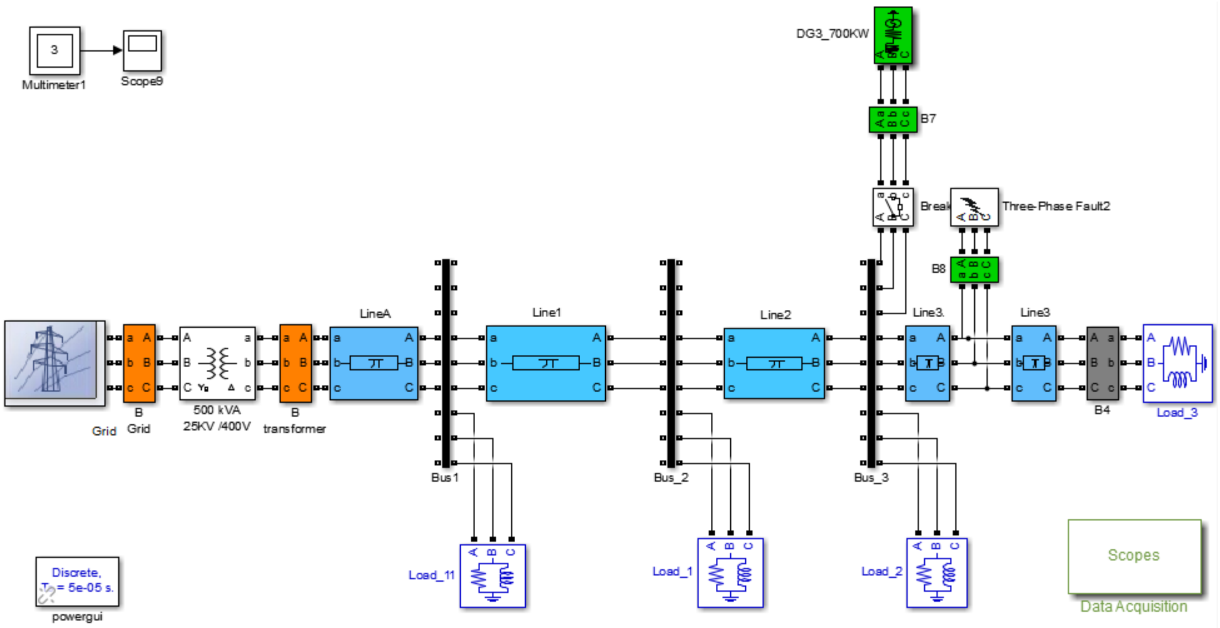


Figure 4.25: EDS with connection of DG 3 at bus 3 and symmetrical fault occurred in line 3.

Figure 4.26 shows the simulation result of EDS with connection and disconnection of DG 3 at bus 3 which can be seen as the change between both cases in the fault current level.

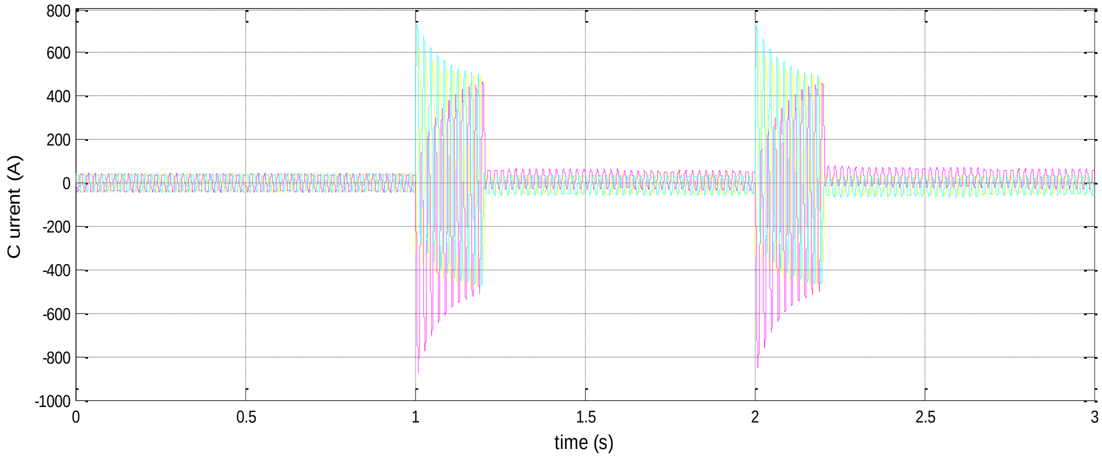


Figure 4.26: The measured current at bus 1.

The temporary fault was simulated at t = 1 s. The nominal current value which was equal to 700 A rose to-900 A. At the time t = 2 s was simulated again in the presence of DG 3. The current measurements at bus 1 are presented in figures 4.26. The current level before connection of DG 3 is higher because the fault was fed by the main source. However, after DG 3 was connected the fault it was fed by it, because DG 3 was closer to the fault location than the main source. The levels of current flow are presented in figure 4.26.

Figure 4.27 shows current level measurements during the fault conditions at bus 2, in both the connection and disconnection of DG 3.

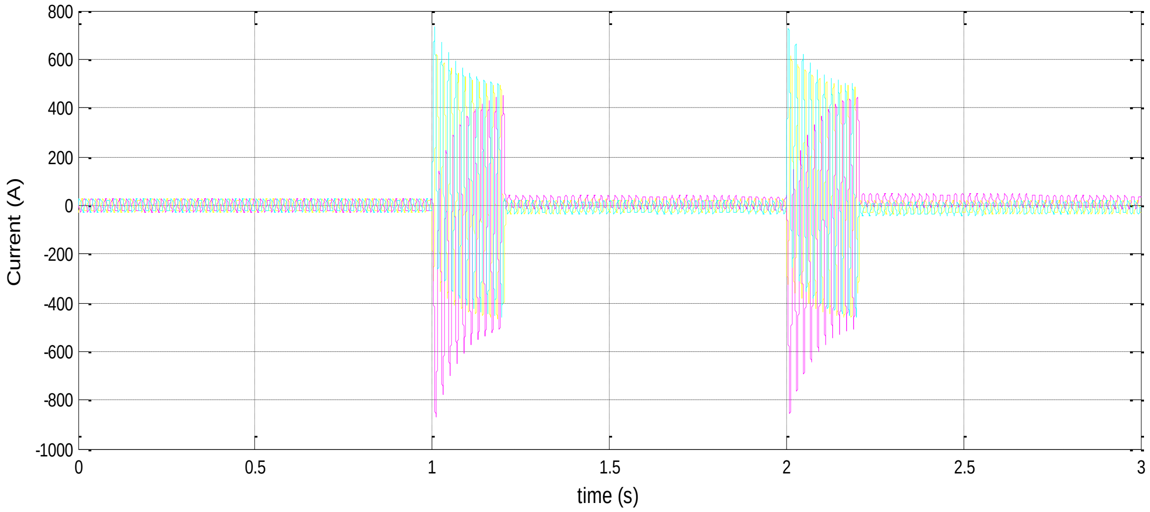


Figure 4.27: Current level measurements during the fault conditions at bus 2.

The measurements at bus 3 were completely different from the measurements at bus 1 and bus 2. When DG 3 was located at bus 3, the current measured there before DG 3 was connected at t = 1 s, would be less than the current measured after connection of DG 3 at t = 2 s. This alteration is thought to be mostly due to the contribution of DG 3 in the fault current level. Figure 4.28 demonstrates the current level measurements during the fault conditions at bus 3. Figure 4.29 shows the fault current measurements at the fault zone.

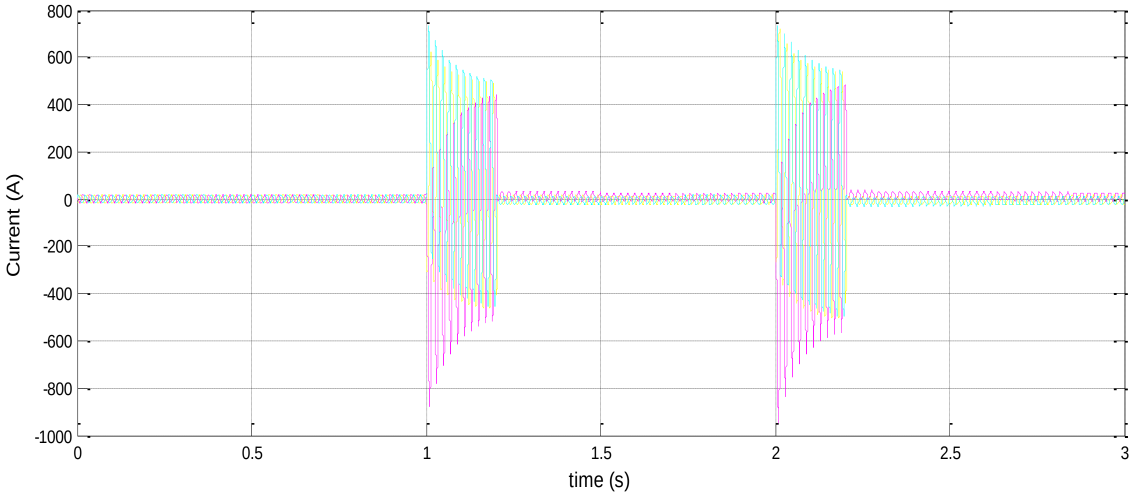


Figure 4.28: Current level measurements during the fault conditions at bus 3.

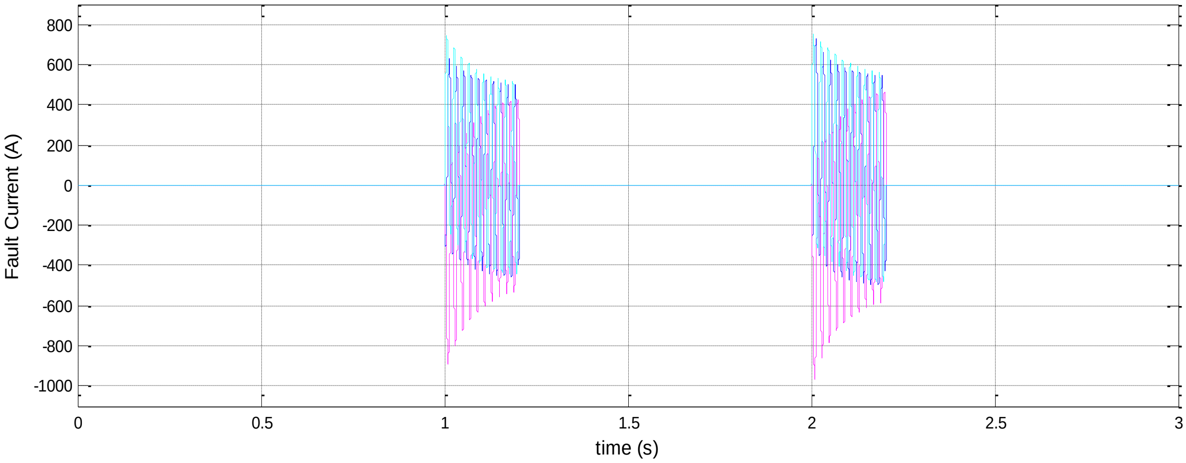


Figure 4.29: Fault current measurement at fault zone with connection and disconnection of DG 3

4.12.4 **Case 4 (the three DGs are connected)**

The model in figure 4.30 displays the three DGs; DG 1, DG 2 and DG 3 are connected respectively to buses B1, B2 and B3, also when a temporary fault current occurred at the middle of line 3.

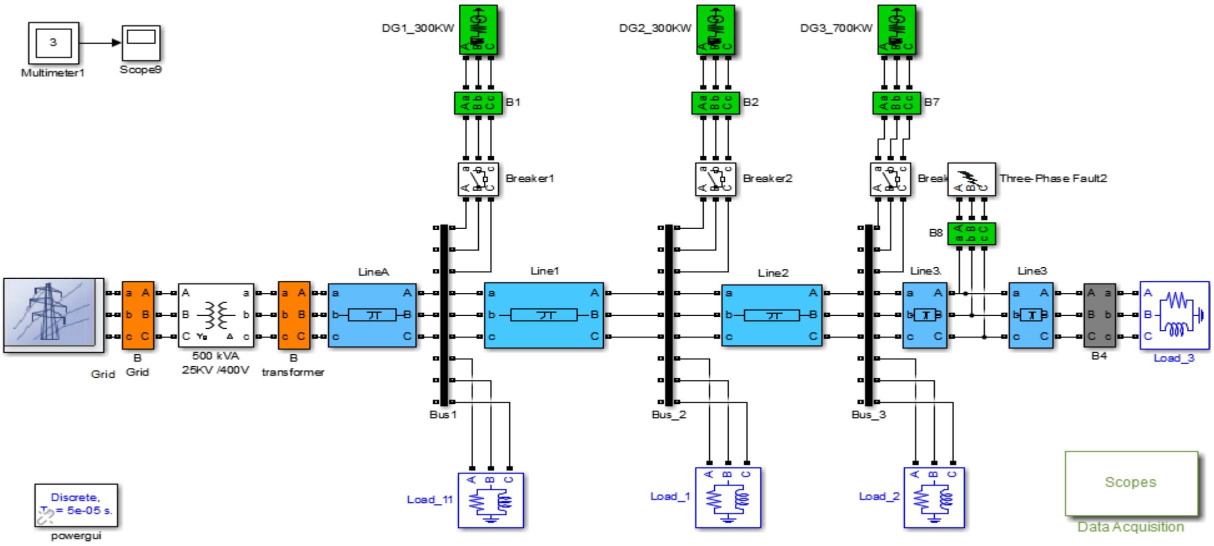


Figure 4.30: EDS with connection of DG1, DG2 and DG3 and a symmetrical fault is applied on line 3.

The contribution in the fault current level due to the connection of the three DGs, is apparent in figure 4.31 at t = 1s. The simulations were done in both cases, with and without DGs connected, and it can be seen that the fault current level at t = 2 is greater than the fault current level at t = 1s, where DGs were connected at t = 1 s and were not connected at t = 2 s. Figure 2.31 illustrates the simulation results of the above case model.

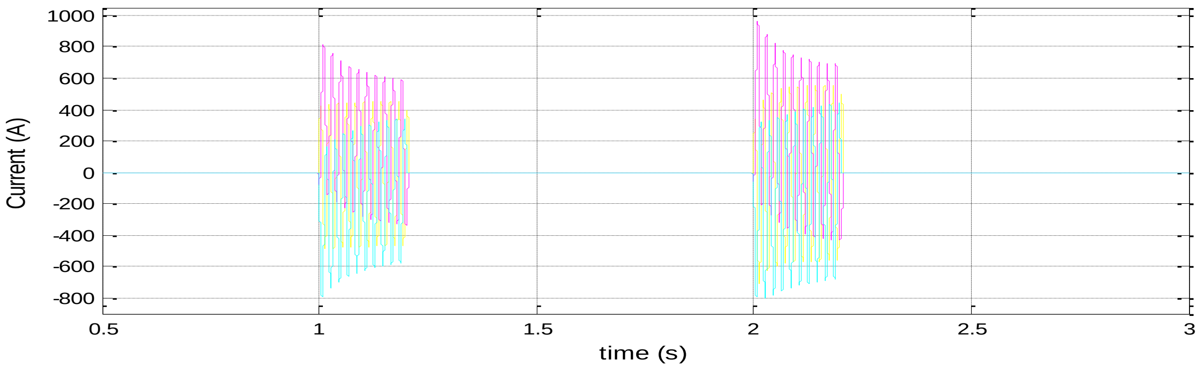


Figure 4.31: The result of a fault current at the fault location in both disconnection and connection of 3 DGs at t = 1 s and at t = 2 s, respectively.

Figure 4.32 indicates the current measurements taken on the bus transformer during both connection and disconnection of the DGs. In the second case, when the fault was applied at t = 2, as shown in the graph, the current fault level was smaller than the current level at t = 1 s, because the fault was fed by the main source only. After connection of the DGs the fault was fed by both the main source and the DGs, which lead to an increase in the fault current level.

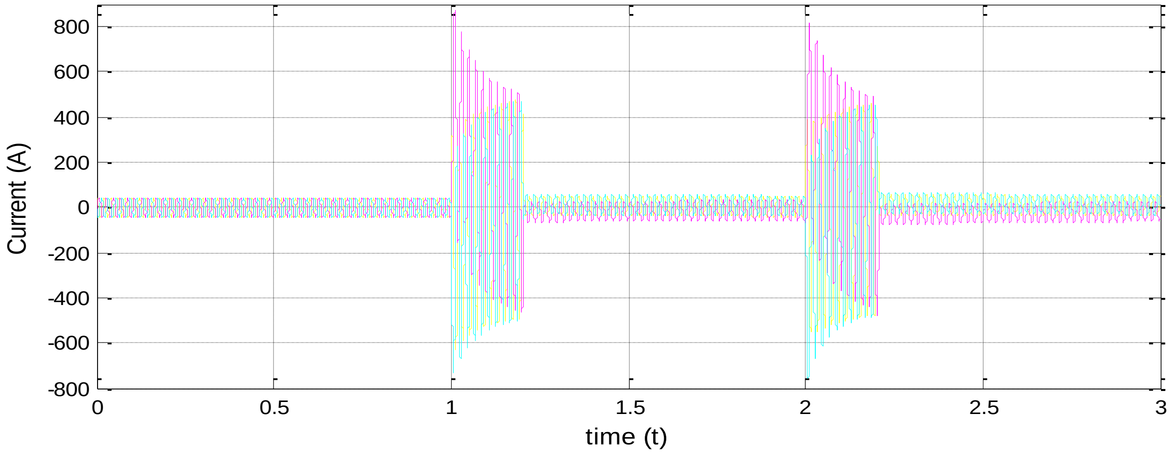


Figure 4.32: Current measurements taken on a bus transformer while the fault is applied

There is a slight voltage drop as can be seen in figure 4.33 at t =1 s and at t = 2 s due to the fault current at those two period ranges. Figure 4.33 demonstrates voltage measurements taken at the bus transformer during the fault application at t =1 s and t = 2 s.

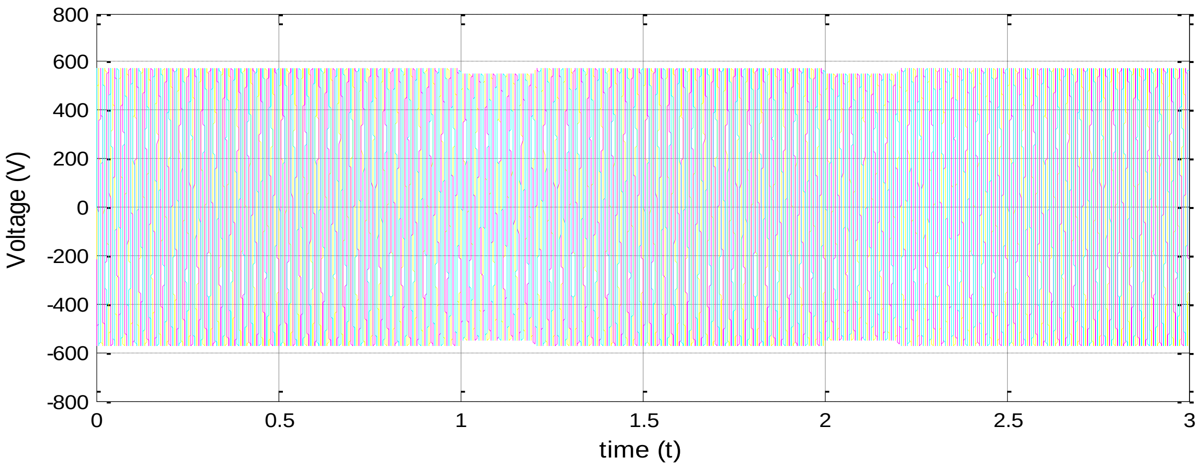


Figure 4.33: Voltage measurements taken at the bus transformer during the fault application at t =1 s and t = 2 s

However, if we maximize the graph below we can see the improvement in voltage during the second period at t = 2 s, compared to the first period at t = 1 s, which shows that the connection of DGs is useful for the voltage during the fault conditions and it may assist in keeping the voltage at an acceptable range, which will not affect the customer further away from the fault zone. Figure 5.6 in the appendix shows the maximization of voltage measurements taken at the bus transformer.

4.13 Scenario 2

4.13.1 Case 1 (the fault is applied on line 2)

.In this scenario the same EDS model is used and the fault is applied on line 2 instead of line 3. With connection and disconnection of the three DGs only, The same cases will be simulated. Only connection and disconnection of the three DGs cases will be discussed while other cases will be mentioned later in the appendix.

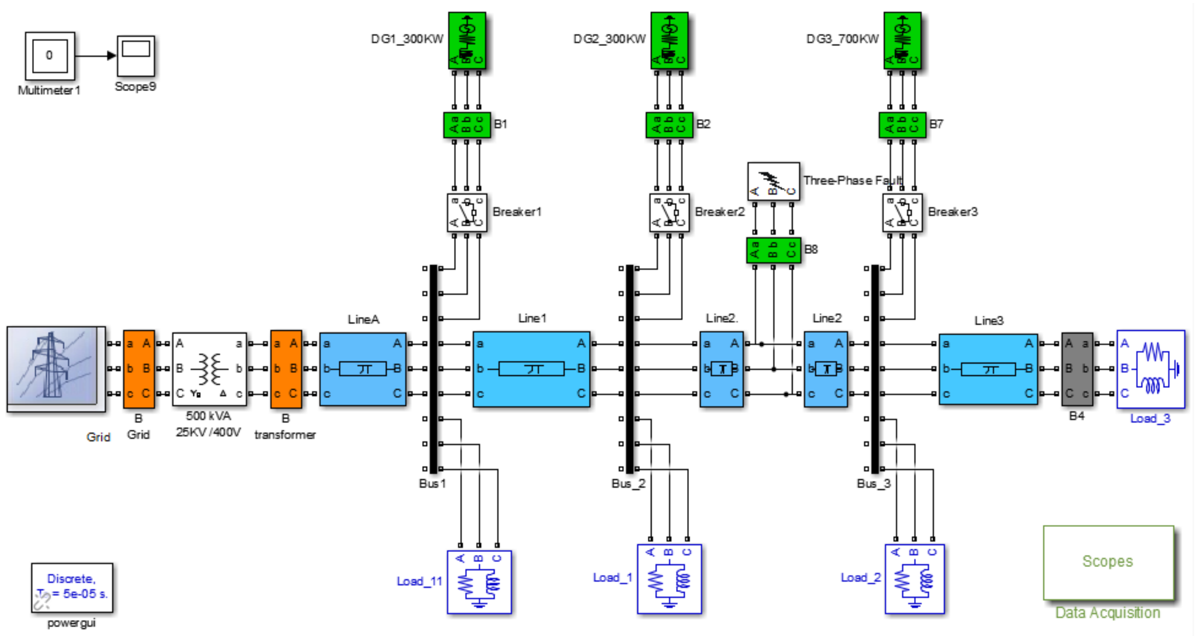


Figure 4.34: EDS model and three phase fault implemented in line 2.

Figure 4.34 illustrates the EDS model and the three phase fault applied in line 2. The implementation is done for only two cases of connection and disconnection of the three Combined DGs and the simulation result is given in one graph as for the work done previously.

The simulation result of the EDS model in figure 4.35 shows that the fault current level at t = 1 s is much higher than the fault current level at t =2, which indicates that the fault was supplied by the grid only, whilst the fault was supplied by both in the second period.

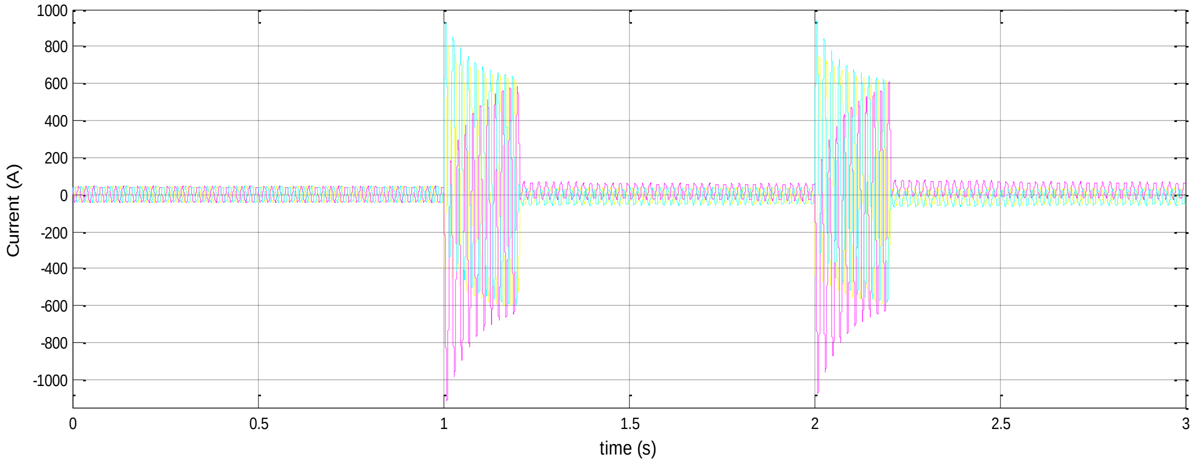


Figure 4.35: Current measurement at bus 1, at t = 1s, 3 DGs are disconnected and t = 2s 3 DGs are connected

The fault current levels in both cases are not the same as seen in figure 4.36, which refers to the measured current at the transformer bus. The fault current level at t = 1s in the case of disconnection, and the current is higher than the fault current level at t =2 s at reclosing. This action indicates that the main power supply was feeding the fault in the first case.

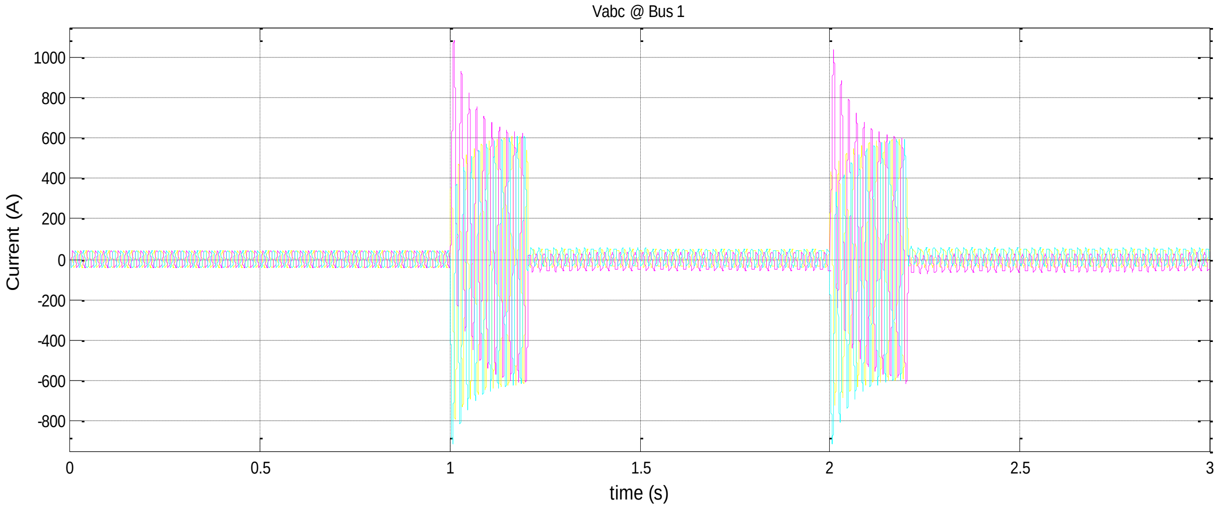


Figure 4.36: fault current measurement at transformer bus with and without connection of the three DGs

Figure 4.37 shows the fault current at fault location which indicates the increment of the fault level at t = 2 s when the three DGs were connected, which is greater than the fault current level at t = 1 s, which means the DGs contributed to the fault current level.

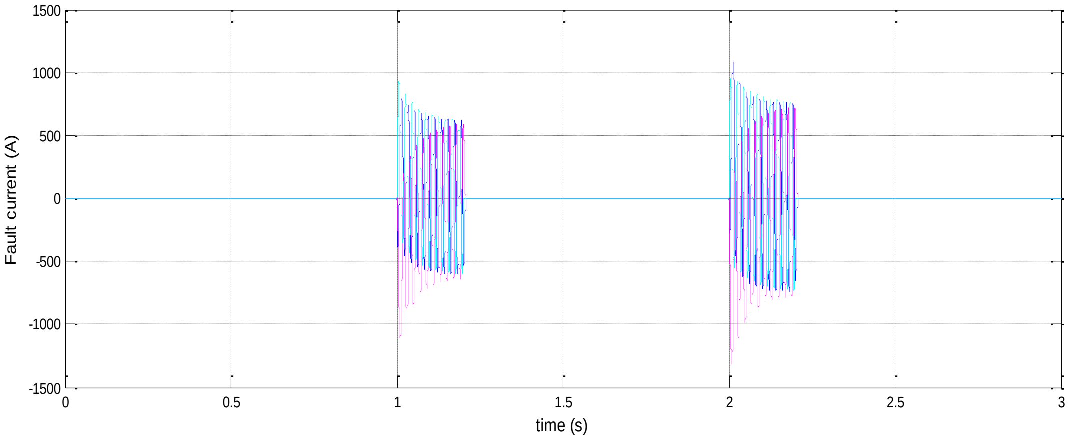


Figure 4.37: Fault current at fault location with and without use of 3 DGs.

The measured currents flow through the bus grid as shown in figure 4.38. This figure illustrates the fault current level without connection of DGs at t = 1 and is slightly more than the current level at t = 2 s. An increment in fault level due to integration of DGs can be seen by the protective devices in this case at the farther power source slightly lower.

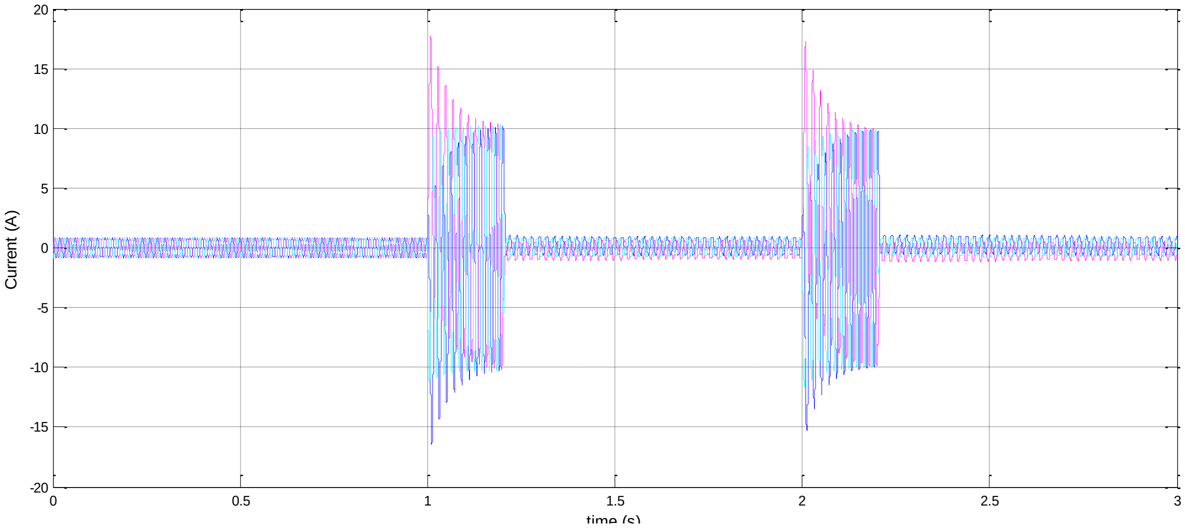


Figure 4.38: Fault current measurements at bus grid.

4.14 Scenario 3

4.14.1 **Case 1 (the fault is applied on line 1) with connection and disconnection of DG3.**

Scenario 3 is smaller than scenario 2. The only difference is that the fault is applied in the middle of line 1 instead of line 2. The same EDS model is used and the same cases will be simulated. The discussion of the simulation will only focus on the connection and disconnection of the three DG cases, while other cases will be mentioned later in the appendix as well.

Figure 4.39 depicts EDS model with three phase-ground faults implemented in line 1.

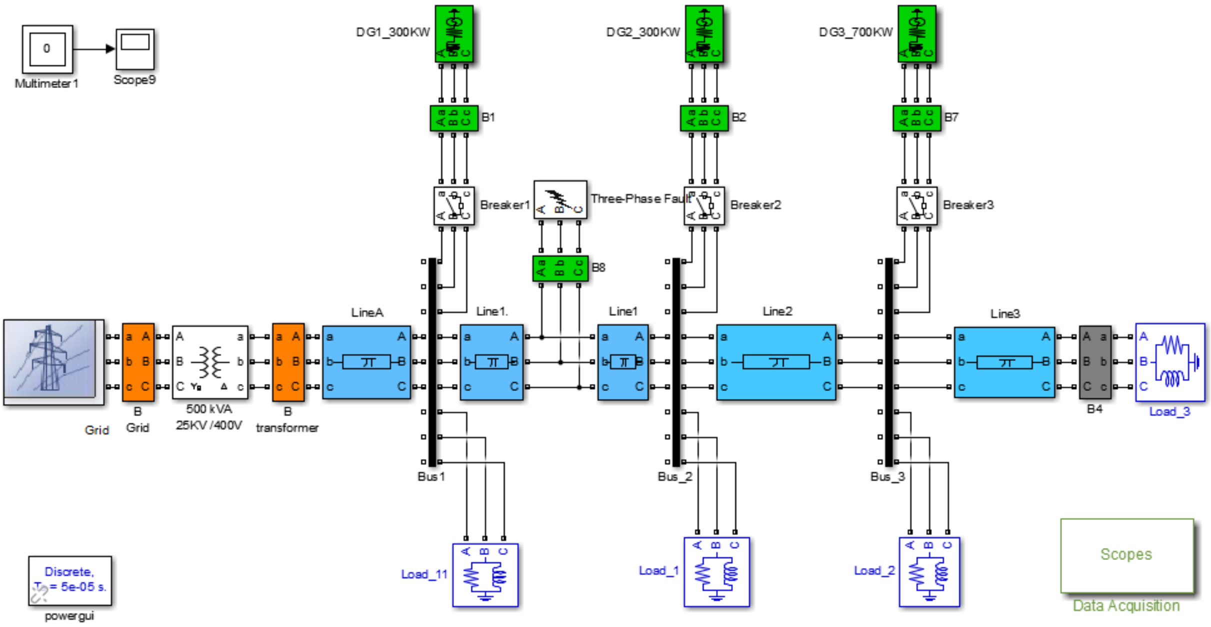


Figure 4.39: EDS model with three phase-ground faults implemented in line 1.

Figure 4.40 shows the simulation results of three phase-ground at line 1, which displays the difference between the fault current level in the case of connection and disconnection of DGs. The increment in the fault current level after the connection of the three DGs can be seen.

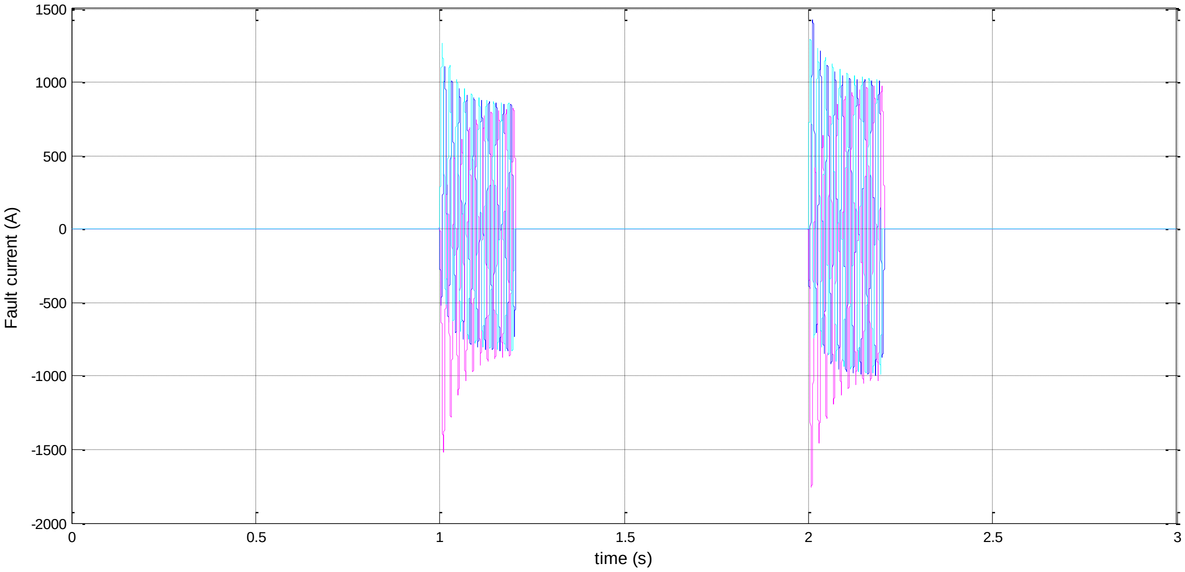


Figure 4.40: Fault current level measurements at fault location.

4.15 Summary

This chapter outlines an investigation of fault current contribution scenarios, for power distribution in the presence of a distributed generation system, using MATLAB/Simulink model in a wide area system. The investigation has successfully identified the increment in fault current level due to the connection of DGs in power distribution interconnected systems. The investigation was based on measured current at different locations under different conditions and compared the simulation results. The results were displayed in one graph in order to show the differences between them. The idea was implemented and investigated using the powerful MATLAB/Simulink package. Power system configuration, fault detection, fault calculation, discrimination, and classification were achieved through the MATLAB/Simulink program.

CONCLUSION

In this research study there were two objectives: Firstly, to establish an algorithm for operating limits imposed by the increment of fault current levels. Secondly, to investigate the contribution of distribution generation in fault current levels, under different configurations and penetration levels of DG, on the protection of distribution systems. In this investigation different size of distribution generations were used.

The purpose of doing this research was to investigate the contribution of distributed generation in fault current level in power distribution systems. The simulation results indicate that DG can have a positive or negative impact on the fault current level in distribution network systems. The DG location and size affect the fault level. In addition, implementation of the protection scheme was performed. The second goal of this research was to suggest a model-based method for the design and implementation of a protection scheme for power distribution systems, by establishing algorithms in some hardware environments. The overcurrent relay was chosen for the model development because it is considered as a simple and popular protection scheme and it is a common scheme in relaying applications. The proposed relay model was tested for fault conditions applied on a simple power system in different scenarios. The overcurrent relay model was implemented in MATLAB/Simulink by using MATLAB programming languages and SimPowerSystem Tool.

A literature review covered the general structure of a power system: firstly, generation system, secondary power transmission system, lastly power distribution system; conventional and non-conventional methods; multi-distribution levels and configuration have been presented in terms of distribution systems; different types of distributed generation, their size and capacity, advantages and disadvantages are mentioned; as well as the energy resources used and the components which are part of a power distribution system. In addition, some of the interconnected interface methods and components used for grid connection application systems have been discussed.

There are many impacts derivable from integration of distributed generation in the power distribution network, where different issues can arise due to this integration of distributed generation in the power system networks mentioned. Other operating issues of distribution protection in the presence of distributed generation, control strategies for distribution power generation, and a protection system for a distribution system has been presented.

As contained in Section 4.2, a simple approach to simulation of an interactive protection system for power distribution system, however the reasons for choosing to model an instantaneous overcurrent relay are: Firstly, it is considered as the simplest protection scheme in protection engineering and it is a common scheme in relay application. Secondly, an overcurrent relay provides protection against overcurrent as the name states. However, the simple operating principle of this relay is that it uses current input from a breaker and compares the measured current values with the present values.

This study used a MATLAB function for collecting the data and issuing the tripping signal. The model was implemented and investigated using the commanding MATLAB code, and Simulink blocks, the programming is done in C++ language, and the first-time user can spend a long time with setting everything under proper control. Power system configuration, fault detection, fault calculation, discrimination, and classification were achieved with the MATLAB/Simulink program.

The investigations including a straight connection of DG have shown that for particular fault current contribution scenarios for power distribution in the presence of a distributed generation system, using MATLAB/Simulink model in a wide area system. The investigation has successfully identified the increment in fault current level due to the connection of DGs in power distribution interconnected systems. The investigation was based on measured current at different locations under different conditions and compared the simulation results. The results were displayed in one graph in order to show the differences between them. The idea was implemented and investigated using the powerful MATLAB/Simulink package. Power system configuration, fault detection, fault calculation, discrimination, and classification were achieved through the MATLAB/Simulink program.

Future work

The proposed model of protection scheme can be used to validate the substation Bus and distribution line, implementation of this protection scheme will be done in a future work.

The investigation of DG contribution in fault current level was done by used a radial distribution configuration in this thesis, and also used symmetrical fault current, however future work could include developments to fit it for ring distribution networks including the single phase connections as outlined, as well different kind of fault current could be implemented.

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APPENDIX

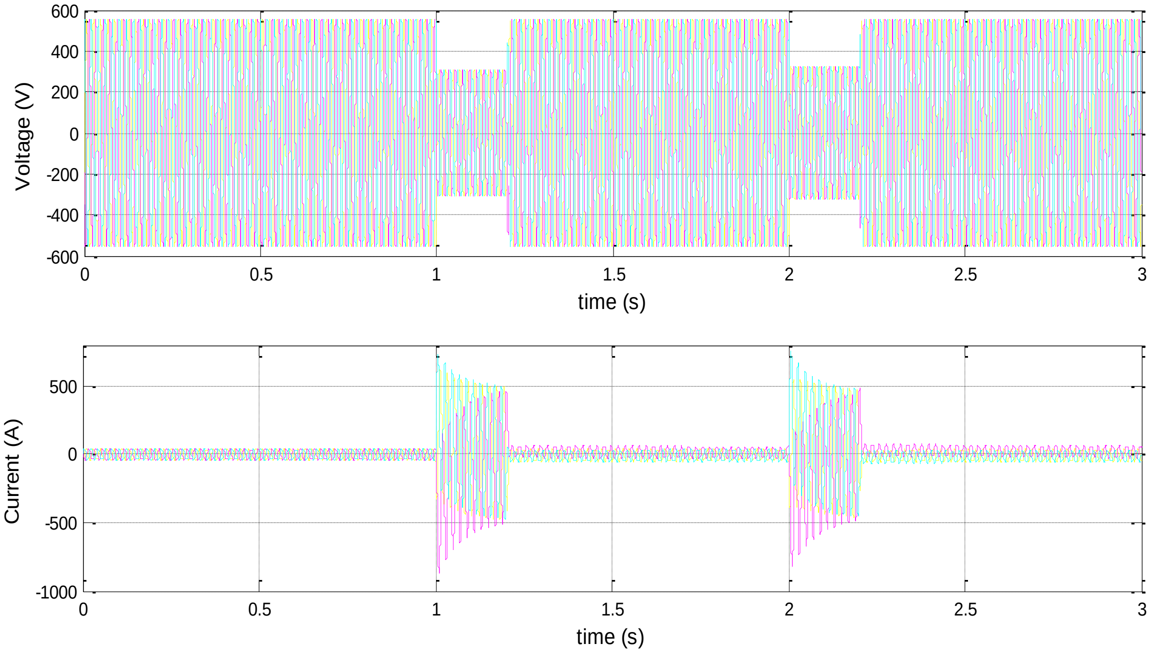

Figure 7.1: Voltage and current measurement at bus 1 in scenario one fault at line three and 3 DG are connected

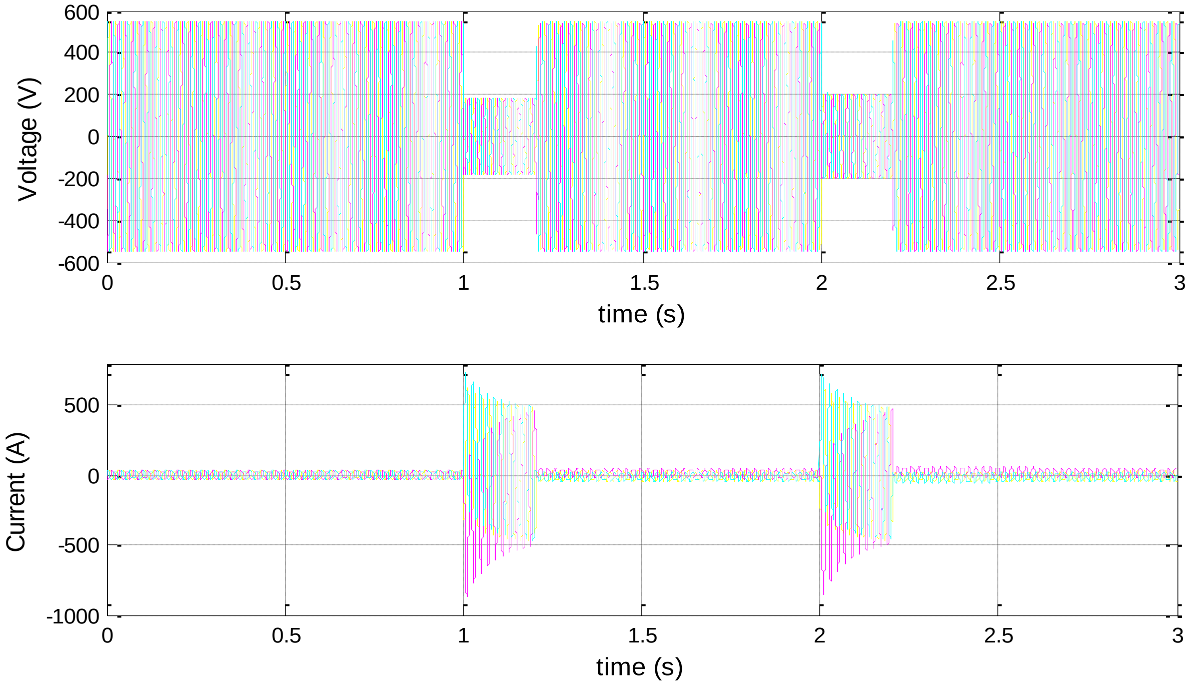

Figure 7.2: Voltage and current measurement at bus 2 in scenario one fault at line three and 3 DG are connected.

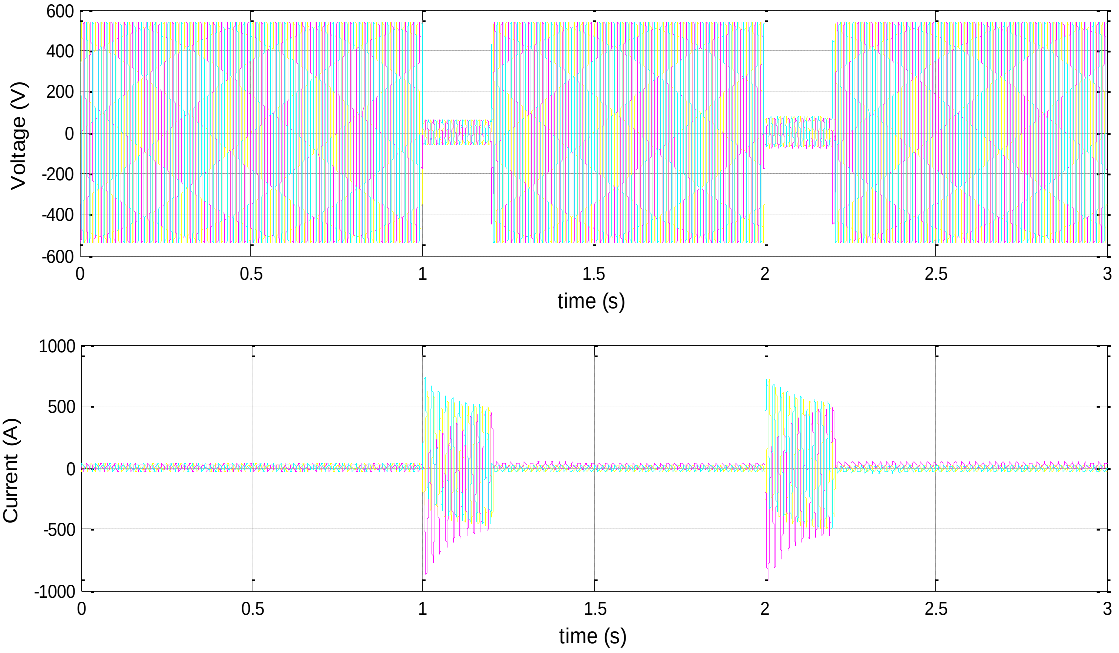

Figure 7.3: Voltage and current measurement at bus Grid in scenario one fault at line three and 3 DG are connected.

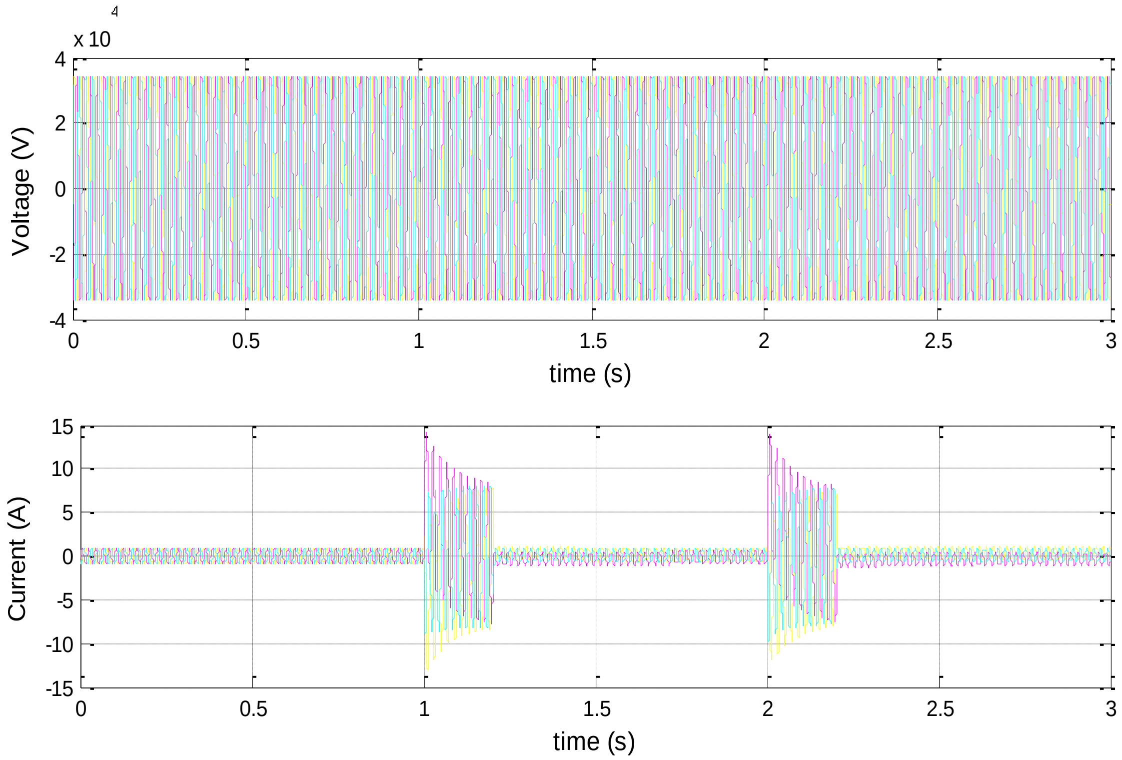

Figure 7.4: Voltage and current measurement at bus Grid in scenario one fault at line three and 3 DG are connected.

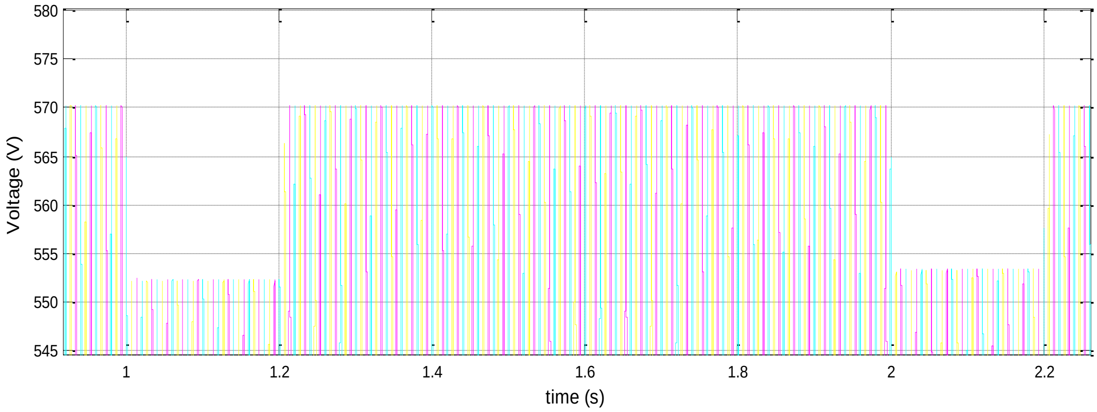

Figure 7.5: Maximization of voltage measurements taken at bus transformer during the fault is applied at t =1 and t = 2, which illustrates the improvement of voltage when the fault is applied.