Assessment of Renewable Energy Resources and the Impacts of Distributed Generation on Power Quality in a Distribution Network

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THIS DISSERTATION IS SUBMITTED TO THE DEPARTMENT OF
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Declaration

I hereby declare that:

(i) This dissertation is my own unaided work, both in conception and execution, apart from the normal guidance of my supervisors. Where collaboration with other people has taken place, or material generated by other researchers is included, the parties and/or materials are indicated in the acknowledgements or are explicitly stated with references as appropriate.
(ii) Except as stated below, neither the substance nor any part of the dissertation has been submitted in the past for a degree at this University or any other University.
(iii) I am now presenting the dissertation for examination for the MSc (Eng) Degree

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Akinyemi Ayodeji Stephen **Date**

Dedication

To
My wife, Oluwatoyin Rhoda AKINYEMI

Acknowledgements

I give glory, honour and adoration to God almighty for his infinite mercy and unmerited favour he bestowed on me before, during and after the completion of this programme, may his name be praised for evermore.

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Abstract

For many years, power systems were vertically operated; large power generation plants produced all of the electrical power. This kind of generation is often related to adequate geographical placement such as water sources, coal sources etc. The power is then transmitted towards large consumption centres over long distances using different high-voltage transmission levels. This operating structure was built on the basis of economy, security, and quality of supply. This very centralized structure is operated by hierarchical control centres and allows the system to be monitored and controlled continuously. The generation is instantly adjusted to match consumption by monitoring the frequency, on the basis of very elaborate load forecasting models. The voltage is also controlled to be within specific limits by means of appropriate coordination of devices such as, generators, online taps changers, and reactive compensation devices. The power system operation is changing due to the restructuring and continuous growth in the demand however, due to major changes in the legislative framework for the power sector and the fast movement towards liberalization of the electricity markets, renewable energy sources were introduced to distribution systems. These units are of limited size (2 MVA or less) and can be connected directly to the distribution network or on the customer side of the meter.

Efforts to reduce CO_2 emissions related to electricity generation, and to reduce fuel imports, have led to a significant increase in the deployment of renewable energy generation technology. Renewable energy sources (RES) are predicted to play a key role in the power distribution systems; they are the key to a sustainable energy supply infrastructure because of their inexhaustible and none polluting nature. However, the integration of renewable energy resources create special technical and economical challenges that have to be comprehensively investigated in order to facilitate the deployment of these renewable energy sources units in the distribution system.

This dissertation investigates the renewable energy resources, types, advantages and disadvantages of renewable energy resources, the prospects of renewable energy resources in South Africa and Nigeria, challenges facing the integration of renewable energy resources into the distribution network. The simulation work covered the impacts of renewable distributed generation on a distribution network, the wind energy converter used is doubly fed induction generator which is modelled in both PSCAD/EMTDC and MATLAB/SIMULINK. The research investigation covered in the dissertation are the impacts of WEC on locations, voltage profiles, voltage swell/rise, voltage dips, harmonic injections and voltage flickers. The overall results show that WEC impacts can be positive and negative on the network; positive impacts in the sense that, the connection of DGs to a distribution network can improve the voltage profiles, reduce the voltage dips or voltage drops as a result of grid disturbance or large load switching, minimize voltage flickers and strengthen the network. While the voltage instability as a result of grid disturbance, the voltage rise and contributions to harmonic injection into the network are some of the negative impacts of the WEC. The proper placement and coordination of DGs in a distribution network can offer more advantages than the disadvantages they have.

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Nomenclature

AC	alternating current
AHP	Analytic Hierarchy Process
AVR	automatic voltage regulator
CDM	Clean Development Mechanism
CHP	combined heat and power
CS	Constant speed
CSIR	Council for Scientific and Industrial Research
CSP	Concentrating solar power
CTF	Clean Technology Fund
DC	Direct Current
DEC	Demand for Energy Control
DFAG	Doubly Fed Asynchronous Generator
DFIG	Doubly Fed Induction Generator
DFIs	Development Finance Institutions
DG	Distributed generation
DoE	Department of Energy
DSM	Demand side management
DSM	Demand side management
DTP	Dynamic tidal power
EFO	Energy for Opportunity
EIA	Energy Information Administration
IEA	International Energy Agency
EMS	energy management system
FACTS	flexible alternating current transmission system
FIT	Feed-in Tariff
FSWTs	fixed speed wind turbines
GWEC	Global World Energy Council
GUI	graphical user interface
HAN	Home Automation Network
HAWT	Horizontal Axis Wind Turbine
HD-PLC	High definition power line communication
HVDC	High voltage direct current
IDZ	Industrial Development Zone
IRES	Integrated renewable energy systems
IRP	Integrated Resource Plan
ITU-T	International Telecommunication Union Telegraphique
KVA	kilo volt ampere
LTWP	Turkana Wind Power
MATLAB	matrix laboratory
MVA	mega volt ampere

MV	Medium voltage
MW	Megawatt
kW	kilowatt
W	Watt
NERC	national energy regulatory commission
NESCO	the Nigerian Electricity Supply Company
NT	National Treasury
OPF	optimal power flow
OWC	Oscillating Water Columns
PCC	point of common coupling
PLCs	Power line communications
POC	point of connection
PPF	palm press fibre
PSCAD	power system computer aided design
PSPC	Partial Scale Power Converter
PU	per unit
PV	Photovoltaic
RAS	remedial action scheme
RE	renewable energy
REFIT	the Renewable Energy Feed-in Tariff
REIPPPP	Renewable Energy Independent Power Producer Procurement Programme
RES	Renewable Energy Summit
RET	renewable energy technologies
RPP	Renewable power plant
SCADA	supervisory control and data acquisition
SCR	Short circuit ratio
SERC	Sokoto Energy Research Centre
SO	system operator
SPS	Special Protection System
STATCOM	static synchronous compensator
SVC	static Var compensator
SWH	Solar Water Heaters
TW	Terawatt
TCSC	Thyristor controlled series compensator
TSC	Thyristor switched Capacitor
TSG	Tidal stream generators
WEC	Wind energy converter
VAWT	Vertical Axis Wind Turbine
VS	Variable speed
VSWT	Variable Speed Wind Turbine
WEC	wind energy converter

WEFs	wind energy facilities
WECS	wind energy conversion system
WLAN	wireless local area network
WPPs	wind power plants

Chapter 1

Introduction

1.1 Background

Energy is fundamental to the quality of our lives; any living organism relies on an external source of energy. Nowadays, we are totally dependent on an abundant and uninterrupted supply of energy for living and working. It is a key ingredient in all sectors of modern economies. It is assumed that the energy demand will increase significantly in the future. For an example, in 1980, global energy consumption stood at around 10 TW, if per capita use remained at the same levels as today; by 2025 a global population of 6.2 billion would need about 14 TW an increase of 40 per cent over 1980. But if the energy consumption per head became uniformed worldwide at current industrial country levels; by 2025 that same global population would require about 55 TW [**1**]. How can this huge energy requirement in an environmentally friendly way be achieved?, energy provides us with heat and electricity daily; it powers our industry, transport and modern way of life. A large part of energy in the world has been produced from fossil fuels such as petroleum, gas, coal and oil [**2**]. However, there are many disadvantages of fossil fuels. The common thought is that fossil fuels would run out within the next one hundred years and the world will face energy shortage by 2050. The World Energy Council anticipates the global energy mix will be made up of at least eight energy sources (coal, oil, gas, nuclear, hydro, biomass, wind and solar) and with none expected to have more than a 30 % share of the market [**3**]. The second and most important disadvantage of fossil fuels is the release large amounts of carbon dioxide (CO_2) to the atmosphere, resulting in climate change and global warming issues [**4**]. To reduce these effects, and improve the energy generation system, alternative and reliable sources of energy are to be considered to build effective power systems, reduce pollution and mitigate climate change. Renewable energy sources have gained great importance due to their inexhaustibility, sustainability, ecological awareness and a means to energy security. It is expected to play an important role, especially in electrical energy generation in the next decades [**5**].

The new energy development is drawing the attention of the world, and is going through great changes, from conventional centralized energy generation to the new model of distributed generation (DG) [**6**].

This dissertation presents a comprehensive literature review of renewable energy source and assesses the origin and trend in Nigeria and South

Africa. The dissertation also demonstrates the impacts of the integration of renewable energy source such as wind energy into the grid. In particular, its impacts on voltage and power quality in a distribution system under a variety of conditions are evaluated.

1.2 Objectives of the research

The objectives of this dissertation are:

- *To investigate the various sources of renewable energy, advantages and disadvantages, assess the prospects of renewable energy resources in South Africa and Nigeria.*
- *To review the types and classifications of distributed generation extraction of wind energy, wind turbine configurations, wind energy converter topologies, wind energy converter devices in use and modelling of a doubly fed induction generator.*
- *Overview of power electronic devices at the point of common coupling in power system, the basic principle, types and applications.*
- *To explore the issues and challenges associate with renewable energy integration, the concept of the grid code and its requirement in relation to DGs connection.*
- *To determine the maximum penetration level on the selected buses, investigate the effect of WEC location, determine the impact of WECs at the point of common coupling using MATLAB/SIMULINK and PSCAD/EMTD.*
- *To make comparisons between the simulation results obtained using MATLAB/SIMULINK and PSCAD/EMTD*
- *To investigate the impacts of WECs on harmonics, voltage flicker, dips, and the dynamic response of a STATCOM. The performance of a STATCOM and SVC during fault conditions should also be compared.*

1.3 Methodology

The investigation of the impacts of DG on the power quality of a distribution network is carried out using a standard test system which is the IEEE 13 bus test feeder. MATLAB/SIMULINK and PSCAD/EMTD are used for the network design and modelling of WEC based on doubly-fed induction generators by considering the following:

- The network voltage profile graph is drawn (base case) to know the weakest bus when the WEC is not connected to the network. Some buses and the farthest bus are chosen for WEC connection. Voltage at each bus bar is then measured and plotted to assess the impact of the WEC on the voltage profile of the network in relation to the penetration level.

- Dynamic loads such as arc welding machines are connected to the network. The results are obtained without and with the WEC connection in other to assess the impact of the WEC on voltage flicker of the network. Also, a disturbance is introduced into the system and results are obtained with and without the WEC connected to investigate its impact on voltage dips.
- All the loads in the network are replaced by non linear loads and the Fast Fourier Transform (FFT) of the network voltage and current are analysed to investigate the harmonics generated into the system without and with the WEC connected.

1.4 Scope of the Research

This dissertation covers the assessment of different types of renewable energy resources, prospect of renewable energy resources in South Africa and Nigeria. It is limited to the impacts of renewable distributed generation (wind energy converter using doubly fed induction generator) on voltage profile, voltage dips, voltage flicker and harmonic generation in a distribution network.

1.5 Contribution of the research

The outcome of the research done in this dissertation shows that there are opportunities for Renewable energy resources in Africa, and that theses should be focussed upon. Based on the simulation results in this dissertation, it is advisable for utility companies to draw the voltage profile of any distribution network in order to know the weakest buses. DGs should be connected at the weakest bus at the of the DG network to voltage profiles of the network. The recommendation should be given to the Independent Power Producers that want to connect their DGs to the network, that the power of the DG to be integrated must not be more than the loads in the network to avoid a voltage rise or an over voltage. The point of common coupling should be monitored by installing a voltage control device, either to regulate the voltage at that point or to switch off the generator in case of over voltage or excess generation. Small amounts of WECs power installed in a wrong location can result in an unacceptable voltage profile, whilst large amounts of WECs power installed at strategic locations can improve the voltage profile. The connection of WEC to a distribution network can limit voltage flicker and voltage dips but can contribute to harmonic generation especially if it is a power electronic based DG such as doubly fed induction generator.

1.6 Outline of the dissertation

The dissertation is organised as follows:

Chapter one gives the background, objectives, methodology, scope, contributions to knowledge, and the outline of the dissertation.

Chapter two assesses the various sources of renewable energy, advantages and disadvantages, perspectives on how to utilize renewable energy resources, prospects of renewable energy resources in South Africa and Nigeria.

Chapter three provides basic concept of distributed generation, types, classifications, WEC parts, extraction of wind energy, wind turbine configurations, WEC topologies, wind energy converter devices and modelling of doubly fed induction generator. It provides an overview of power electronic devices in power systems; basic principles, types, and applications; the principle of reactive power compensation, the reasons and need for reactive power compensation, and effect of reactive power on the system operation.

Chapter four discusses the issues and challenges associated with renewable energy integration, deployment of renewable energy resource into the power system and its benefits.

Chapter five investigates the changes in power system operation due to the introduction of distributed generation. It discusses the concept of the grid code and its requirement in relation to DGs connection, and provides a detailed understanding of the software used for the WEC integration and modelling

Chapter six discusses the description of the test system used and compare the network simulated results with previously published results, provides the modifications done to the network and discusses the simulation results obtained using MATLAB/SIMULINK and PSCAD/EMTD. Different simulation scenarios are considered to investigate the impacts of WEC location, penetration level and the point of common coupling.

Chapter seven investigates the behaviour of a distribution network using MATLAB/SIMULINK and PSCAD/EMTD under fault conditions with and without WEC integration and under steady state conditions. Power quality improvement using a compensation device such as a STATCOM is also investigated and comparisons are discussed between the simulation results obtained using MATLAB/SIMULINK and PSCAD/EMTD.

Chapter eight investigates the impacts of WEC on harmonic injection, voltage flicker and dips. The *dynamic response of a STATCOM and a comparison of the performance of a STATCOM and a SVC s during fault conditions to improve power quality are also enumerated.*

Conclusion and recommendation for future work are presented in **chapter nine**

Chapter 2

Renewable energy resources

Introduction

Energy is one of the essential inputs for economic development and industrialization. Fossil fuels are the main resources and play a crucial role to supply world energy demand. However, fossil fuel reserves are limited, and usage of fossil fuel sources has negative environmental impacts. It is the priority subject of the countries in the world to maintain pollution free environment which is a prerequisite for sustainable development and for fighting poverty. The population of a country and the level of energy consumption indicate the level of development in economical, industrial, educational and social ways.

Economic efficiency, energy security, and environmental sustainability are concerns that must be considered in any energy policy of a country. These key aspects remain a challenge currently in Africa and all parts of the world. High energy consumption growth, worldwide rising fossil fuel prices, strong environmental pressure toward reducing greenhouse gas effects, and promotion of renewable energy production have been a common challenge in Africa energy markets. The development of vast unexploited renewable energy resources is also at the centre of attention.

The amount of electrical energy required to improve the basic living environment, both domestic and community, is quite small about 0.3 kWh per person per day [**7**]. This is the energy needed for domestic and portable water pumping, water sanitation, water purification, domestic and community street lighting, and for powering educational, emergency, and communications equipment. Thus, for a village with a population of 500 people, about 150 kWh per day can take care of the basic domestic and community electricity needs. This can be met by employing a combination of devices- wind energy converters, solar cells, micro hydroelectric units, and biogas-fuelled-engine driven generators [**7**]. Experts predict that the price of renewable energy will compete with fossil energy from 2020 [**8**]. This aspect of the dissertation discusses various sources of renewable energy, their advantages and disadvantages.

2.1 Solar energy systems

Solar energy is low density sun's radiation. It can be harnessed using a range of technologies such as solar heating, solar photovoltaic, solar thermal energy. Photovoltaic effect which converts sunlight directly into electricity was discovered in 1839 [**9**]. A photovoltaic cell (PV) cell consists of two or more thin layers of semiconductor material mostly silicon. Electric charges are generated when the silicon is exposed to light and this can be conducted by metal contacts as Direct Current (DC). Multiple PV cells are connected together and encapsulated usually with glass to form a module called 'panel'. The PV panel is the main building block of a PV system and a number of panels are connected together to get the desired electrical output. A solar module for a required voltage is formed by connecting the solar cells in series. To get the required current modules are connected in parallel and this arrangement is called a solar array [**10**]. Photovoltaic is one of the fastest growing technologies in the world with a growth rate of 35-40 % per year [**11**]. The global cumulative installed capacity of the PV plant in 2000 was 1.5 GW while it had increased to almost 70 GW at the end of 2011 with a growth rate of 44 % per year. In 2012, the cumulative installed capacities became almost 100 GW [**11**]

Advantages of solar energy

It reduces greenhouse pollution and its adverse effects; it removes any dependence on fossil fuels and their associated price volatility, it is used in low power consuming device, and rural or remote area where it is too expensive to extend electrical grid power. Many everyday items such as calculators and other low power consuming devices can be powered by solar energy [**12**]

Disadvantages of solar energy

Solar energy can only be harnessed when it is daytime and sunny, solar panels or cells are expensive to manufacture, and cloudy sky reduces their effectiveness.

2.2 Wind Energy System

Wind power is the conversion of wind energy into a useful form of energy (electrical energy), such as using wind turbines to produce electrical power, windmills for mechanical power, wind pumps for water pumping or drainage, or sails to propel ships. A wind farm or wind park is a group of wind turbines in the same location used to produce energy. Wind energy as a renewable energy is infinite, naturally replenished energy generated from natural resources such as wind or air flow which can be extracted using wind turbines. Wind energy is currently the second most commercially deployed renewable energy after hydroelectric energy. Wind power, as an alternative to fossil fuels, is plentiful, widely distributed, produces no greenhouse gas emissions during operation and the wind turbine installation can cover little portion of land [**13**]. Wind energy is a source of renewable energy which comes from the air current flowing across the earth's surface, wind turbines harvest this kinetic energy and convert it into electrical power, the generated power or electricity is sent through transmission and distribution lines to customers [**14**]. In 2010 wind energy production was over 2.5 % of total worldwide electricity usage, and growing rapidly at more than 25 % per annum [**13**]. The effects on the environment are generally less problematic compared to the conventional method of energy generation.

Advantages of wind energy

The wind turbine can be very tall; each takes up only a small land area, this means that the land below can still be used, especially in the agricultural areas, as farming can still continue. In remote areas that are not connected to the electricity, wind turbines can be used to produce electricity supply. Wind turbines are available in a range of sizes which means a vast range of people and businesses can use them.

Disadvantages of wind energy

Wind resources are erratic and can be used only at certain speeds, the environmental impacts of wind energy can include noise, visual pollution and negative impacts on bird, 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 [**15**].

2.3 Geothermal Energy

Most of the energy resources used in the world at present (86 %) come from finite energy sources embedded in the crust of the Earth (oil, gas, coal, and uranium). Only one energy resource of the crust is renewable, namely geothermal energy. The word "Geothermal" comes from the combination of the Greek words Geo, meaning earth, and therm, meaning heat. The source of geothermal energy is the continuous energy flux flowing from the interior of the earth towards its surface. Geothermal energy can be described as natural heat extracted from the crust, which comes from lava inside the earth in the form of heat. Energy contained in hot rock can be converted by using water to absorb heat from the rock and transport it to the earth's surface, where it is converted to electrical energy through turbine-generators. Not all geothermal energy is used to make electricity. Some of it is actually used directly to heat houses, the power plant then uses nearby clean water source to heat up with the underground steam [**16**]. The geothermal energy source is contained underground and needs not to be exposed to the atmosphere. The surface energy conversion equipment is relatively compact, therefore making the overall footprint of the entire system small. According to calculations, the geothermal energy is as rich as 12.588 X 10^{20} MJ in calories, only on the crust surface within 10 km, which is equivalent to 200 times coal heat of all the world's reserves [**17**].

Advantages of geothermal energy

It has a relatively low environmental impact; its cost is extremely low compared to many other energy sources. It has low pollution compared to fossil fuels and nuclear energy. Geothermal heat pump systems can reduce energy use by storing heat from the summer/sun and makes use of it in the night and winter. It has low maintenance systems [**17**]

Disadvantages of geothermal energy

The most important disadvantage is absolutely the geological problem, some geothermal plants use a lot of water and it needs to go somewhere after use. Polluting chemicals in that water and steam are sulphur, mercury, hydrogen sulphide, arsenic and ammonia. It can cause earthquake. It cannot be transported over vast distances, if it is used to heat up houses or for hot tap water, it is only the quality of the pipe that delivers the water that determines how far it can go and if it will be of any use when it arrives. Composition of the chemicals can vary, but it is always a problem, they need to heat up clean water to use and do not use it directly for heating of houses. In cases where it has been used directly, it causes pipes to corrode. In nuclear heating rock, the rock cools down over a few decades and hundreds of years are needed to get initial heating back [**16**]. Geothermal heat pump systems have high installation cost, some areas run out of water or run low on ground water during seasonal dry spells, less water means less heat and less energy to produce. Some drilling sites are too hot to handle.

2.4 Biomass Energy System

Biomass can be described as biological material derived from living organisms. It refers to plants or plant-based materials which are specifically called lignocelluloses, means plant dry matter. Biomass gets energy from the sun. During photosynthesis process, sunlight gives plants the energy they need to convert water and carbon dioxide into oxygen and glucose (sugars). These sugars supply plants, animals and humans that eat plants with energy. Biomass is a renewable energy source because more trees and crops are planted and wastes always exist [**18**].

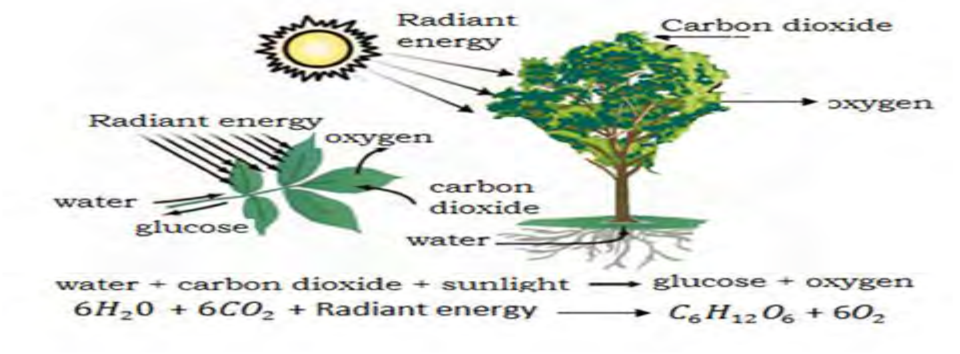


Figure 2.1: Photosynthesis and energy stored in plant

As an energy source, biomass can either be used directly via combustion to produce heat, or indirectly after converting it to various forms of bio-fuel. Biofuel is a fuel that contains energy from geologically recent carbon fixation. Conversion of biomass to bio-fuel can be achieved by different methods which are broadly classified into: thermal, chemical, and biochemical methods. Wood remains the largest biomass energy source today; examples include forest residues (such as dead trees, branches and tree stumps), yard clippings, wood chips and even municipal solid waste. It can be grown from numerous types of plants, including miscanthus, switch grass, hemp, corn, poplar, willow, sorghum, sugarcane, bamboo, and a variety of tree species, ranging from eucalyptus to oil palm [**19**]. Solids oil palm biomass in the form of empty fruit bunches (EFB), palm press fibre (PPF), palm kernel shell (PKS), palm trunks and fronds has been identified as one of the main sources of renewable energy with great potential in Malaysia.

Advantages of biomass energy

Biomass energy, for the most part, creates no harmful carbon dioxide emissions, but captures carbon dioxide for its own growth, Carbon dioxide released by fossil fuel is released into the atmosphere and are harmful to the environment. Biomass products are abundant and renewable. Since they come from living sources, life is cyclical, these products potentially never run out, so long as there is something living on earth and there is someone there to turn that living things components and waste products into energy. Another benefit of this energy is that it can take waste that is harmful to the environment and turn it into something useful, Ethanol and similar fuels can be made from corn and other crops [**20**]. It can be used to generate electricity with the same equipment or in the same power plants that are now burning fossil fuels. Its energy is not associated with environmental impacts such as acid rain, mine spoils, open pits, oil spill, radioactive waste disposal or the damming of rivers. Biomass is easily available and can be grown with relative ease in all parts of the world [**21**]

Disadvantages of biomass energy

It is expensive, living things are expensive to care for, feed and house and all of that has to be considered when trying to use waste products from animal for fuel. Ethanol, as a biodiesel is terribly inefficient when compared to gasoline, it is harmful to combustion engines over long term use. Using animal and human waste to power engines may save on carbon dioxide emissions, but it increases methane gases, which are also harmful to the earth's ozone layer. Using waste products, there is the smell to consider. While it is not physically harmful, it is definitely unpleasant, and it can attract unwanted pests (rats, flies) and spread bacteria and infection. Using trees and tree products to power machines is inefficient as well. It also creates environmental problems of its own [**20**]. To amass enough lumber to power a nation full of vehicles or even a power plant, companies would have to clear considerable forest area. This results in major topological changes and destroys the homes of countless animals and plant. The combustion of biomass products requires some land where they can easily be burnt.

2.5 Wave Energy System

Wave energy refers to the extraction of electricity from the up-and-down motion of ocean waves. The energy of water in motion is tremendous for water at sea level is about 800 times denser than air, it displaces more mass as it moves, it is clean and renewable. Unlike coal, oil, and gas, which currently account for more than two-thirds of electricity generation and whose burning is the major contributor to global warming and a variety of public health and environmental concerns, wave energy production is not related to the emission of any harmful gases. It has been estimated that the clean generation of 7 megawatt hours of electricity by a wave energy device will offset the release of about 10,000 tonnes of carbon dioxide every year. It is a local resource that doesn't have to be imported and has low transmission costs [**22**].

Wave height is determined by wind speed, the duration of time the wind has been blowing, fetch (the distance over which the wind excites the waves) and by the depth and topography of the seafloor (which can focus or disperse the energy of the waves [**23**]. Power is determined by wave speed, wavelength, and water density. Waves in the oceans can travel thousands of miles before reaching land, it ranges in size from small ripples to huge waves over 30 m high. Waves are a result of the effects of wind on the oceans and seas. The highest concentration of wind power is found in the windiest areas, which are mainly between latitudes 40 and 60 in both northern and southern hemispheres [**24**]. The potential of worldwide sea wave energy contribution is estimated to be about 10 % (2 000 TWh/year) of the total energy consumption. Despite the obvious progress made in recent years, wave energy conversion technologies are still very much in their infancy [**25**].

Advantages of wave energy

It is clean and renewable; its production is not related to the emission of any harmful gases, it is a local resource that doesn’t have to be imported and has low transmission costs, it will help to curb air pollution and it can be easily predictable

Disadvantages of wave energy

It is difficult to obtain maximum efficiency because of irregularity in wave direction, amplitude and phase. Problem of coupling irregular, slow motion of wave to an electrical generator and very high loading in the case of extreme weather conditions is also associated with wave power(hurricanes) over 100 times higher than average conditions [**26**]. Only power plants and towns near oceans will benefit directly from it because of its source, it is not a viable power source for everyone.

2.6 Tidal Energy System

The tide is the rise and fall of sea levels caused by the combined effects of the gravitational forces exerted by the moon and the sun and the rotation of the Earth. Tidal Power is the generation of electrical power through the harnessing of the ebb and flow of the tides. Due to the strong attraction to the oceans, a bulge in the water level is created, causing a temporary increase in sea level. When the sea level is raised, water from the middle of the ocean is forced to move toward the shorelines creating a tide. Tidal energy or tidal power is a renewable energy source that converts the energy of tides or tidal flows into useful forms of power mainly electricity. Its power is practically inexhaustible [**27**]. Tidal power production applies the same principles as hydroelectric power generation, except that tides flow in both directions and generators are designed to respond to two directional water flows [**28**]. A barrage, which is in fact a huge dam, is built across a river estuary or bay, this barrage has gates in it which allow the water to flow into the barrage with the incoming tide. These gates are then closed when the tide begins to go back. This water, which is now trapped inside the barrage, is now called a ‘hydrostatic head’. The greater the head the more power can be generated from the water flowing out. There are other gates within the barrage which are now open; these gates contain hydroelectric generators, very similar to the ones used in hydropower. These generators are now turned by the out flowing water and power is generated.

Advantages of tidal energy

It is very cheap to maintain, there is no waste or pollution, very reliable, it can be predicted when the tides will be in or out, the barrage can help to reduce the damage of very high tidal surges or storms on the land, The turbines only need to be changed every 30 years, the barrage can be used as a road to cross the bay easily. There will be a calm lot of water behind the wall; this can be used for recreational purposes such as yachting or swimming [**29**].

Disadvantages of tidal energy

It changes the coastline completely and the estuaries are flooded so any mud flats or habitats that birds or animals live on are destroyed. Initial building cost is very expensive, water is not replenished, it cannot flow away so any dirt or pollution lingers around the coast much longer. Silt builds up behind the barrage, disrupts creatures' migration in the oceans, needs a very big piece of sea to be cost effective, not many sites are suitable for this kind of power generation, building the barrage can be used to produce power for about 10 hours of the day. The capital necessary to build the barrage is very high.

2.7 Hydropower Energy System

Hydro-power or water power is the power derived from the energy of falling water and running water, which may be harnessed for useful purposes i.e. converted to electrical energy, it is a renewable energy source. Uses of water power dated back to Mesopotamia and ancient Egypt, where irrigation has been used since the 4th millennium BC and water clocks had been used since the early 2nd millennium BC [**32**]. The first use of moving water (hydroelectric power) to produce electricity was a waterwheel on the Fox River in Appleton, Wisconsin in 1882. The plant, later named the Appleton Edison Light Company, was initiated by Appleton paper manufacturer H.J. Rogers, who had been inspired by Thomas Edison's plans for an electricity-producing station in New York [**31**]. Unlike Edison's New York plant which used steam power to drive its generators, the Appleton plant used the natural energy of the Fox River. When the plant opened, it produced enough electricity to light Rogers's home, the plant itself, and a nearby building. Hydropower continued to play a major role in the expansion of electrical service early in this century around the world [**30**]. Hydroelectric power plants are responsible for lighting many of our homes and neighbourhoods. Hydropower has been used for irrigation and the operation of various mechanical devices, such as water mills, sawmills, textile mills, dock cranes, domestic lifts, power houses and paint making.

Advantages [32]

- Once a dam is constructed, electricity can be produced at a constant rate.
- If electricity is not needed, the sluice gates can be shut, stopping electricity generation. The water can be saved for use another time when electricity demand is high.
- Dams are designed to last many decades and so can contribute to the generation of electricity for many years and decades.
- The lake that forms behind the dam can be used for water sports and leisure or pleasure activities. Often large dams become tourist attractions in their own right.
- The lake's water can be used for irrigation purposes.

Disadvantages [**31**]

- Dams are extremely expensive to build and must be built to a very high standard.
- The flooding of large areas of land means that the natural environment is destroyed.
- People living in villages and towns that are in the valley to be flooded, must move out. This means that they lose their farms and businesses. In some countries, people are forcibly removed so that hydro-power schemes can go ahead.
- The building of large dams can cause serious geological damage. For example, the building of the Hoover Dam in the USA triggered a number of earth quakes and has depressed the earth’s surface at its location.
- Dams built blocking the progress of a river in one country usually means that the water supply from the same river in the following country is out of their control. This can lead to serious problems between neighbouring countries.

2.8 Biogas energy system

Biogas is produced from anaerobic biodegradation of organic materials in the absence of oxygen and the presence of anaerobic microorganisms. The waste industry, agriculture, rural plant offal, sugar refineries, alcohol factories and animal excreta are the sources from which it can be got very easily [**33**], [**34**]. It is a kind of high-quality gaseous fuel, and has practical significance in solving the energy crisis [35], [36]. Animal manure can be left on the ground to decompose and act as a natural fertilizer or it can be processed to produce biogas. Using manure to produce energy can solve many problems, manure becomes an energy source instead of waste to produce electricity [37].

Advantages of biogas energy

Biogas contributes to a cleaner environment as it reduces the need for wood fires. It reduces greenhouse gas emissions, deforestation and prevents the inhalation of smoke from wood fires which can cause health problems in rural communities.

Disadvantages of biogas energy

Biogas is a flammable gas, dangerous fire and explosion can occur during its production [36].

2.9 Perspectives to Utilize Renewable Energy Sources

Three approaches can be used to harness renewable energy sources.
Stand-alone renewable energy system, integrated renewable energy system, Hybrid renewable energy system

2.9.1 Stand-alone renewable energy system

It involves making use of a source of renewable energy to supply loads. It is usually used in conjunction with a storage device, e.g stand-alone solar system with battery storage to power street light. It is illustrated in the block diagram in Figure 2.2 below.

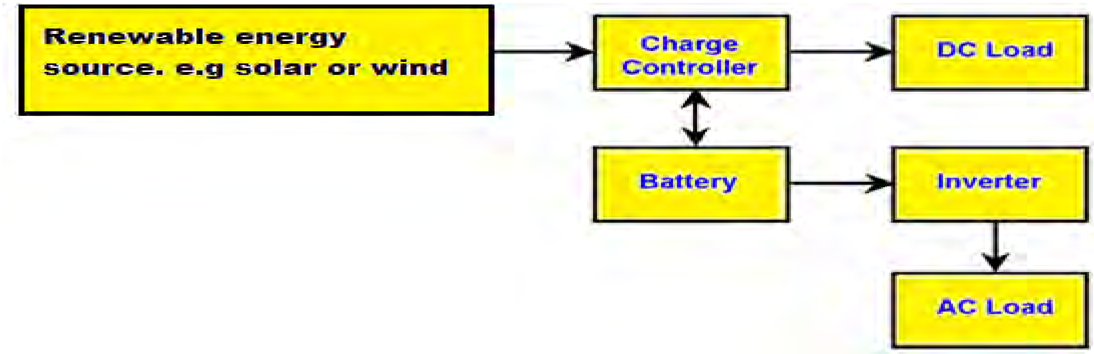


Figure 2.2: Stand-alone renewable energy systems [38]

2.9.2 Integrated renewable energy systems

It utilizes two or more locally available renewable energy resources (such as small hydro, solar, wind, biomass etc.) in order to supply electricity in local villages. Example of biomass-wind-small hydro- and solar based IRES is shown below. The control system which controls the flow of energy from source to load is the heart of IRES [**39**].

Figure 2.3: Integrated Renewable Energy resources [**39**].

2.9.3 Hybrid Renewable Energy System

It combines two or more renewable energy resources with some conventional option (diesel or petrol powered generator, thermal plant) to supply electricity to local villages situated in remote areas [**39**]. Most of the hybrid systems use the diesel generator (DG) as conventional option. Few examples of HRES are biomass-wind-geothermal-small hydro-diesel generator, wind-diesel generator etc. It is shown in the diagram below.

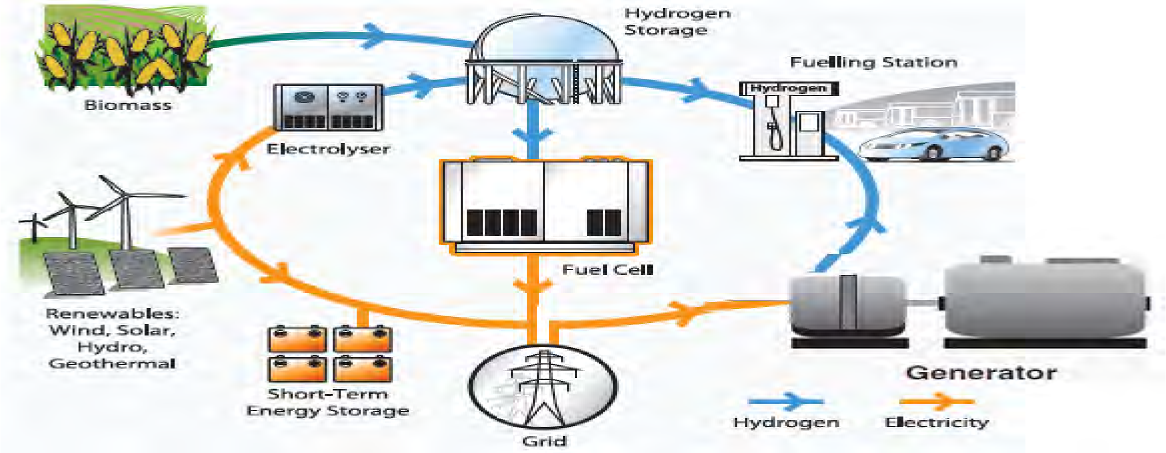


Figure 2.4: Hybrid Renewable Energy [**40**]

2.9.4 Reasons for the Deployment of Renewable Energy Sources

- Privatisation and Deregulation in the power market, which encourages public investment to sustain the development in the power demand. This development has led to the breaking up of investments (small generating units) [**161**].

- Emergence of new generation techniques with small ratings, ecological and geographical benefits, and increased profitability.
- Saturation of existing networks and the continuous growth of the demand.
- To reduce CO_2 emission.
- Reduction of security margins [**162**].
- Stability and security problems (need for expensive preventive measures, increase of short circuit currents) [**162**].
- Continuous growth of demand, especially in emerging countries.

2.9.5 Benefits of Renewable Energy Technologies [163]

Modularity: By adding or removing units, PV modules can be adjusted to meet demand [**163**].

Short Lead: Small mini-grids can be planned and built more quickly than large systems, reducing risks of overshooting demand, longer construction period and technological obsolescence.

Fuel diversity and reduces Price volatility: Renewable - based mix of energy and reduced sources, exposure to fossil fuel price fluctuation.

Load growth insurance: Some types of small scale power, such as load matching, co-generation and end-use efficiency, expand with growing loads; the flow of other resources, like solar and wind, can correlate closely with electricity demand.

Reliability and resilience: Small plants are unlikely to fail all simultaneously; they have shorter outages, are easier to repair, and can be more geographically optimally sited.

It avoids plant and grid distribution losses: Small-scale provides local choice, control and the option of relying on local fuels and sparring community economic development.

It voids emissions, environmental impacts: Small-scale power generally emits lower amounts of particulates, sulphur dioxide, nitrogen oxides and Carbon dioxide. It has a lower accumulative environmental impact on land, water supply and quality [**164**].

2.10 Assessment of Renewable energy in South Africa and Nigeria

Introduction

The developing nations of Southern African are popular locations for the prospect of the renewable energy resources; the application of renewable energy technology has the potential to alleviate many of the problems that face the countries every day. Access to energy is essential for the reduction of poverty and the promotion of economic growth, communication technologies, education, industrialization, agricultural improvement and expansion of municipal water systems [**41**].

2.10.1 Why renewable energy?

Growth in demand is not the only reason to consider alternative energy supply options, it is known that the current energy supply in South Africa is primarily coal-based [**42**], although these resources will last for more than a century if used at current rates, large power plants will need to be replaced over the next 30 years, secondly, coal has many other uses, and needs to be conserved for future use, thirdly, coal and other fossil fuels, including oil, produce Carbon dioxide when burned to produce energy. It is now widely accepted that climate change, partially caused by human-generated Carbon dioxide, represents an extremely serious environmental threat to the world as a whole. Human-induced climate change is already being blamed for the higher-than-usual incidence of extremely damaging weather experiences (e.g. storms, droughts, melting polar ice caps). Local air pollution is strongly related to energy supply options, with coal and oil products being major contributors to urban and rural air pollution and acid rain [**42**]. Renewable energy resources are sustainable energy supply options that can significantly reduce reliance on fossil fuels, carbon dioxide generation and environmental hazard caused by the conventional energy generation.

2.10.2 Electricity issues in South Africa

In 2008, the South African power utility had to implement a series of load shedding and planned power outages. This was due to insufficient supply as some plants had to be shut down due to maintenance issues. The shortage of generation was experienced throughout the day, meaning that the capacity shortage was not limited to the peak period times of 6-8 pm only. This led to a situation whereby peaking stations were forced to operate during off-peak times. About 5000 MW capacity was unavailable from January 14th 2008 due to unplanned equipment failure [**43**]. This became a wakeup call to the authorities that the country needs to deploy more capacity and find alternative sources for meeting the increasing electrical energy demand. Legal and policy reforms regarding renewable energy (RE) in South Africa began in 2003 with the development of the white paper on renewable energy policy. This was to build the future of the RE legal framework. The 2004 white paper addresses the concept of sustainable development [**44**], IRP 2010 launched South Africa on a programme that should by 2030; achieve 14 % of demand met from renewable sources. The Department of Energy pursued this with commendable energy, and already approved bidders for 1049 MW of photovoltaic energy, 200 MW of concentrated solar power 1197 MW of wind power and 14 MW of mini-hydro power [**45**].

2.10.3 Assessment of renewable energy resources in South Africa

Generation potential for wind energy is estimated to be about 20-70 GW, and the solar generation potential is about 200 - 800 GW. The Integrated Resource Plan (IRP 2010-2030) allocated 17.8 GW to RE resources; 8.4 GW of wind, 8.4 GW of solar PV and 1 GW of CSP. However, the number of applications for grid integration received by Eskom from Independent Power Producers (IPPs) indicates a potential interest of 35 – 40 GW (wind and solar). South Africa is well endowed with renewable energy resources with the potential to produce energy from biomass, wind, solar, small-scale hydro and waste; these resources remain largely untapped and presently has in place a target of 10 000 GWh of Renewable Energy. The coastal regions of South Africa have the highest potential for power generation from wind, other areas such as the Eastern Highveld, Bushman land and the Drakensberg foothills show moderate potential for wind generation. National electrification in South Africa is far more developed than other African countries where grid connected electrification are available to more than 65 % of the population as compared to an average of less than 30 % of the population in sub-Saharan Africa. Yet in South Africa, the remaining 3 million households remain disconnected from the grid and are geographically isolated and dispersed [**46**] [**47**], [**48**], [**49**].

The South African generation capacity is mainly coal based due to large coal reserves. The Government's plan is to change this and the expected 17 800 MW of renewable energy is to represent about 20 % of installed capacity by 2030 [**49**]. Table 2.1 shows the current installed electricity generating capacity; Figure 2.5 depicts a road map for Eskom and Independent Power Producers up to the year 2030.

Table 2.1: Current Electricity Generation in South Africa [**50**]

Installed generation capacity	**44.28 GW**
Fossil fuel	90.8 %
Nuclear fuel	4.1 %
Hydroelectric	1.5 %
Renewable energy	0.5 %
Others	3.1 %

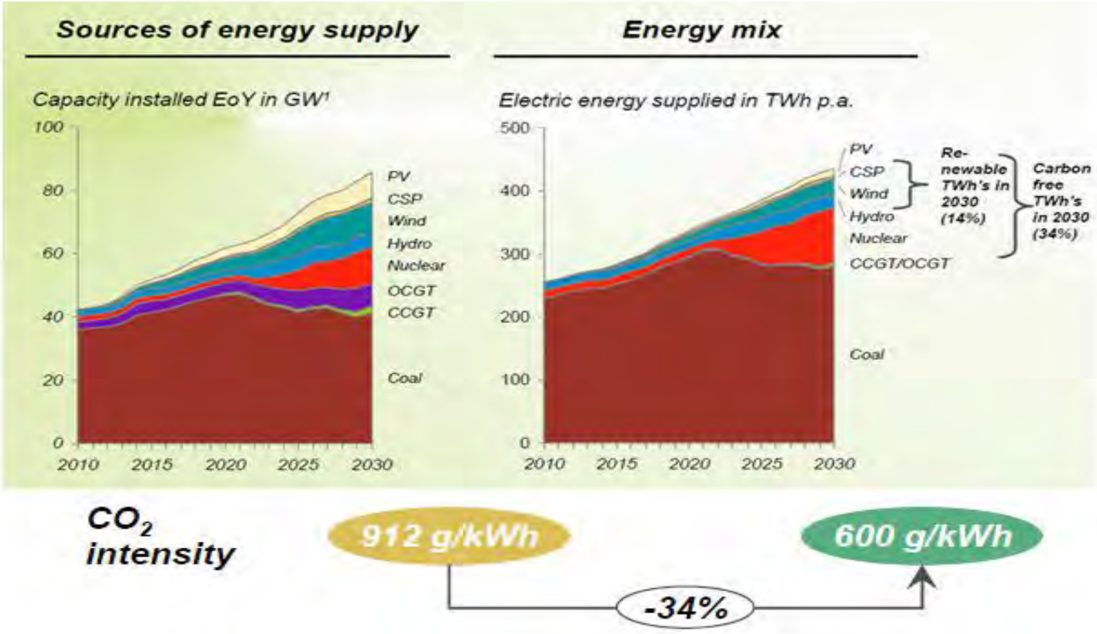


Figure 2.5: 2010 to 2030 energy road maps [**51**]

2.10.4 Planned Generation Capacity

South Africa region commissioned 2,321 MW of generation in 2013 this will result in sufficient generation capacity reserves in 2016, if all projects are commissioned as planned while energy adequacy will be achieved by 2017. A total of approximately 17,000 MW of the new generation is expected to be commissioned between the period 2013 and 2016 of which 3 % will be renewable energy from wind and solar [**56**].

2.10.5 Renewable Energy Potential in South Africa

The renewable energy resources in South Africa include, wind energy, biogas, solar power, biomass, geothermal energy, hydro power, waste to energy, wave power and landfill gas.

Wind energy prospect

Wind powered water pumps are common in South Africa, with an estimated 30 000 systems installed. The Darling wind farm, established in the Western Cape, is an example of a potential South African independent power producer. This DME-supported 'National Demonstration Project' has a planned initial capacity of approximately 5 MW, and could be extended to 10 MW. Eskom started to generate electricity from three wind turbines at the Klipheuwel site in 2002 with a view to investigating the potential of large-scale wind energy for bulk electricity generation in South Africa. The total energy available from the wind is proportional to the cube of the wind speed. Thus, an area with average wind speed of 6m.s^{-1} could deliver eight times energy per km^2 as an area with an average wind speed of 3 ms^{-1}. South Africa has a fair wind potential, especially along the coastal areas of Western and Eastern Cape. At present only about 0.05 % of South Africa's installed electricity generation capacity is derived from wind energy and is divided into large grid connected wind turbines (10.2MW), small wind turbines (0.56 MW), borehole windmills (approx 22,000 units -12 MW). The large grid connected wind turbines are made up of Eskom Klipheuwel (3.17 MW), Darling (5.2 MW) and Coega (1.8 MW) [**53**], [**58**], [**59**]. An overview of wind farms in South Africa is shown in Table 2.2 below and the amount of electricity derived from wind power is also displayed in Table 2.3.

Biogas energy prospect

Six biogas production operations in rural KwaZulu-Natal, South Africa were approved and required to register in 2013 by the National Energy Regulator of South Africa (Nersa). The biogas production operations registered are in Izimpongo village, Melmoth and Mgwabi village at Eshowe. Twenty-one similar operations in Limpopo and one in Pretoria, this brings to 38 the total number of biogas operations registered in South Africa since 2011 [**60**]. Most of these biogas operations are in rural areas and consist of a fixed dome plant that uses bio-digesters to produce biogas from waste material, which will be supplied to heating appliances in peri-urban and rural dwellings. As these projects use cow dung, pig manure, kitchen waste and agricultural residues to produce biogas through anaerobic digestion, communities are able to use the technology to produce energy for their own needs, such as cooking, lighting, warmth and even generating electricity. This helps improve South Africa's energy mix and alleviates some of the pressure on the national grid.

Solar energy prospect

Solar radiation levels in South Africa are amongst the highest in the world, average daily solar radiation varies between 4.5 and 7 kWh/m^2 even in winter and parts of the country receive more than 6.5 kWh/m^2 per day. Central and western regions have an excellent radiation resource, and even the eastern and southern coastal areas have good radiation exposure.

- **Solar grid-connects South Africa**

South Africa has 75 MW solar PV connected to national Grid, this is the first REIPPPP project in 2013 [**61**]. The solar farm is located at Kalkbult, in the sun drenched Northern Cape region. It consists of about 312000 solar panels mounted on 156 km of substructure, inverters, transformers and a HV sub-station. Combined annual production will be in excess of 135 million kWh per year, enough to cover the electricity demand of 33 000 Southern African households. Harvesting solar power from this plant represents CO_2 abatements of almost 115 000 tons per year. The second phase of the solar PV worth of 115 MW is under construction located at Linde in Northern Cape and Dreunberg in Eastern Cape respectively. Combined annual production will be in excess of 225 million kWh per year, enough to cover the electricity demand of 53 000 South African households [**61**].

- **Solar water heaters for hot water supply**

A draft of the South African National Solar Water Heating Framework and Implementation Plan was presented in November 2009, which highlights a target of 1 million SWH within the next four and a half years within all categories of formal households and a vision for 5.6 million installations by 2020 creating a minimum of 40 % SWH penetration in the existing 12 million households [**62**].

- **Concentrating solar power to generate electricity**

The IEA's Energy Technology Perspectives identifies solar thermal technology as a very promising option for areas of the world with extremely good solar resources, which includes about half the land area of South Africa [**61**]. South Africa has an excellent solar regime, with ample resource to provide significant future electricity generation, and potentially has the right mix of skills and manufacturing capabilities to create a competitive market [**64**]. The SKA MeerKAT radio telescope array programme collaborated with the University of Stellenbosch on a feasibility study for a 100 MW CSP plant and a 0.5 MW PV system. The Clinton Climate Initiative is partnering with the Department of Energy to set up a solar park in the Northern Cape, which could add up to 5 GW of capacity to South Africa's electricity generation [**63**]. Various solar resource assessments for South Africa indicate that the Northern Cape Province has the highest solar resource in the country. The annual radiations measured from the best sites in the Northern Cape are more than 30 % higher than for the best sites in Spain. Upington, for example, has more than 6.5 kWh/m^2 daily average global horizontal irradiation. In the Free State, North West, Limpopo and in the interior parts of the Western Cape and the Eastern Cape the solar resources are excellent, the rest of the country still has a good solar resource [**64**]. The solar potential in South Africa is therefore considerable, and it is estimated that the theoretical potential is 8,500,000 PJ/yr (2,361,300 TWh/yr) [**65**]. South Africa's Integrated Resource Plan

(IRP 2012) envisages generation of an additional 56 500 MW by 2030, compared with current capacity of about 38 000 MW, most of which is produced by Eskom coal-fuelled power stations, 21 534 MW, or 38 %, is scheduled to be generated through renewable energy technologies, with 1200 MW allocated to CSP [**68**].

Table 2.2: Overview of wind farms in South Africa [**59**]

Wind farm	Province	Turbine model	Power per turbine (MW)	No. of Turbines	Total Nameplate capacity (MW)	Online
Coega	Eastern Cape	Vestas (V90-1800)	1.8	24	43.2	2010
Darling	Western Cape	Fuhrländer	1.3	14	18.4	2008
Jeffreys Bay	Eastern Cape		3.2	60	138	2014
Klipheuwel	Western Cape	Vestas V47, V66, Jeumont J48	0.66, 1.76, 0.75	3	3.16	2002
Dorper WF	Eastern Cape	Nordex N100 Turbines	2.5	40	100	Under construction
Sere	Western Cape	Siemens SWT-2.3-108	2/2.3	46	100	Under construction
Nobelsfontaine	Northern Cape		-	41	75	-
Hopefield	Western Cape	Vestas V100	1.8	37	66.6	-
Grassridge	Eastern Cape	Vestas V112	3.075	20	61.5	-

Table 2.3: Electricity derived from Wind Power [**53**]

Large Grid connected Wind turbines	(10.2 MW)	Darling	5.2 MW
		Eskom Klipheuwel	3.16 MW
		Coega	1.8 MW
		Total	10.2 MW
Small Wind Turbine		0.56 MW	
Borehole Wind Mill		12 MW	
Total Wind Power		22.7 MW	

- **Photovoltaic systems**

In South Africa, PV systems are all small-scale (less than 1 MW) mainly for off-grid (rural) applications where the cost of extending the grid is high. Typical applications include schools, health centres, and for rural households, with a total estimated installed capacity of 21 MW. This type of PV use is known from key markets like Bangladesh, China, Sri-Lanka and

Kenya. Globally, PV is primarily used in grid-connected application, 60 % average annual growth rates are seen in the period 2002-2006 [**67**].

Biomass prospects

South Africa has tremendous biofuel potential when considering the capacity to grow total plant biomass. According to conservative estimates, South Africa produces about 18 million tonnes of agricultural and forestry residues every year [**71**]. The Biofuels target for 2008-2013, according to Industrial Biofuels Strategy (2007), is fixed to 2 % penetration level in the national liquid fuel supply, which corresponds to 400 million litres per annum. Southern Africa has the potential to substitute the bulk of its current liquid fossil fuel usage (currently 21.2 BL/annum) with renewable biofuels [**69**]. Table 2.4 below shows the most productive biomass areas are in KwaZulu-Natal and the wetter parts of Mpumalanga.

Table 2.4: Amount of waste generated in South Africa in 2014 [**70**]

Province	Kg/capital/ Annum	Waste generated as % of total waste
Western Cape	675	20
Eastern Cape	113	4
Northern Cape	547	3
Free State	199	3
Kwazulu Natal	158	9
North West	68	1
Gauteng	761	45
Mpumalanga	518	10
Limpopo	103	3

Hydropower

South Africa has low average rainfall. The seasonal flow of the country's rivers and frequent droughts or floods, limit opportunities for hydropower. The majority of the country's hydropower resource is concentrated in 6,000 – 8,000 sites in the Eastern region. Currently, the installed hydropower in South Africa has reached a capacity of 2,267 MW, generating on average annually about 4,368 GWh. This represents about 2.3 % of the total energy output [**74**], 68 MW is produced by eight 'small hydro plants', each of less than 10 MW. Three of the 'small hydro plants' are privately owned. It is estimated that there are also approximately 0.2 MW of installed mini hydro capacity that are primarily powering isolated mini-grid systems. There are also pumped storage schemes with a capacity of 1 580 MW installed. [**72**] estimated that the Thukela and Mzimvubu to Keiskama catchments alone have a combined potential of 4950 MW of large hydro-power, 23 MW of small hydro-power. There are 3500 to 5000 potential sites for micro hydro power generation concentrated in areas along the eastern region. Realisable small-scale hydro generation potential is approximately 9 900 GWh per annum [**73**].

2.10.8 Policy developments using Renewable energy for electricity generation

The Department of Energy established a target for renewable energy production at 10,000 GWh in December 2013. According to the draft, 6000 GWh of this target is expected from on-grid electricity generation. At the Renewable Energy Summit in March 2009, it is indicated that more ambitious targets 'for the period between 2013 and 2018 could be set in the range of 6 % to 9 % and 9 % to 15 % of the current capacity respectively' [**62**]. This results in a renewable energy target of 14.5 – 22 TWh in 2013 and 22 – 36 TWh in 2018. The Renewable Energy Feed-in Tariff (REFIT) was developed by NERSA to support the introduction and development of renewable energy options. Phase 1 of this programme focuses on wind; concentrated solar, landfill gas and small hydro plant. The respective REFFIT tariffs published by NERSA are: Wind: R 1.25/kWh; small hydro: R 0.94 /kWh; landfill gas: R 0.90 /kWh; and concentrating solar: R 2.10 /kWh as shown in the Table 2.5 below. According to [**67**] the key principles that underpin the establishment of the REFIT in South Africa include, guaranteed access to the national grid, guaranteed purchase price for a fixed duration, obligation to purchase and to discharge the power generated, burden sharing of the additional cost throughout electricity consumers, new projects, cost reduction, potential to set a cap on the maximum available subsidy per year, willing seller and willing buyer approach still applies.

Table 2.5: REFIT tariffs published by NERSA [**67**]

Year	2009	2011
REFIT phase	Phase I	Phase II
Technology	R/kWh	R/kWh
CSP	2.10	1.84
Wind	1.25	0.94
Small hydro	0.94	0.67
Landfill gas	0.90	-
CSP trough without storage	3.14	1.84
LARGE SCALE GRID CONNECTED PV SYSTEM (≥1MW)	3.94	2.31

In general the REFIT was established in South Africa on the grounds that it has proved to be the most effective policy instrument to deploy renewable, as experienced in Germany and Spain. The benefits of a feed-in tariff include that the premium risk for investors can be minimised by establishing long-term assurance of their electricity sales at a set tariff. This allows for improved access to finance for developers, as well as market assurance, which is thought to drive renewable energy technology development resulting in lower costs of electricity generation in the long run.

2.10.9 Summary

The investigations undertaken to provide clear evidence that there are sufficient renewable energy resources in South Africa to provide more than 15 percent of the electrical demand by 2030, and easily 70 percent or more by 2050 (progressive renewable scenario) from a total energy perspective, if the renewable energy resource can be focused upon more than coal, nuclear and fossil fuel, greatest achievement will be recorded in CO_2 reduction and the establishment of sustainable energy in South Africa.

2.11 Overview of renewable energy sources in Nigeria

Introduction

Energy is an essential ingredient or tool for socioeconomic development and an index of prosperity in any nation. It is one of the basic requirements of human sustainability and technological advancement. In general, energy can contribute to widening opportunities and empower people for a living. Due to population outburst, over the past two decades, the population has increased to over 150 million, with an average GDP growth rate of 6.66 % over the last five years, inevitable industrialization, more agricultural production and improving living standards, Nigeria needs more energy to meet the rising demands. It also serves as an input into the production of goods and services in the nation’s industry, transport, agriculture, health, education sectors, as well as an instrument of politics and security [**77**], [**75**].

2.11.1 Why renewable energy?

Commercial electricity generation in Nigeria currently comes from 7 power stations and various independent power projects around the country. Thus, the nation’s current installed electricity generating capacity is about 9,920 MW, with per capital power capacity of 28.57 Watts and this is grossly inadequate even for domestic consumption [**76**], [**83**], [**84**]. For Nigeria to meet up its energy needs, it requires per capital power capacity of 1000 Watts or power generating/handling capacity of 140,000 MW compared to current capacity of 6,701 MW. Availability of power in the country varied from about 27 % to 60 % of installed capacity, while transmission and distribution losses accounted for about 28 % of the electricity generated in the country [**77**] . The energy consumption mix in Nigeria is dominated by fuel wood (50.45 %); fossil fuel (41.28 %) and hydroelectricity (8 %) as depicted in Table 2.6. Coal, nuclear, geothermal, tidal, wind and solar energy are currently not part of Nigeria's energy mix [**78**]. Nigeria is struggling to provide minimal power and is yet to achieve an acceptable level of power supply, which is seriously needed for economic development. There is a need to focus on renewable energy, especially, off-grid systems that would not depend on the national grid. In 2010, a bold "Power Sector Roadmap" was launched, which many saw as a potential framework to redeem the comatose electricity in sub-sector. The framework contained policies and institutional reforms that promised, among other things, a super transmission network, the generation of additional 5,000 megawatts by the international oil companies, active exploitation of hydro, nuclear and coal power, privatization of the power sector and the addition of 4,775 megawatts from the Independent Power Plants (IPPs) by December 2016. Turning to renewable energy to achieve a suitable energy mix is a sure alternative. Nigeria is blessed with abundant sunlight, wind, rain, tides, waves and geothermal energy, they are natural energy sources that should be exploited and put to beneficial use.

Table 2.6: Current Energy consumption mix in Nigeria [**78**]

Fossil fuel	41.28 %
Fuel wood	50.45 %
Hydro power	8 %
Renewable energy	0 %
Others	0.27 %

2.11.2 Electricity issues in Nigeria

Only about 40 % of the nation's 150 million people have access to grid electricity and in the rural areas, where about 70 % of the population live, and the availability of electricity drops to 10 %. Nigeria requires per capital power capacity of 1000 Watts per person or power generating/handling capacity of 140,000 MW compare to the current available capacity of 3,920 MW [**77**]. This will put Nigeria slightly below South Africa with the per capita power capacity of 1047 Watts, UK with the per capita power capacity of 1266 Watts and above Brazil with per capita power capacity of 480 Watts, China with per capital power capacity of 260 Watts [**77**]. Nigeria is endowed with sufficient renewable energy resources to meet its present and future development requirements as well as complement its current oil-dependent economy [**79**], [**85**].

2.11.3 Prospects of renewable energy resources in Nigeria

Nigeria has high potential to harness energy from renewable sources such as small hydro, mini hydro, solar, wind, biomass, wave and tidal power as shown in Table 2.7 below. Meanwhile, the current electricity generated in Nigeria (Table 2.8) is very small compared to the population growth of the country i.e. about 150 million population, the number of the people that have access to the electricity in the rural area is 10 % and renewable energy resources are available in abundance in the country. Nigeria has a capacity of 11,500 MW of large hydropower and only 1972 MW has been exploited while for small hydro power, the country has about 3,500 MW and only about 64.2 MW has been exploited [**81**] , this may be due to the fact that the soaring upfront investment expenses of RE development is sometimes responsible for their being ignored by potential investors.

With the wide range of measures proposed in the renewable energy and energy efficiency partner (REEP), it is hoped that the sector will continue to grow in the country. The finalisation and implementation of a legislative framework for the energy sector, with consideration for the use of renewable energy technologies (RETs) and their dissemination, will further enable the development of the renewable energy resources in Nigeria. The national energy regulatory commission (NERC) is actively seeking to promote renewable energy (RE) development through the introduction of more comprehensive licensing arrangements for private-sector operators, ensuring that the FIT is appropriately-set as an RE incentive mechanism, and clarifying market rules for RE services and products. The prospective of renewable energy resources in Nigeria are stated in Table 2.7 below.

Prospect of solar power

Nigeria is endowed with an annual average daily sunshine of 6.25 hours, ranging between about 3.5 hours in the coastal areas and 9.0 hours at the far northern boundary. Similarly, it has an annual average daily solar radiation of about 5.25 kWm^2/day varying between 3.5 kWm^2/day and 7.0 kW/m^2/day at the coastal area and northern boundary [**85**]. Nigeria receives about 4.851x 1012 kWh of energy per day from the sun. This is equivalent to about 1.082 million tons of oil equivalent per day, and is about 4 thousand times the current daily crude oil production, and about 13 thousand times that of natural gas daily production based on energy unit. Nigeria has an average of 1.804 x 1015 kWh of incident solar energy annually. This annual solar energy insolation value is about 27 times the nation's total conventional energy resources in energy units and is over 117,000 times the amount of electric power generated in the country [**85**]. In other words, only about 3.7 % of the national land area is needed to be utilized in order to annually collect from the sun an amount of energy equal to the nation's conventional energy reserve. If solar energy can be harnessed, this will boost the Nigerian economy and extend power to the remote areas, creating jobs for people and provide sustainable environment.

Table 2.7 Renewable energy sources reserves in Nigeria [**85**]

Resources	**Reserves**	
Hydropower	14,750 MW	
Small Hydropower	3,500 MW	
Wind	1.4-5.1m/s^2 at 10m height	
Geothermal	Ikogosi warm spring in Ekiti state, Wikki warm spring in Bauchi state,Lagos sub-Basin	
Solar Radiation	2.25-7 kWh/m^2/year	Estimated
Saw Dust	1.8 Million Tonnes	Estimated
Bio-ethanol	120-140 Million Litres/year	Estimated
Fuel Wood	43.4 Billion kg	Estimated

Table 2.8: Conventional energy generation in Nigeria data extracted from [**82**], [**83**], [**84**]

Installed Capacity (MW)	**9,920 in December 2013**
Energy Generation (MW)	3,920
Peak Generation (MW)	4,500
Highest Peak Generated (MW)	4,517.6
Transmission capacity (nominal) MW	6870
Technical losses MW	12 %
Distribution capacity (nominal) MW	7,325
Peak Demand (MW)	12,800
Access to Electricity	40 %
Access to Electricity- Rural	10 %

Wind energy prospect

Wind Energy is available at annual average speeds of about 4.0 m/s in the coastal region and 8.0 m/s in the far northern region of the country [**85**]. With an air density of 1.1 kg/m^2, the wind energy intensity perpendicular to the wind direction ranges between 4.4 W/ m^2 at the coastal areas and 35.2 W/ m^2 at the far northern region. At present, the share of wind energy in the national energy consumption has remained at the lower end with no commercial wind power plants connected to the national grid, only a few numbers of stand-alone wind power plants were installed in the early 1960s in 5 northern states, mainly to power water pumps and a 5 kW wind electricity conversion system for village electrification installed at Sayyan Gidan Gada, in Sokoto State [**85**]. In recent times, numerous studies have been carried out to assess the wind speed characteristics and associated wind energy potentials in different locations in Nigeria. Promising attempts are being made in the Sokoto Energy Research Centre (SERC) and Abubakar Tafawa Balewa University, Bauchi, to develop capability for the production of wind energy technologies [**86**].

Hydro power prospect

The country is reasonably endowed with large rivers and some few natural falls. Small rivers and streams also exist within the present split of the country into eleven River Basin Authorities, some of which maintain minimum discharges all the year round. Hydropower currently accounts for about 32.8 % of the total electrical power supply, in a study carried out in twelve states and four river basins, over 278 unexploited small hydropower (SHP) sites with total potentials of 734.3 MW were identified [**87**]. However, SHP potential sites exist in virtually all parts of Nigeria with an estimated total capacity of 3,500 MW [**82**]. Nigeria possesses the potential renewable source of energy along her numerous river systems, a total of 70 micro dams, 126 mini dam and 86 small sites have been identified. A private company, the Nigerian Electricity Supply Company (NESCO) and the government have installed eight SHP stations with aggregate capacity of 37.0 MW, most of these stations are found around Jos at Kwall and Kurra Falls [**86**].

Biomass energy prospect

The biomass resources of Nigeria can be identified as crops, forage grasses and shrubs, animal wastes and waste arising from forestry, agriculture, municipal and industrial activities, as well as aquatic biomass [**91**] . Crops such as sweet sorghum, maize and sugarcane are the most promising feedstock for bio-fuel production. Plant biomass can be utilized as fuel for small-scale industries; it could also be fermented by anaerobic bacteria to produce a cheap fuel gas (biogases). Biogas production from agricultural residues, industrial, and municipal waste does not compete for land, water and fertilizers with food crops like is in the case with bio-ethanol and biodiesel production and, will reduce the menaces posed by these wastes [**89**]. In Nigeria, identified feedstock substrates for an economically feasible biogas production include water lettuce, water hyacinth, dung, cassava leaves and processing waste, urban refuse, solid (including industrial) waste, agricultural residues and sewage. It has been estimated that Nigeria produces about 227,500 tons of fresh animal waste daily [**89**] . Since 1 kg of fresh animal waste produces about 0.03 m^3 of biogas, then Nigeria can potentially produce about 6.8 million m^3 of biogas every day from animal waste only. Various research works on the technology and policy aspects of biogas production Such as reactor design that would lead to process optimization in the development of anaerobic digesters have been carried out by various scientists in the country [**91**]. Sawdust and wood wastes are other important biomass resources associated with the lumber industry. Small particle biomass stoves already exist for burning sawdust and wood shaving. Biomass utilization as energy resources is currently limited to thermal application as fuel for cooking and crop drying [**91**], [**89**].

2.11.4 Challenges of Renewable energy source in Nigeria

Despite the recognition that RE are important sources of energy in Nigeria, it has attracted neither the significant level of investment nor tangible policy commitment. Although the energy reforms and national resources allocated to developing and disseminating RE in the last decades may appear substantial, the total amount is still insignificant compared to that allocated to the conventional energy sector that service less than 50 % of the population. The success of RE technologies has been limited by a combination of factors which include, poor integrated institutional framework, inadequate policy implementation, lack of co-ordination and linkage in RE programmes, pricing distortions which have placed renewable energy at a disadvantage, funding and high initial capital costs, weak technology dissemination strategies, lack of skilled manpower and poor baseline information on location. Currently, Nigeria is plagued with a dilapidated, unreliable, obsolete and ineffective power supply sector, which is not able to meet the challenges of power demand in the country.

2.11.5 Integration of renewable energy sources in Nigeria

One of the key indices for measuring the development and utilization of productive capacity of a nation is the level of electricity consumption and the readiness of such country to meet demand for power while also having spare generation, transmission and distribution capacity. Nigeria ranked low on all these indices, the power sector is being deregulated. The Government has privatized the generation, transmission and distribution sub-sectors [**90**]. The development of any nation depends to a large extent on the ability to provide an enabling environment for industrialization to thrive. Taking into consideration the relevance of the power sector, these lofty goals cannot be achieved unless the rising demand for power is met by a corresponding increase in supply. Urban and rural development can only thrive where power is available and cheap. At present, most of Nigeria's generation is from high head water storage reservoirs like Kainji Dam and the Gas (thermal power) generation plants like Egbin Thermal station which are becoming increasingly costly and difficult to maintain. The development of renewable energy technologies in Nigeria has been slow, however, research and record show that recommendations for the integration of renewable energy into Nigeria's energy mix, beyond other measures, have been offered [**94**]. Stand-alone renewable energy supply system is being practiced partially and utilised in Nigeria for example, solar power which may be directly coupled with battery or direct coupled without battery.

Summary

There is a need to harness alternative energy sources in Nigeria to reduce dependence on fossil fuel which is not environmentally friendly and is exhaustible. The federal government should partner with private organizations to sponsor research in this new area in view of its numerous benefits.

Chapter 3

Distributed Generation Technologies overview

Introduction

The introduction of DGs has brought drastic changes in the power system planning and operation. DG may be dispatchable or non-dispatchable. When the DG is dispatchable, the DG operator can determine a power output of the DG units by controlling the primary energy sources that are supplied to the DG units, the system operator is able to change the production of large generation units when its production level would endanger the operational security of the system which means it can be turned on or off on demand. When the DG is non-dispatch-able, the operator cannot dispatch the DG units because the behaviour of the primary energy sources cannot be controlled, the system operators have to accept their production whatever it is. Non dispatchable units are normally the ones driven by renewable energy sources, where the power output will depend on the availability of the energy sources.

3.1 Distributed Generation (DG)

Distributed generation can be described as a method of generating electricity on a small scale from renewable and non-renewable energy sources which are located close to where the electricity is being used or load centres, the capacities may range between 1 kW and 100 MW [**92**], [**96**]. They are the generating units with relatively lower capacities compared to the conventional units and serve as an alternative to or an enhancement of the traditional electric power system [**94**], [**98**]. DGs have gained drastic importance, the number of distributed generators such as photovoltaic systems, combined heat and power (CHP) micro units and windmills increases rapidly. In comparison with large-scale power plants, distributed generators are installed very close to the end consumer to avoids high transportation and transformation losses over several voltage levels as shown in Figure 3.1 below [**96**], [**97**].

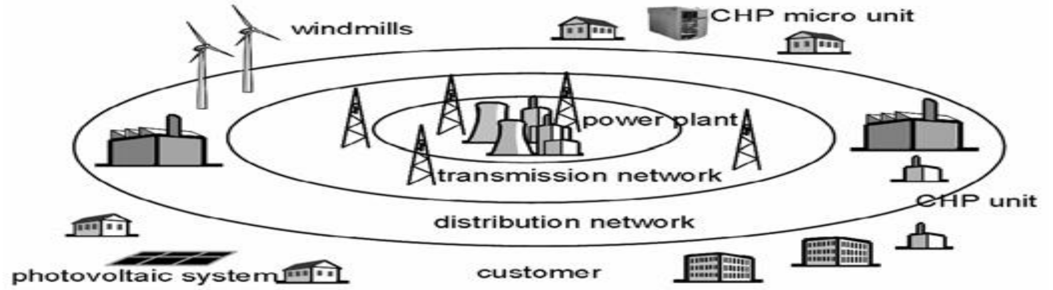


Figure 3.1: Closeness of DGs to the load centre [**96**]

3.1.1 Type of Distributed Generation

Distributed generation can be divided into two groups

- Renewable distributed generation
- Non-renewable distributed generation

Renewable distributed generation

Renewable DG can be described as the energy production units that make use of renewable sources (e.g. water, sun, wave, wind) to produce power on a small scale or in the vicinity of the load centres whose produced power and energy can either be directly fed into the distribution system or directly supplied to the customers/load.

Non-renewable distributed generation

Non-renewable DG can be described as the energy production units that make use of fuel, gas, or internal combustion engines to produce power on a small scale in the vicinity of the load centres whose produced power and energy can either be directly fed into the distribution system or directly supplied to the customers/load. Figure 3.2 shows the structure where DGs are connected at both transmission and distribution level. Figure 3.3 below shows different kinds of DGs and their classification.

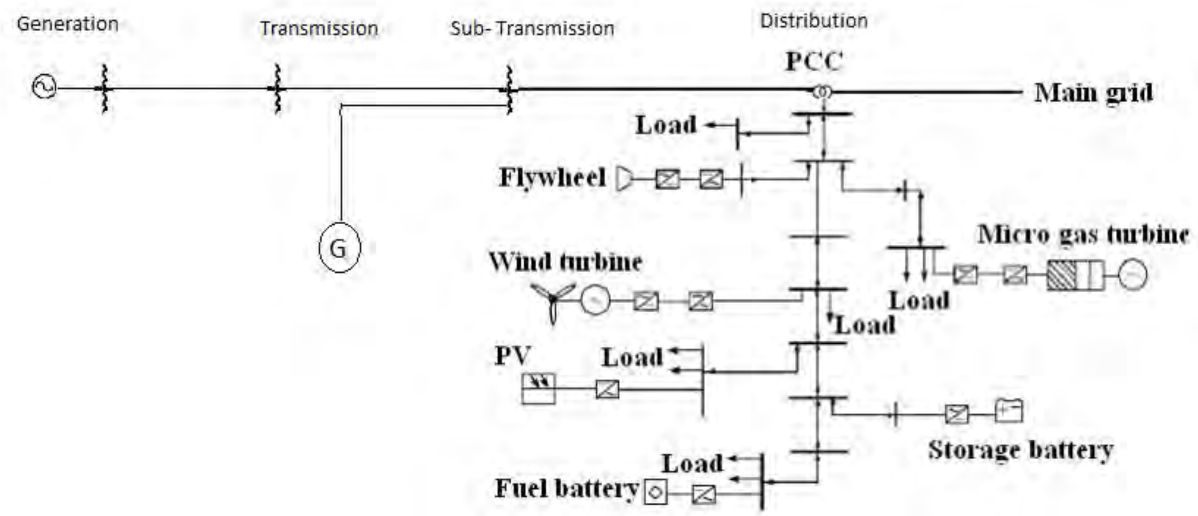


Figure 3.2: Structure of distributed generation system (Own creation)

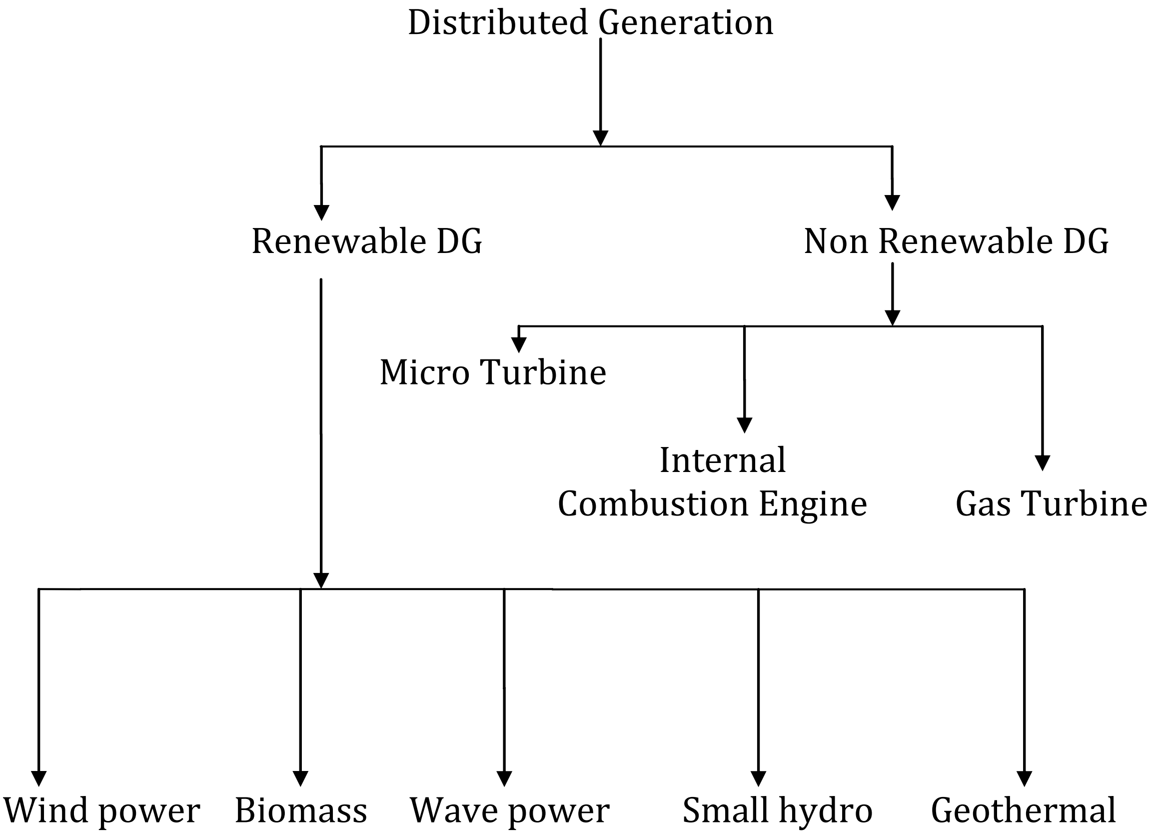


Figure 3.3: Flow chart of DG (Own creation)

3.2 Micro-turbine power system

Micro-turbine power capacity can be in the range from 20 to 500 kW. It has high rotational speed, up to 120,000 rpm. Its basic technical characteristics are the uses of the runoff impeller engine (centrifugal turbine and centrifugal compressor) and return heat cycle. It primarily uses natural gas, methane, gasoline and diesel as fuels. It is known to have some advantages like high reliability, long life, low noise, light weight, small size, low pollution, multi-fuel and low fuel consumption. It produces high frequency AC power, and use a power electronic inverter to convert this high frequency power into a usable form. The use of renewable energy sources, such as ethanol, is also possible with micro-turbines [**101**].

3.3 Fuel Cell Generation System

Fuel cells make use of hydrogen directly from fuels (natural gas, gas, oil, etc.) to react with oxygen in the air by the help of electrolyte, and forms water at the same time generating electricity, in a simple way. It converts the chemical energy of a fuel directly to usable energy, electricity and heat without combustion, it is simple and more efficient [**96**]. The advantages of the fuel cell are numerous; it has great energy conversion efficiency, zero emissions, no noise, no vibration, stable and reliable power output. The main challenge of the commercialization of fuel cells is the high investment cost [**99**].

3.4 Solar Thermal Systems

Solar thermal systems generate electricity by concentrating the incoming sunlight and then trapping its heat, which can raise the temperature of a working fluid to a very high degree to produce steam and then generate electricity. This process is different from that of a photovoltaic panel where the sunlight is directly converted into electricity without the intermediate heat collection. There are three basic methods to concentrate solar energy, central receiver, trough-based, and dish-based systems [**99**].

Solar thermal is more economical, as it eliminates the cost of semiconductor cells; it can be grid connected or stand-alone applications, for central generation or DG applications. They are suitable for fossil-hybrid operation or can include cost effective and thermal storage to meet dispatch requirements [**101**].

3.5 Gas Turbine

Gas turbines consist of a compressor, combustor, and turbine-generator assembly that converts the rotational energy into electric power output. It is in the range of 1 – 20 MW, which are commonly used in combined heat and power (CHP) applications [**100**]. They are particularly useful when higher temperature steam is required (higher than the steam produced by a reciprocating engine). The maintenance cost is slightly lower than that of reciprocating engines. Gas turbines can be noisy. Emissions are somewhat lower than for a combustion engine.

3.6 Benefits of Distributed Generation [101], [102].

The introduction of distributed generation into the power system has many benefits, which can be categorised into two modes, namely; standalone mode and grid connection mode.

3.6.1 Standalone operating mode

- It provides electricity more cheaply than grid extension especially in rural areas where there is no access to grid connected electricity
- It is efficient and reliable means of power generation
- Allows better use of local natural resources
- It is modular and relatively easily assembled from standardized packages
- Low cost sources to serve demand during peak price period

3.6.2 The grid connected mode

- It improves voltage profile when connected to a distribution network
- Reduction in power loss and increased overall energy efficiency
- Reduction in security risk
- Relieved transmission and distribution (T&D) congestion.
- Better customer control over their energy
- Helps in peak load shaving and load management programs.
- Improved competitiveness and market opportunities

3.7 Wind energy conversion system

A wind energy conversion system (WECS) is a machine that is powered by the energy of the wind, generates mechanical energy that can be used to directly power an electrical generator for making electricity. It is a structure that transforms the kinetic energy of the incoming air stream into electrical energy. The conversion process takes place in two steps, the extraction device e.g., wind turbine rotor (blade) turns under the wind stream action, thus harvesting mechanical power, and while the rotor drives a rotating electrical machine i.e., the generator produces electrical power in the output. A power electronic device can be used as a coupler or an interface between the generator and the grid as shown in Figure 3.4 below.

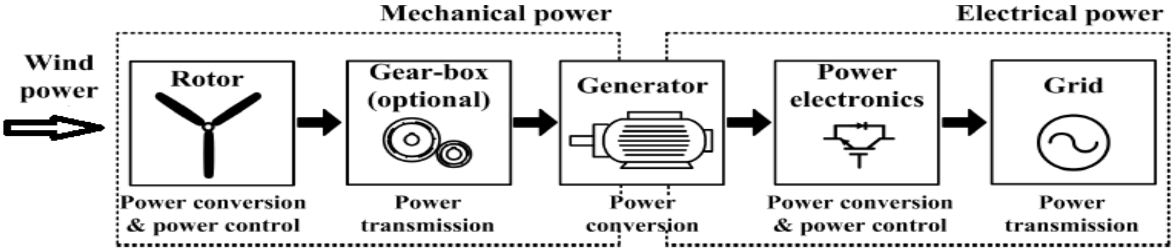


Figure 3.4: Basic power conversion principle in a wind power system [104]

3.8 Wind Generator structure [107]

The general structure of wind model is depicted in Figure 3.5 below. It incorporates six blocks and each of these six blocks is available in any wind model regardless of the technologies.

- Mechanical system (turbine rotor, shafts, gearbox and the generator rotor)
- Generator drive (generator and power electronic converters, if any)
- Wind turbine Aerodynamic system
- Pitch control system
- Wind turbine control system

3.8.1 The mechanical part: It extracts the kinetic energy from the wind and makes it available to a rotating shaft. The mechanical system of a wind turbine consists of the drive train. The drive train consists of the rotating masses and the connecting shafts, including a possible gear system. This is where the pitch of the blade, the yaw of the turbine shaft and the speed of the motor shaft are regulated [**105**].

3.8.2 Electromechanical stage: This has variable components such as pole pairs and rotor resistors, an external excitation and/or a power converter that adapts the speed or the torque of the motor shaft and waveforms of the generator voltages/currents [**106**].

3.8.3 The electrical part: The electrical model consists mainly of electrical generator interfacing with the power system via the voltages and current. It transforms the electrical energy so that it is suitable for the electrical grid. It also provides the generator, air gap torque and uses the generator speed as an input. At the same time, the electrical model outputs the active and the reactive power which are also used as control parameters. The mechanical energy is converted to electrical energy by an electric generator connected between the mechanical system and the electrical system [**106**]. Power electronic converters may be present in the second and/or third stage [**105**].

3.8.4 Aerodynamic model

The aerodynamic model interfaces the wind and the mechanical model while the electrical model interfaces the mechanical model with the grid. The aerodynamic model provides the torque for the mechanical drive train and uses the turbine rotor speed, blade pitch angle and equivalent wind speed as inputs. The aerodynamics drives the turbine rotor which transforms kinetic energy to mechanical power [**107**]. Wind turbine power production depends on the interaction between the wind and the turbine rotor. The blades of a wind turbine rotor extract some of the energy flow of air in motion, convert it into rotational energy, and then deliver it via a mechanical drive unit to the generator. The wind turbine rotor that extracts the energy from the wind and converts it into mechanical power is a complex aerodynamic system. For the state of the art modelling of the rotor, blade element theory must be used [**108**].

Aerodynamic power control

At high wind speeds it is necessary to limit the input power to the turbine, i.e. Aerodynamic power control. There are three major methods of aerodynamic power control: stall, pitch and active stall control [**107**]. The three methods are described as follows:

Stall control: It implies that the blades are designed to stall in high wind speeds and no pitch mechanism is thus required.

Pitch control: It is the most common method of controlling the aerodynamic power generated by a turbine rotor for newer larger wind turbines. Almost all variable speed wind turbines use pitch control. Below the rated wind speed, the turbine should produce as much power as possible, i.e. using a pitch angle that maximizes the energy capture. Above rated wind speed the pitch angle is controlled in such a way that the aerodynamic power is kept at its rated value. In order to limit the aerodynamic power, at higher wind speeds, the pitch angle is controlled to decrease the angle of attack.

Active stall controls: It is also possible to increase angle of attack towards stall in order to limit the aerodynamic power. This method can be used to fine-tune the power level at high wind speeds for fixed speed turbines. This control method is known as active stall.

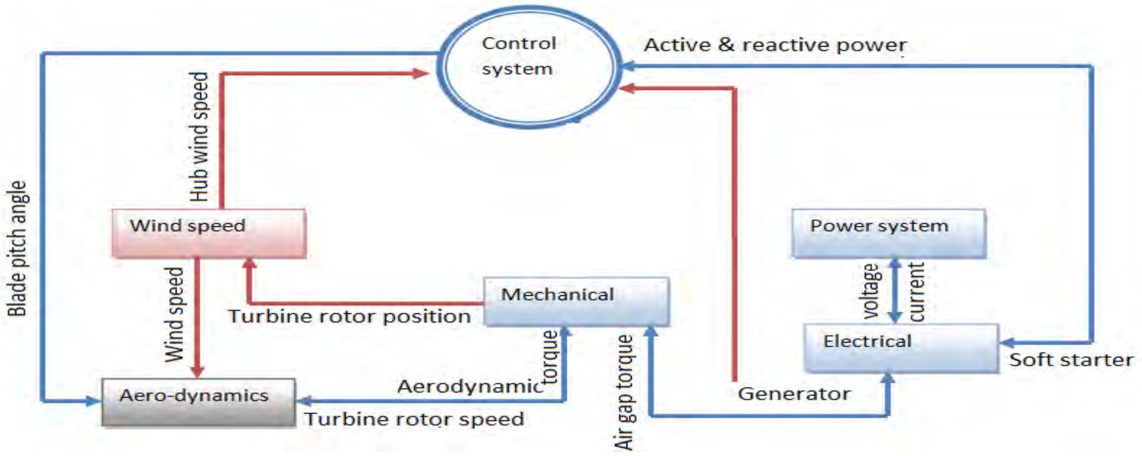


Figure 3.5: Wind turbine structure [**107**]

3.9 Wind Turbines

A wind turbine is a machine for converting the kinetic energy of wind into mechanical power [**109**], [**110**]. If the mechanical energy is used directly by machinery, such as a pump or grinding stones, the machine is usually called a windmill. But if the mechanical energy is then converted to electricity, the machine is called a wind generator or turbine.

3.9.1 Types of Wind Turbines configuration

There are four types of wind turbine configuration in use

Horizontal Axis Wind Turbine (HAWT) – Up Wind [109]

The shafts of the rotor and generator are positioned horizontally and the wind hits the blade before the tower. It is designed to operate in an upwind mode with the blades upwind of the tower. Large wind turbines use a motor-driven mechanism that turns the machine in response to a wind direction. The conversion process uses the aerodynamic force of lift to produce a net positive torque on a rotating shaft to produce mechanical power and then transforms it into electricity in a generator [**109**].

Horizontal Axis Wind Turbine (HAWT) – Down Wind [111]

The shafts of the rotor and generator are positioned horizontally and the wind hits the tower first then the blades. It operates in a downwind mode so that the wind passes the tower before striking the blades. Without a tail vane, the machine rotor naturally tracks the wind in a downwind mode as shown in Figure 3.6 below.

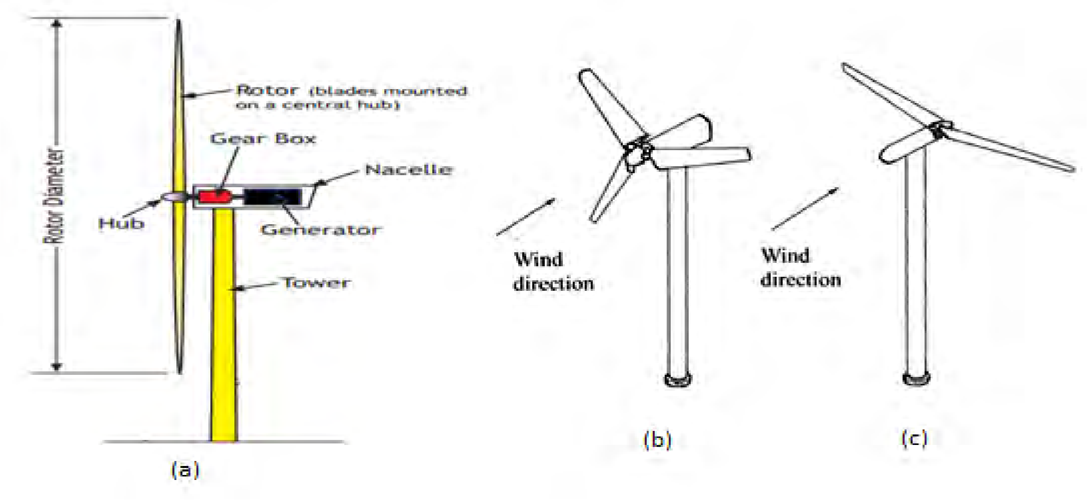


Figure 3.6: (a) Horizontal Axis Wind Turbines (HAWT), (b) upwind (c) downwind **[**111**]**

Vertical Axis Wind Turbine

This kind of wind turbines has existed for centuries (Figure 3.7), it is not as common as horizontal axis wind turbines, the main reason for this is that they cannot track the wind speeds at higher elevations above the ground. The Vertical Axis Wind Turbines do not require a yaw mechanism to harvest the wind energy [**112**]. Since the blades rotate 360 degrees on the vertical shaft of the wind turbines, wind of any direction can turn the turbine. It is known that the power generation efficiency of VATs is lower than that of HATs. Typical HATs face currents in one direction so electricity power can be generated during only a half of one tidal period. On the other hand, the power generation of a VAT does not need to consider directions of tidal currents. The maintenance of a VAT tidal current system is relatively less difficult because, its generator can be mounted over the seawater surface and its blades rotate on an axis perpendicular to the ground since the turbines are usually installed on or close to the ground level [**113**]. There are also 2 types of blades that are used on these turbines.

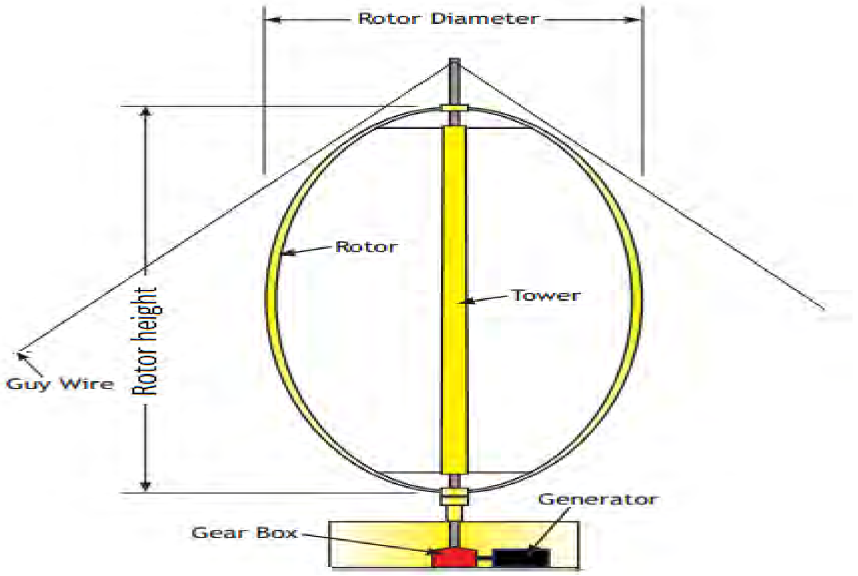


Figure 3.7: Vertical Axis Wind Turbines (VAWT) [**113**]

Vertical Axis Wind Turbine (VAWT) – Drag based: The generator shaft is positioned vertically with the blades pointing up. The blades are generally of flat type with large area. They are hit by the wind to cause the rotation. The turbines are usually mounted on the ground or a short tower. This type is also called the Savonius turbine, after its inventor, S. I. Savonius. It was invented in the 1920’s. It uses drag, like a cup anemometer, to produce torque. It is S-shaped if viewed from above. This drag-type VAWT turns relatively slowly, but yields a high torque. It is useful for grinding grain, pumping water, and many other tasks, but its slow rotational speeds make it unsuitable for generating electricity on a large-scale and has a relatively lower efficiency but, it is used in the developing countries because of its simple design, easy and cheap technology for construction and a good stating torque, independent of wind direction and starts at low wind speeds [**114**].

Vertical Axis Wind Turbine (VAWT) – Lift based: The generator shaft is positioned vertically with the blades pointing up. The blades use the lift design. This type is called Darrieus or egg beater, it was invented by Georges Darrieus and first patented in 1927 [**115**], is the most famous vertical axis wind turbine. It is characterised by its C-shaped rotor blades which give it its egg beater appearance. It is normally built with two or three blades. The Darrieus turbine is not self-starting. It needs to start turning before the wind will begin rotating it. It is used in most modern wind turbines and on airplanes. The design uses the aerodynamic properties of the blade profile to provide lift force to turn the blades such that the wind turbines can harvest the wind energy at high wind speed, with this design, the rich energy in the high wind speed area can then be harvested efficiently. The blade shapes are different than the lift type used on the Horizontal Axis Wind Turbines.

Giromill Wind Turbines

The giromill is typically powered by two or three vertical aerofoils attached to the central mast by horizontal supports. Giromill turbines work well in turbulent wind conditions and are an affordable option where a standard horizontal axis windmill type turbine is unsuitable.

Shrouded Wind Turbines

This is the type of turbines that have an added structural design feature called an augmentor. The augmentor is intended to increase the amount of wind passing through the blades.

3.10 Parts of a Wind Turbine [111]

Wind turbine consists of different parts which are stated and explained below

- The nacelle contains the key components of the wind turbine, including the gearbox, and the electrical generator.
- The tower of the wind turbine carries the nacelle and the rotor. Generally, it is an advantage to have a high tower, since wind speeds increase farther away from the ground.
- The rotor blades capture wind energy and transfer its power to the rotor hub.
- The generator converts the mechanical energy of the rotating shaft to electrical energy
- The gearbox increases the rotational speed of the shaft for the generator

3.10.1 Wind generators

There are five basic wind generators types that are very common in use. They can be categorized into either synchronous or asynchronous generator, fixed speed wind turbines or variable speed wind turbines. Figure 3.8 shows the topology of a variable speed wind energy converter. The advantages and disadvantages of each generator technology with respect to grid connection are hereby discussed.

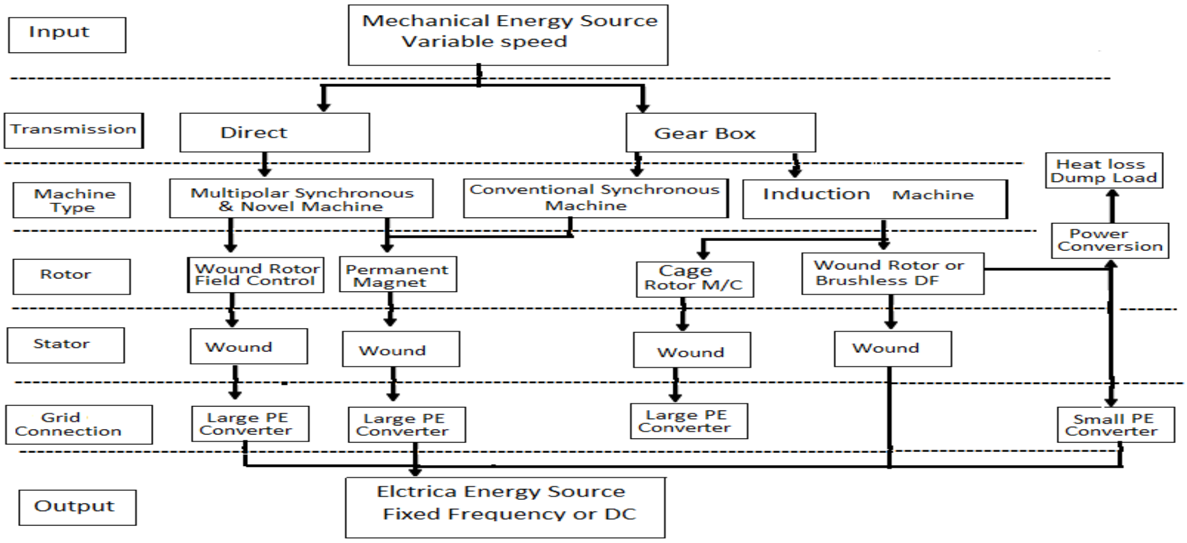


Figure 3.8: Variable speed wind energy converter topologies [**117**], [**118**].

Type I Wind Turbine [119]

The wind turbine generator is implemented with a squirrel-cage induction generator (SCIG) and is connected to a step-up transformer directly (Figure 3.9). The turbine speed is fixed to the electric grid's frequency, and generates real power (P) when the turbine shaft rotates faster than the electrical grid frequency, creating a negative slip. Normal operating slips for an induction generator are between 0 % and -1 %. Turbines typically operate at or very close to a rated speed. A major drawback of the induction machine is the reactive power that it consumes for its excitation field and the large currents the machine can draw when started across-the-line [**119**], [**120**].

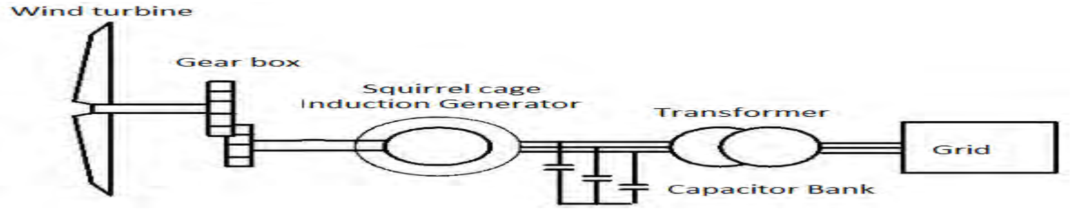


Figure 3.9: Squirrel cage synchronous wind turbine generators [**120**]

It lacks power electronic interfaces; therefore reactive power control is very difficult. The tracking of optimum active power and assuring power quality cannot be fulfilled. In case of a grid fault there is a large amount of fault current contribution, thus the turbines need to rely on protection devices, over current, over- and under voltage and under frequencies. As a result fixed speed wind turbines (FSWTs) cannot meet grid code demands without any form of external support such as FACTS devices.

Type II Wind Turbine

The wind turbine generator is implemented with wound rotor induction generators which are connected directly to the WTG step-up transformer through a soft starter in a fashion similar to Type 1, but it includes a variable resistor in the rotor circuit to control the rotor current. It is depicted in Figure 3.10 below.

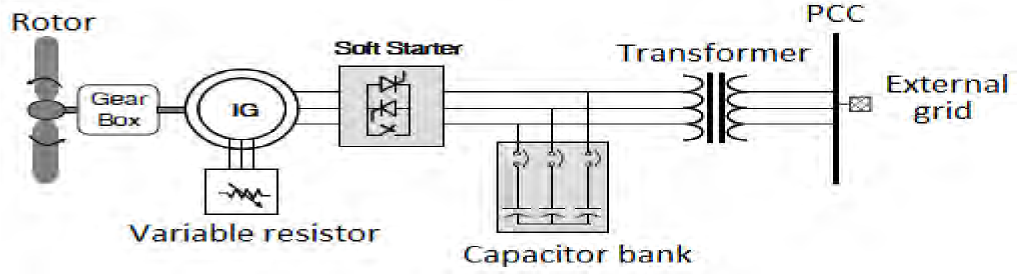


Figure 3.10: Wound rotor induction wind turbine generator [120]

An improvement can be made on the machine by adding resistance in series to the rotor winding so that it will spin faster to create output power, this will allow the increase of speed in the range of 0-10 % above synchronous speed, allowing for some degree of freedom in energy capture and self protective torque control.

Type III Wind Turbine

This category is the Variable Speed, Wind Turbine (VSWT) with Partial Scale Power Converter (PSPC). Variable frequency AC excitation is added (instead of simply resistance) to the rotor circuit. It uses a Doubly Fed Induction Generator (DFIG) or Asynchronous Generator (DFAG) with the stator connected to the grid and the rotor speed is controlled by a partially scaled power converter often a bidirectional power converter as shown in Figure 3.11 below. This rotor-side converter is connected back-to-back with a grid side converter, which transfer power directly to the grid. This capability will allow a speed variation in the range of ±30 % of the synchronous speed, the reactive power exchange is controlled by the grid-side converter, but the control is limited due to the partial rating of the converter.

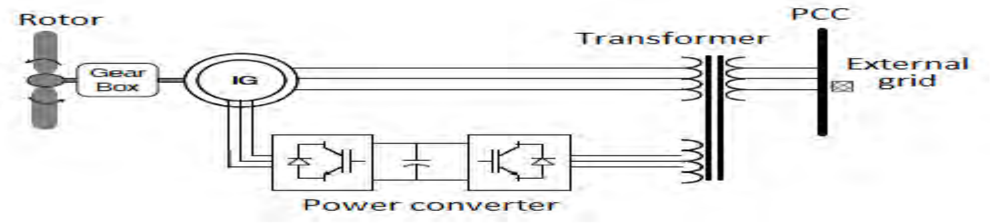


Figure 3.11: Doubly Fed Induction wind turbine generator [120]

Therefore, in large wind farms, additional reactive power support may be required from external sources. This concept in case of grid faults, contributes to the fault current but for very short periods because the control of the converter detects fast the voltage drop and disconnects the unit. The greatest advantage of the DFIG is that it offers the benefits of separate real and reactive power control, much like a traditional synchronous generator, while being able to run asynchronously. It is more expensive than the Type 1 or 2 machines; still it is becoming popular due to its advantages.

Type IV Wind Turbine

The Type 4 turbine offers a great deal of flexibility in design and operation as the output of the rotating machine is sent to the grid through a full-scale back-to- back frequency converter as depicted in Figure 3.12. The turbine is allowed to rotate at its optimal aerodynamic speed, resulting in an AC generated from the output of the machine [**120**].

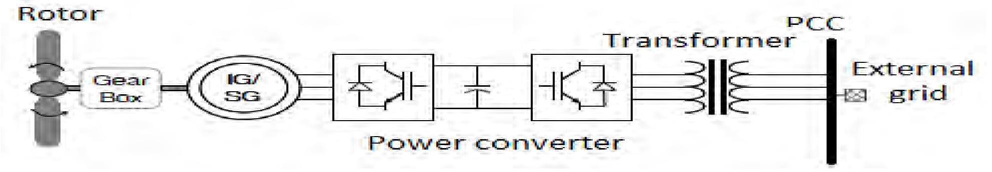


Figure 3.12: Wound rotor synchronous generator [**120**]

The gearbox can be eliminated, such that the machine spins at the slow turbine speed and generates at an electrical frequency well below that of the grid. More than one generator type can be supported by this concept; any machine can be used such as permanent magnet synchronous machines. It does not contribute to the fault currents due to the converter topology, but has set back in that the converter injects harmonics to the network.

Type V Wind Turbine

It consists of variable-speed drive train connected to a torque/speed converter coupled with a synchronous generator (Figure 3.13). The speed converter changes the variable speed of the rotor shaft to a constant output speed. The closely coupled synchronous generator, operating at a fixed speed corresponding to grid frequency, can be directly connected to the grid through a synchronizing circuit breaker.

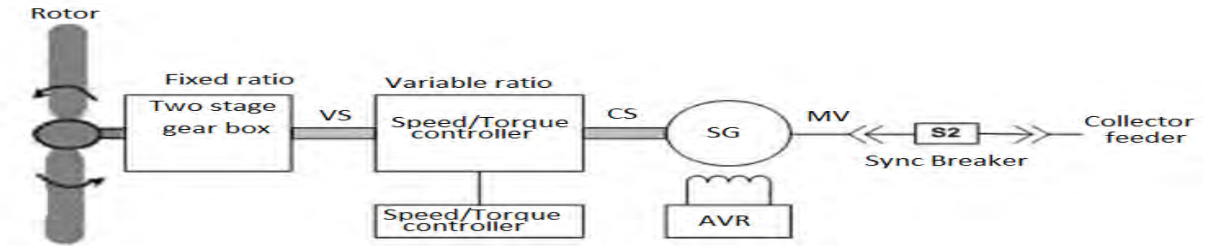


Figure 3.13: Type V wind turbine [120]

Where:
VS = Variable speed
CS = Constant speed
MV = Medium voltage
The turbine controller, sensor and protection are not shown

The synchronous generator can be designed appropriately for any desired speed typically 6 poles or 4 poles and medium voltage or higher capacities. This approach requires speed and torque control of the torque/ speed converter along with the typical voltage regulator (AVR), synchronizing system, and generator protection system inherent with a grid-connected synchronous generator [**120**].

3.11 Doubly fed Induction Generator

Doubly fed induction generator has been receiving increasing attention due to the fact that it is more controllable and efficient, it can supply power at constant voltage and frequency while the rotor speed varies, it is not necessarily to be magnetized from the power grid since it can be magnetized from the rotor circuit, the size of the converter is not related to the total generator power but to the selected speed range and hence to the slip power. In this section, modelling of doubly fed induction generator is considered.

3.11.1 Doubly fed induction generator modelling

The DFIG is a wound rotor induction generator, where the rotor circuit is connected to the grid through power electronic devices. The ability to supply or subtract power to or from the rotor makes it possible to operate the DFIG at sub- or super-synchronous speed, while keeping constant voltage and frequency on the stator terminals. Therefore, the DFIG is often used where variable speed, constant frequency generation is required.

The working principle of a DFIG is based on its capability to control its speed through rotor resistance variation that is the reason why DFIG is wound rotor. With different values for the rotor resistance, for the same electrical power, it is possible to have different values for the speed of the machine. The control of terminal voltage or power factor by the DFIG is performed by the two back-to-back converters connected to the rotor replacing the variable rotor resistance [**121**]. Therefore, electrical power can be transferred through the machine's rotor, until the nominal value of the stator current is reached, the output power is thereby controlled in order to optimize the tip speed ratio of the rotor blade and to maximize the performance coefficient of the turbine. When the direct axis current is used to control the dc link voltage constant, and quadrature axis current regulate the reactive power flow, constant output power can be attained.

The velocity control through the use of the slip energy provides the possibility of the machine to be working as a generator when the slip is positive. This is only possible if active power is supplied to the rotor.

The AC/DC/AC converter is divided into two components: the rotor-side converter and the grid-side converter. Grid side converter and rotor side converter are Voltage-Sourced Converters that use forced-commutated power electronic devices (IGBTs) to synthesize an AC voltage from a DC voltage source. A capacitor connected on the DC side acts as the DC voltage source [**122**], [**123**]. A coupling inductor L is used to connect the grid side converter to the grid. The three-phase rotor winding is connected to rotor side converter by slip rings and brushes and the three-phase stator winding is directly connected to the grid. The power captured by the wind turbine is converted into electrical power by the induction generator and it is transmitted to the grid by the stator and the rotor windings. The control system generates the pitch angle command and the voltage command signals Vr and Vgc for rotor side and grid side converter respectively in order to control the power of the wind turbine, the DC bus voltage and the reactive power or the voltage at the grid terminals.

In recent years, the use of VSWT has become worldwide. This type of wind turbine was designed to increase the aerodynamic efficiency in various ranges of wind speeds. Their electrical system is more complex than the fixed-speed wind turbines. Better power qualities, higher amount of energy extracted and less mechanical stress on the turbines are considered as the major advantages of VSWTs. The scope of this dissertation will be limited to the VSWTs with a partial converter (DFIG) concepts as it is the state of the art turbine technologies, the equivalent circuit of the DFIG is shown in Figure 3.14 below.

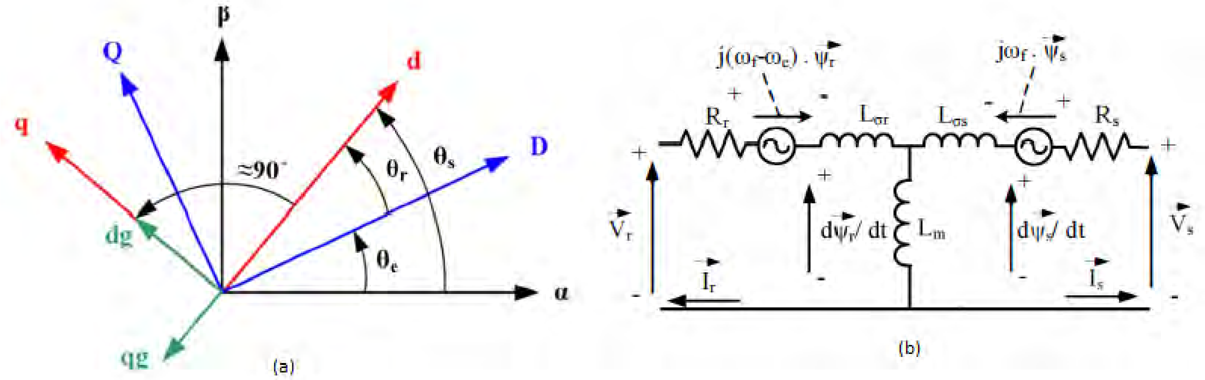


Figure 3.14: (a) Relation among different reference frames and (b) Electrical model of DFIG [124]

There are four different reference frames in the complex plane for the DFIG system:

- Stator reference frame ($\alpha - \beta$);
- Rotor reference frame (D–Q);
- Synchronous reference frame (d–q);
- Grid voltage vector reference frame

Figure 3.15 (a) shows the relation among the aforementioned reference frames. θ_s θ_r and θ_e are the synchronous angle, the slip angle, and the electric angle of the rotor, respectively. The dg–qg reference frame is almost 90^0 ahead of the synchronous reference frame. With the relation among these reference frames, the space vector can be easily transformed into any reference frame by the following mathematical equation:

$$\overrightarrow{X^{final}} = \exp(-\theta).\ \overrightarrow{X^{initial}} \text{..........} \quad (3.1)$$

Where θ is the angle between two reference frames, the vector of X can be represented as voltage, current, and flux.

Doubly fed induction generators consists of three-phase windings on both stator and rotor. According to the Lenz's law, the induced voltage depends on the variation of flux and turns ratio of the inducing side core. The voltage equations of the space vector for the stator and rotor are:

$$\overrightarrow{\mathrm{V}_{s}^{\mathrm{s}}}\,(\mathrm{t}) = \mathrm{R_s}\overrightarrow{\imath_{s}^{\mathrm{s}}}\,(\mathrm{t}) + \frac{d\overrightarrow{\psi_{s}^{\mathrm{s}}(t)}}{dt} \tag{3.2}$$

$$\overrightarrow{\mathrm{V}_{r}^{\mathrm{r}}}\,(\mathrm{t}) = \mathrm{R_r}\overrightarrow{\imath_{r}^{\mathrm{r}}}\,(\mathrm{t}) + \frac{d\overrightarrow{\psi_{r}^{\mathrm{r}}(t)}}{dt} \tag{3.3}$$

Where the superscripts “s” and “r” indicate the space vectors that are referred to the stator and rotor reference frame.

When equation (3.1) is inserted into (3.3) it becomes

$$\overrightarrow{\mathrm{V}_{r}^{s}}\,.\,e^{-j\theta_\mathrm{e}} = \mathrm{R_r}\overrightarrow{\imath_{r^{s}}}\,.\,e^{-j\theta_\mathrm{e}} + \frac{\mathrm{d}\left(\overrightarrow{\psi_{r}^{s}}\,.e^{-j\theta_\mathrm{e}}\right)}{d\mathrm{t}} \tag{3.4}$$

$$\overrightarrow{\mathrm{V}_{r}^{s}}\,.\,e^{-j\theta_\mathrm{e}} = \mathrm{R_r}\overrightarrow{\imath_{r^{s}}}\,.\,e^{-j\theta_\mathrm{e}} + \frac{d\overrightarrow{\psi_{r}^{s}}}{dt}.\,e^{-j\theta_\mathrm{e}} - \mathrm{j}w_\mathrm{e}\overrightarrow{\psi_{r}^{s}}\,.\,e^{-j\theta_\mathrm{e}} \tag{3.5}$$

$$\overrightarrow{\mathrm{V}_{r}^{s}}\,(\mathrm{t}) = \mathrm{R_s}\overrightarrow{\imath_{r}^{s}}(t) + \frac{\mathrm{d}\overrightarrow{\psi_{r}^{s}(\mathrm{t})}}{\mathrm{dt}} - \mathrm{j}w_\mathrm{e}\overrightarrow{\psi_{r}^{s}}(t) \tag{3.6}$$

The relation between the fluxes and currents in the space vector can be expressed as

$$\overrightarrow{\psi_{s}^{s}} = \mathrm{L_s}\overrightarrow{\imath_{s}^{s}} + \mathrm{L_m}\overrightarrow{\imath_{r}^{s}} \tag{3.7}$$

$$\overrightarrow{\psi_{r}^{\mathrm{r}}} = \mathrm{L_m}\overrightarrow{\imath_{s}^{\mathrm{r}}} + \mathrm{L_r}\overrightarrow{\imath_{r}^{\mathrm{r}}} \tag{3.8}$$

By substituting equation (3.1) into (3.8)

$$\overrightarrow{\psi_{r}^{s}}.\,e^{-j\theta_\mathrm{e}} = \mathrm{L_m}\overrightarrow{\imath_{s}^{s}}.\,e^{-j\theta_\mathrm{e}} + \mathrm{L_r}\overrightarrow{\imath_{r}^{s}}.\,e^{-j\theta_\mathrm{e}} \tag{3.9}$$

$$\overrightarrow{\psi_{r}^{s}} = \mathrm{L_m}\overrightarrow{\imath_{s}^{s}} + \mathrm{L_r}\overrightarrow{\imath_{r}^{s}} \tag{3.10}$$

Solving the $\overrightarrow{\imath_{s}^{s}}$ and $\overrightarrow{\imath_{r}^{s}}$ by using the equation (3.7) and (3.10), it becomes

$$\overrightarrow{\imath_{s}^{s}} = \frac{\mathrm{L_r}\overrightarrow{\psi_{s}^{s}} - \mathrm{L_m}\overrightarrow{\varphi_{r}^{s}}}{\mathrm{L_s L_r} - L_m^2} \tag{3.11}$$

$$\overrightarrow{\imath_{r}^{s}} = \frac{\mathrm{L_s}\overrightarrow{\psi_{\mathrm{r}}^{s}} - \mathrm{L_m}\overrightarrow{\varphi_{s}^{s}}}{\mathrm{L_s L_r} - L_m^2} \tag{3.12}$$

Replacing (3.11) and (3.12) with (3.2) and (3.6), respectively, yields the state equations of DFIG, as follow:

$$= \frac{d\overrightarrow{\psi_{s}^{s}}}{d\mathrm{t}} = -\frac{\mathrm{R_s L_r}}{\mathrm{L_s L_r} - L_m^2}\,\overrightarrow{\psi_{s}^{s}} + \frac{\mathrm{R_s L_m}}{\mathrm{L_s L_r} - L_m^2}\,\overrightarrow{\psi_{r}^{s}} + \overrightarrow{\mathrm{V}_{s}^{s}} \tag{3.13}$$

$$= \frac{d\overrightarrow{\psi_{rq}^{s}}}{d\mathrm{t}} = -\frac{\mathrm{R_r L_m}}{\mathrm{L_s L_r} - L_m^2}\,\overrightarrow{\psi_{s}^{s}} + \left(\mathrm{j}w_\mathrm{e}\frac{\mathrm{R_r L_s}}{\mathrm{L_s L_r} - L_m^2}\right)\overrightarrow{\psi_{r}^{s}} + \overrightarrow{\mathrm{V}_{r}^{s}} \tag{3.14}$$

3.12 Overview of FACTs Devices for Wind Energy Integration

The advent and usage of power electronics device or FACTS devices for the mitigation of most power quality challenges encountered in the integration of renewable energy sources into the distribution system have made it to be more popular. It helps with the conversion and control of electrical power with the help of electronic switching devices. Most of the FACTS devices have the ability to generate and control both the capacitive and inductive power with fast response unlike capacitors that cannot generate both at the same; a capacitor is very slow in action and cannot be used to mitigate the transient case.

3.12.1 Flexible Alternating Current Transmission Systems (FACTS)

The main objective of the power system operation is to match supply and demand, provide compensation for transmission loss, voltage, frequency regulation, reliability provision, more efficient and fast responding electrical systems. This has given rise to innovative technologies in transmission using solid-state devices called FACTS. Its controller is power electronics-based systems that provide control of one or more AC transmission system parameters (series impedance, shunt impedance, current, voltage, phase angle). FACTS controllers are grouped according to how they are connected into the power system i.e shunt, series, and shunt-series connection. They can be active static switch or impedance converter or combination. They inject voltage in series or inject current in shunt or both. They enhance stability and increase line loadings closer to thermal limits [**125**]. The continuing rapid development of high-power semiconductor technology now makes it possible to control electrical power systems by means of power electronic devices. Voltage collapse is one of the major problems which electric power networks face, according to the IEEE Power System Engineering Committee, voltage stability is the ability of a system to maintain voltage when there is an increase in load admittance and load power and both power and voltage can be controlled [**126**], [**127**], [**128**].

The problem of voltage instability can be solved by using dynamic reactive compensation, FACTS devices, such as the static VAR compensator (SVC), Thyristor controlled phase angle regulator (TCPAR), Thyristor controlled series compensator (TCSC), static synchronous series compensator (SSSC), unified power flow controller (UPFC), interline flow power controller (IFPC), generalized unified power flow controller (GUPFC), hybrid power flow controllers (HPFC), and the Static Synchronous Compensator (STATCOM). They have been widely used to provide high-performance steady state and transient voltage control at the point of common coupling (PCC) [**129**], [**132**] [**131**].

If a large wind farm, which is electrically far away from its connection point to the power system, is not fed by adequate reactive power, it presents major instability problem. Though Doubly-Fed Induction Generators (DFIGs), which have the feature of regulating the reactive power demand, have emerged, many of the wind farms worldwide still employ either squirrel-cage induction generators or wound rotor induction generators (WRIG) [**132**].

Growing capabilities of power electronic components resulted in creation of controllers with much faster response time, due to their lack of mechanical switch inertias, lower transient over-voltages are obtained when using semiconductor devices; also a smooth, gradual change in var output is made, compared to the large discrete steps that arise from mechanical switching in capacitor and/or reactor banks. The usage of semiconductor switches instead of mechanical switches, led to an increased lifetime of the system with less maintenance. The drawback of this technology is that it is more expensive.

FACTS controllers using semiconductor devices are the fastest option for obtaining maximum system benefits. They are capable of controlling the network condition in a very fast manner and this feature of FACTS can be exploited to improve the voltage stability, steady state and transient stabilities of a complex power system. This allows increased utilization of existing network closer to its thermal loading capacity, and thus, avoiding the need to construct new transmission lines [**133**], [**134**], [**135**], [**136**], [**137**], [**138**].

FACTS devices can be of two categories namely; Thyristor valve and Voltage source converter. Old generation FACTS devices used thyristor valves while the new generation focuses on using the voltage source converter. The main difference between those two categories is that VSC technology is much faster and has a bigger range of control [**139**]. The overview of FACTs devices is shown in Table 3.1 below.

3.12.2 Uses of FACTS Controllers [136]

FACTS devices find their application in the power system as stated below:

- Power flow control
- Increase of transmission capacity
- Voltage control
- Reactive power compensation
- Stability improvement
- Power quality improvement
- Power conditioning
- Flicker mitigation
- Interconnection of renewable and distributed generation and storage
- Provide greater flexibility in siting new generation

Table 3.1: Overview of FACTS devices [**132**]

Connection mode	Conventional Switch	FACTS Devices (Fast, Static)	
		Thyristor valve controller	Voltage source converter (VSC)
Shunt devices	Switched shunt compensation (LC)	Static Var compensator (SVC)	Static synchronous compensator (STATCOM)
Series devices	Switched series compensation (LC)	Thyristor controlled series compensator (TCSC)	Static synchronous series compensator (SSSC)
Shunt and series devices	Phase shifting transformer	Dynamic flow controller (DFC)	Unified/Interline power flow
Shunt and series devices	-	HVDC Back to back (HVDC B2B)	HVDC VSC Back to back (HVDC-VSC B2B)

3.12.3 Reactive Power Compensation Principles

In alternating current systems power may periodically reverse direction during each cycle of voltage or current. Stored energy in the magnetic or electric field of a load device such as capacitor or a reactor during a quarter of a cycle, it is sent back to the power source in the next quarter cycle thus causing an offset between the current and the voltage waveforms. However, this reactive power that oscillates between the AC source and the capacitor or reactor does it at a frequency equal to two times the rated value (50 or 60 Hz). The two components power thus, one component flows steadily from source to load and can perform work at the load, the other one which is reactive power, is due to the delay between voltage and current and cannot do useful work at the load. For this reason it can be compensated using VAR generators, avoiding its circulation between the load (inductive or capacitive) and the source, and therefore improving voltage stability of the power system. Reactive power compensation can be implemented with FACTS devices connected in parallel or in series.

3.12.4 Reactive Power Compensation

VAR compensation is defined as the management of reactive power to improve the performance of AC power systems. Most power quality problems can be attenuated or solved with an adequate control of reactive power [**140**], [**141**]. The problem of reactive power compensation is viewed from two aspects namely load compensation and voltage support.

Load compensation: the objectives are to increase the value of the system power factor, to balance the real power drawn from the AC supply,

compensate voltage regulation and to eliminate current harmonic components produced by large and fluctuating nonlinear industrial loads
Voltage support: it is generally required to reduce voltage fluctuations at a given terminal of a transmission line. Also, it can improve the voltage of the network when the grid voltage is too low because the presence of reactive power tends to increase network voltage.

3.12.5 Why Dynamic Voltage & reactive power support?

- To prevent system collapse and voltage instability in the occurrence of certain contingencies
- It is very important during power system disturbances such as faults

3.12.6 Reactive Power Effects on the System Operation [142]

Reactive power is made available by components which are included in the system itself and by other components which are added to the system for balancing the system reactive power. The reactive power sources in a system and their compensation components are depicted in Table 3.2 below.

3.12.7 The Need for Reactive Power Compensator

When an induction generator is used for wind energy generation, it consumes reactive power which causes reduction in the voltage profile of wind power plants. Induction generator during start-up requires current of about 7 to 8 times larger than its nominal range at 1.5 second and it causes sudden reduction in the operating voltage of power plant therefore, manufacturers are looking for better solutions to supply reactive power **[143]** , **[144]**, **[147]**.

Table 3.2: Reactive power sources and Voltage support [**142**]

Var Sources in System Components (Static support)	Var Sources in Compensation Components (Dynamic support)
Inductances in electrical machines	Mechanically switched reactors and capacitors
Transmission lines, transformers, and reactors	Synchronous condensers
Capacitances in transmission lines, and cables	Thyristor controlled shunt and series compensation Converter controlled shunt and series compensation

3.12.8 Reactive Power Compensation of Wind Integration

An important operating characteristic of the fixed speed generator is that this type of generator always consumes reactive power, which is undesirable for the transmission system, particularly in the case of large turbines and weak distribution system. Another characteristic of the fixed speed generator such as squirrel cage induction generators is that, in general, this type of generator tends to slow down voltage restoration after a voltage collapse due to its consumption of reactive power and this can lead to voltage and rotor speed instability. When the voltage does not return quickly enough, the generator continues to accelerate and consumes even larger amount of reactive power. This process eventually leads to voltage and rotor speed instability if the wind turbine is connected to a weak system, but in case of variable speed generator such as DFIG, it can still control the reactive power to some extent but it may need to be compensated when large wind farm is required [**146**].

The reactive power compensation of the wind integration is classified into three categories:

- Static synchronous Compensator STATCOM
- Static Var Compensator SVC
- Switchable Capacitor Banks

Static Synchronous Compensator - STATCOM

The STATCOM is a shunt connected reactive power compensation device (FACTS device) that is capable of generating and/ or absorbing reactive power in which the output voltage can be varied to control the specific parameters of an electric power system [**147**]. STATCOM is a Voltage-Source Inverter (VSI), which converts a DC input voltage into AC output voltage in order to compensate the active and reactive power needed by the system [**148**], [**151**]. It exhibits constant current characteristics when the voltage is low or high, under and over the limit, this allows STATCOM to deliver constant reactive power. The relation between the AC system voltage and the voltage at the STATCOM AC side terminals provides the control of reactive power flow. If the voltage at the STATCOM terminals is higher than the system voltage, reactive power will be injected from STATCOM to the system and STATCOM will work as a capacitor. When the voltage at the STATCOM is less than the AC voltage, STATCOM will work as an inductor, and reactive power flow will be reversed [**151**], [**152**], [**151**], [**147**]. The connection of the STATCOM and the equivalent circuit are shown in Figure 3.15.

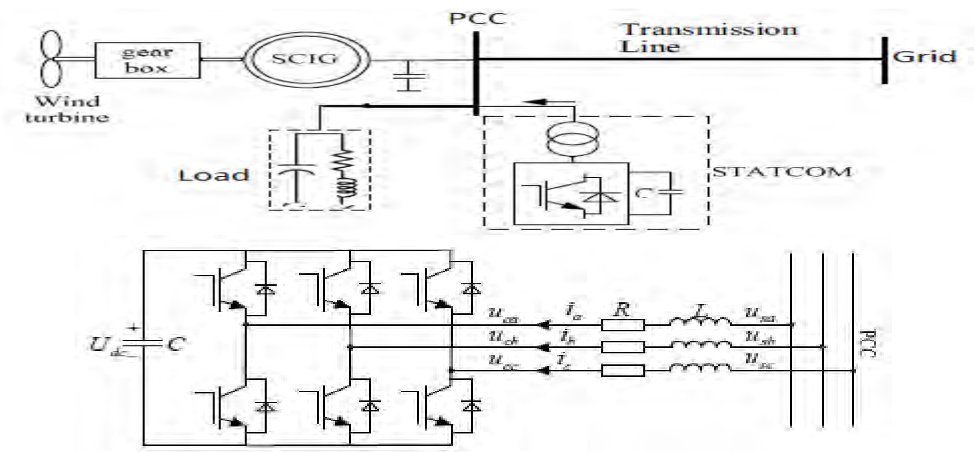
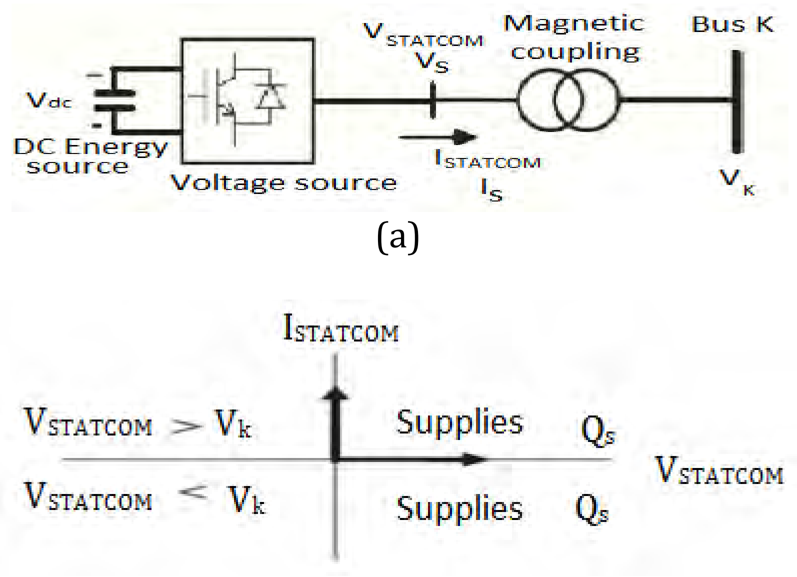


Figure 3.15: STATCOM Scheme and equivalent circuit representation [**142**]

Principle of Operation

If the voltage V_s is below V_k in Figure 3.16 (a), the current through the inductor is phase shifted in relation to the voltage V_k which provides an inductive current, then Qs becomes positive and the STATCOM absorbs reactive power as depicted in Figure 3.16 (b) below.



(a)

(b)

Figure 3.16: Single line STATCOM power circuit and operation [**152**]

If the voltage V_s exceeds V_k the current through the inductor is phase shifted in relation to the voltage V_k which provides a capacitive current, then Qs becomes negative and the STATCOM generates reactive power. If the voltage V_s is equal to V_k the current through the inductor is zero and therefore there is no exchange of energy [**152**].

Applications of STATCOM [147]

Over the last two decades, advancements in static reactive compensation (STATCOM) technology based on voltage source converter (VSC) concepts have produced significant benefits:

- Improves power factor
- Assist voltage after grid faults
- Stabilization of weak system voltage
- Reduced transmission losses
- Enhance transmission capacity
- Flicker mitigation
- Power oscillation damping
- Reduce harmonics

3.12.9 Types of Static Volt Ampere Reactive Compensation (SVC) [140]

Static VAR Compensator (SVC) is an important FACTS device that has been used for a number of years in the improvement of transmission line problem by resolving dynamic voltage problems [**156**]. SVC is a shunt-connected static Var generator or absorber whose output is adjusted to exchange capacitive or inductive current to maintain or control specific parameters of the electrical power system such as bus voltages. SVC can be one of the following types:

- Thyristor controlled Reactor (TCR)
- Fixed capacitor–Thyristor Controlled Reactor (FC–TCR)
- Thyristor switched Capacitor (TSC)
- Thyristor Controlled Reactor–Thyristor Switched Capacitor (TCR–TSC)

It consists of a combination of a fixed capacitor or reactor, Thyristor switched capacitors and Thyristor controlled reactors connected in parallel with the electrical system. It can be represented by an equivalent TC-TCR circuit shown in Figure 3.17 below.

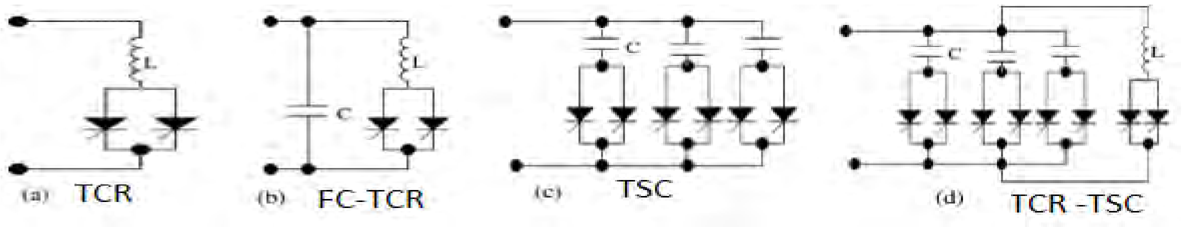


Figure 3.17: Types of SVC [**153**]

The TCR consists of a fixed reactor or an inductor (L) and a bi-directional Thyristor valve. The Thyristor valves are fired symmetrically at an angle, a control range of 90^0 to 180^0, with respect to the SVC voltage. If the controlling voltage equal to the bus voltage performing a Fourier series analysis of the inductor current waveform, the TCR at fundamental frequency can be considered to act like a variable inductance X_{tcr} [**154**], [**155**]

$$X_{tcr} = X_L \frac{\pi}{2(\pi-\alpha)+sin2\alpha} \qquad (3.15)$$

Where

X_L = the reactance caused by the fundamental frequency without thyristor control

α = the firing angle.

Hence, the total equivalent impedance of the controller can be represented as:

$$X_{SVC} = \frac{\boldsymbol{X_C X_L}}{\frac{\boldsymbol{X_C}}{\boldsymbol{\pi}}[\boldsymbol{2(\pi-\alpha)+Sin\ 2\alpha})-\boldsymbol{X_L}} \qquad (3.16)$$

The SVC is connected to a coupling transformer that is connected directly to the AC bus whose voltage is to be regulated for the Fixed Capacitor-Thyristor Controlled Reactor (FC-TCR) configuration as shown in Figure 3.18 below. The SVC is considered as a continuous, shunt variable susceptance, which is adjusted in order to achieve a specified voltage magnitude while satisfying constraint conditions. Suitable control of this equivalent reactance is brought about by varying the current through the TCR by controlling the gate firing instant of the Thyristors and the equivalent susceptance is thus a function of the firing angle [**159**], [**158**]. The effective reactance is varied by firing angle control of the anti parallel Thyristors. The firing angle can be controlled through a PI (Proportional + Integral) controller in such a way that the voltage of the bus, where the SVC is connected, is maintained at the reference value.

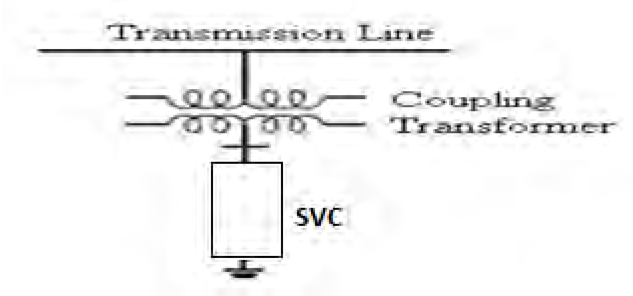


Figure 3.18: Configuration of SVC [**159**]

Uses of SVC

The potential benefits of SVC are now widely recognized in power systems engineering. It uses power electronic controlled devices to control power flows in a transmission network, thereby allowing transmission line plant to be loaded to its full capability. The benefits are stated below:

- Stabilized voltage at the receiving end of long lines
- Increased productivity as stabilized voltage better utilizes capacity
- Reduced reactive power consumption, gives lower losses and eliminates higher or penalty tariffs
- Balanced asymmetrical loads reduce system losses
- Lower stresses in asynchronous machinery
- Enables better use of equipment (particularly transformers and cables)
- Reduced voltage fluctuations and light flicker

Chapter 4

Integration Issues Associated with Renewable Energy Resource

Introduction

In the past, individual wind turbines or smaller wind farms were connected to distribution networks due to the smaller amount of integration, thereby it is regarded as negative load by most of the transmission operators [**160**]. In recent years, owing to increased emphasis on renewable resources, development of suitable isolated power generators driven by energy sources such as wind, has assumed greater significance, as wind turbines from larger farms reached comparable levels with conventional power plants. However, transmission system operators' concern grew due to some integration and network problems like power quality, network stability problems, voltage control, reactive power consumption by most wind generators, interfacing, power factor problem, and frequency deviation. Transmission system operators issued a number of requirements for wind turbines to fulfil in order to get grid connection agreement. These requirements were called grid codes (it is discussed later in this dissertation), and they became more demanding as wind penetration levels increased. For the efficient integration of renewable energy into a network, all these problems and challenges must be attended to and solved.

4.1 Integration issues with renewable energy supply [163]

In power system engineering, system integration is defined as the process of bringing together the component subsystems into one system and ensuring that the subsystems function together as a system.

The integration issue associated with the renewable energy sources is broadly classified into:

- Technical
- Nontechnical.

4.1.1 Technical Issues [163]

Renewable energy sources; solar and wind power generation are highly variable and intermittent. The major technical challenges of integrating renewable generation into utility grid are as follows:

Input variability of the renewable energy sources and the energy demand fluctuations [166]

The sun can vary during the raining season, dry season can reduce the flow to hydroelectric plants, wind may cease to blow for hours, or can be a drawback if it blows at night when there is little or no demand for the energy generated [**166**], tidal power has a cyclic nature, marked by extreme peaks during extreme events such as storms and hurricanes, solar power is equally unpredictable and highly variable in the night. Power generated by renewable energy sources fluctuates significantly on a daily, weekly, monthly and seasonal basis, the same way, loads also fluctuates with different time constants hourly, weekly, monthly and seasonal. There may also be periods of the year with cold weather, no wind, cloudy weather where demand for energy is particularly high and production of energy is particularly low. There must be solutions on how to integrate different sources seamlessly into a single network to supply power cheaply, safely and dependably.

Grid reliability and stability [163]

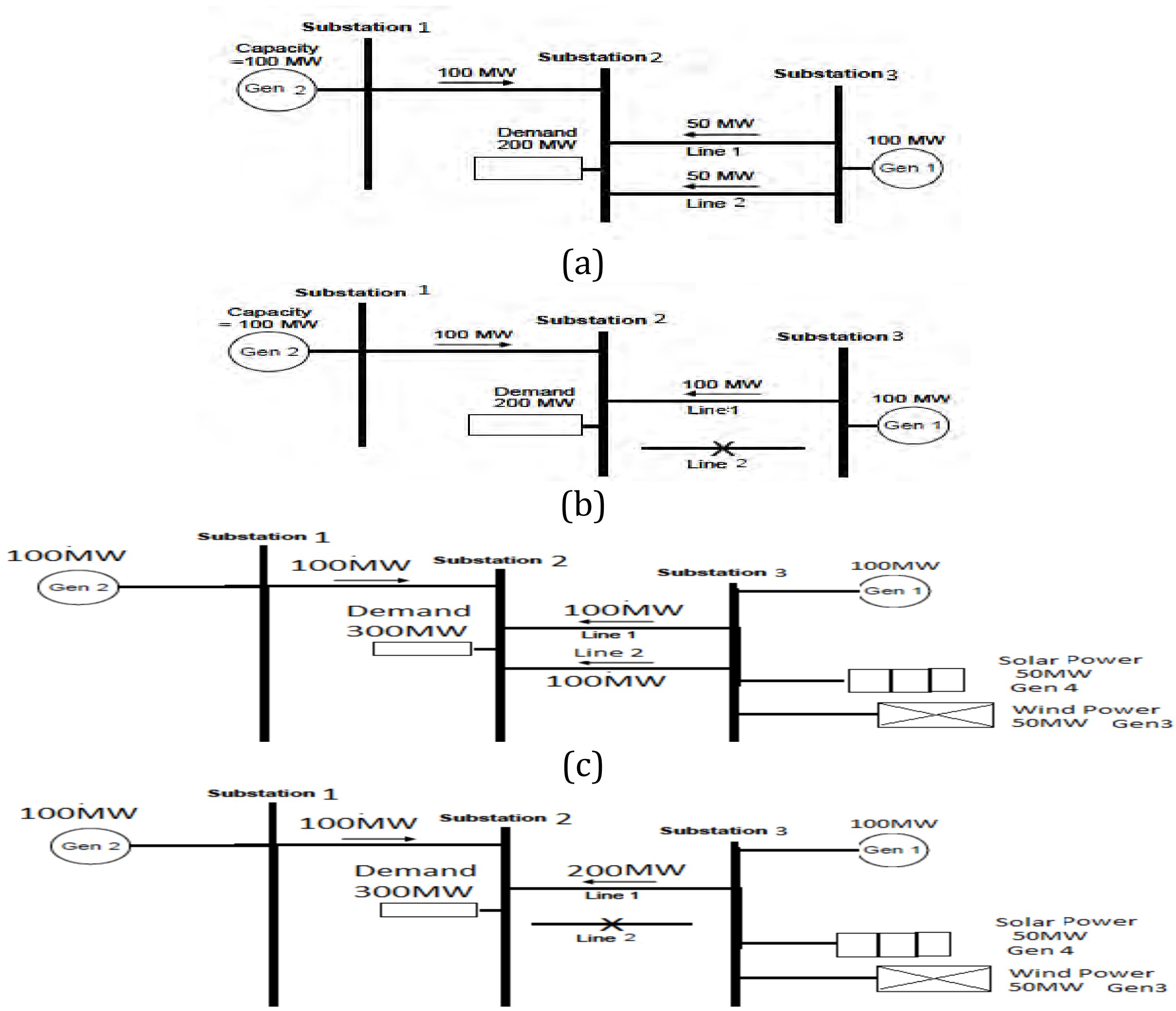
Due to the deployment of the renewable energy into the power system, Transmission operators need to use a number of techniques to improve grid reliability, such as real-time control and monitoring systems to acquire information on the state of the network and make power available on demand, since a power system is no longer a traditional centralised structure, a highly dynamic grid is required, where the electrical network is intertwined with information and telecommunication flows. The distribution network is no longer radial, power flows are no longer defined by the energy from the parent network, which flows to the end user. Renewable energy sources bring a new level of uncertainty in the development, planning and management of the distribution network.

Compatibility, interface, control and standardisation [160]

Lack of standardisation means that the different power systems cannot communicate with each other, equipment from different manufacturers cannot always function properly together, different conversion systems are required before integration of RES to the Grid, a stable grid interfacing is required to feed the grid without any fluctuation e.g. AC to DC, DC to AC etc.

Lack of Sufficient Transmission Infrastructure [167]

The largest barrier to renewable integration is insufficient transmission facilities, associated cost-allocation in a region to access the renewable resources, and connecting these resources to load centres [**167**]. A proper explanation can be done by using Figure 4.1 below for illustration. Figure 4.1 (a) shows the original transmission network under normal operation. Assuming that, the Lines 1 and 2 ratings are 100 MW each. The grid remains secure under N-1 contingency with Line 2 out of service, as shown in Figure 4.1 (b). If some renewable energy sources are added due to increase of loads, as shown in Figure 4.1 (c), it may still be acceptable during normal operation. However, N-1 contingency as indicated in Figure 4.1 (d) with an outage of Line 2 can cause overload of Line 1, consequently, creates a risk of forced tripping of Gen 1, Gen 3 and Gen 4 and interrupting the 200 MW load connected to Sub 2.



(a)

(b)

(c)

Figure 4.1: (a) Two Generations and Three-Bus System (b) Single Contingency of the System (c) Normal Operation of the System with Renewable Generation Connection (d) Single Contingency of the System with Renewable Generation Connection [167]

Storage [168**]**

Lack of storage facility is one of the critical problems that affect the integration of renewable energy source into the grid. Since the power generated from the renewable energy sources varies, there is a need for proper energy storage facility to back up the generation during the unavailable period thus increasing the reliability of the power supply [**168**].

Protection Issues [169**]**

Protection against fault is an important aspect of the power system that needs to be considered. Protection during islanding operations and protection for the backup storage to avoid back feed during the critical fault level [**169**].

4.1.2 Non- Technical Issues

Lack of technical skilled manpower [161**]**

There is insufficiency of technical manpower to maintain the technology of RES. It really requires the service of trained personnel to monitor the operation of most of the equipment for proper optimisation [**161**].

Less availability of transmission line [167**]**

Less available transmission lines to accommodate RES is also another issue. Most of the existing lines need to be replaced for an appropriate rating and size. Some lines need to be upgraded to accommodate RES.

4.2 Mitigation Measures of RES Integration

The solutions to most of the issues above are discussed below:

4.2.1 Power Electronic Technology [170]

Power-electronic technology plays an important role in distributed generation and integration of renewable energy sources into the electrical grid, and it is widely used and rapidly expanding as these applications become more integrated with the grid- based systems. During the last few years, power electronics has undergone a fast evolution, which is mainly due to two factors. The first one is the development of fast semiconductor switches that are capable of switching quickly and handling high powers. The second factor is the introduction of real- time computer controllers that can implement advanced and complex control algorithms. These factors together have led to the development of cost- effective and grid-friendly converters [**170**]. Table 4.1 below shows in brief the application of power electronics.

Table 4.1: Main applications, benefits and requirements of power electronics [**171**]

	Consumer electronics	Automotive transport	Power grids and industry
Application	Battery chargers Switching power supplies Portable devices Household appliances	Trains Automotive Aerospace	Generation (conventional and alternative) Distribution Load side Storage
Benefits	More efficient system Energy savings Stability and robustness Decrease size and weight	More electrical vehicles More efficient and availability New power and traction system Low maintenance cost Storage and regenerative system	More efficient and stability More integration of alternative energies More grid flexibility Increase reliability and robustness
Challenges and requirement	Decrease losses Decrease production cost High reliability Noise reduction	Decrease losses, weight and size Increase of power managed Increase reliability	More complexity Decrease losses Larger power generators Larger industrial motors

4.2.2 Storing energy and releasing it at the right time [170].

One of the biggest challenges with using renewable energy for electricity generation specifically wind and solar power is their intermittency. Significant peaks and troughs in wind and solar power output require energy storage systems to smooth out the intermittent generation and reduce ramp rates for medium and large plants. Therefore, affordable, reliable, and deployable storage devices are seen as the holy grail of renewable energy integration. Storage can help reduce both the amount of conventional generation needed when renewable generation cannot meet the demand and curtailment when there is an excess renewable generation [**173**].

Hydro storage facilities, whether in the form of pumped-hydro or hydro reservoirs, have played a key role in many countries in providing several grid balancing services. Their advantages are the potential for large-scale electricity storage greater than 1000 MW capacity, depending on location, fast response times and relatively low operating costs. Maintaining grid balance is an even greater issue when renewable energy sources such as wind and solar power is part of the energy mix. They are subjected to weather changes, on a particularly sunny or windy day they may yield excess amounts of electricity, only to fall short when conditions change. In order to accommodate these imbalances and to integrate renewable energy sources more smoothly, grid operators rely on electricity storage solutions. As an alternative to simply raise the proportion of conventional, non-renewable energy sources when supplies run low, stored electricity keeps electrical grids balanced while maintaining a light environmental footprint [**170**].

There are different types of technology for storing electricity, e.g. compressed air energy storage, pumped storage, batteries or fuel cells and super capacitors. Storage is a device that stores energy. Grid energy storage or large-scale energy storage lets energy producers send excess electricity over the electricity transmission grid to temporary electricity storage sites that subsequently become energy suppliers when electricity demand is greater. A proposed variation of grid energy storage is called vehicle-to-grid energy storage system, where modern electric vehicles that are plugged into the energy grid can release the stored electrical energy in their batteries back into the grid when needed. It is designed to optimize energy efficiency, enable more flexible, grid management, maximize investments and provide peace of mind knowing energy balance is under control across the entire energy supply chain.

Storage can be a strategic tool for managing variability and capacity concerns of renewable energy integration. A more predictable generation could be obtained from variable sources like wind and solar by storing and utilizing the accumulated energy appropriately. It allows more efficient and practical use of these resources and also provides benefits such as reducing emissions and differing generation and transmission. Storage may be centralized or distributed to be close to the load centres, renewable generation sources or even customer premises.

One fundamental problem with storage is that where energy is converted from one type to another, conversion losses and thus inefficiencies are inevitably incurred, this is true for batteries and hydrogen fuel cells (where electrical energy is converted to chemical energy stored) and flywheels (where electrical energy is converted to kinetic energy). Table 4.2 below shows the details.

Depending on available locations another viable form of storage is compressed air, which is stored in geologic structures under the ground and released when necessary. Typical places for such projects could include disused coal mines or salt domes [**172**].

The example of mitigation of wind power output is shown in Figure 4.2 below. A wind power company (Japan Wind Development) has installed 30 MW NAS batteries in their 50 MW wind-farm in 2008. Since the location of wind-farm tends to be a local sparse area, power fluctuation should be suppressed. The wind-powers started to be accepted in Japan, since they flatten their power generation and behave as well-neighbours charging and discharging is repeated throughout a day to flatten the output.

Table 4.2: Various storage technologies and technical performance [**172**]

Storage technology	Typical round-trip efficiency in %	Typical capacity range MW
Pumped-hydro station	80	100 - 1000
Compressed air storage	75	50 - 100
Flywheel	90	0.001 - 0.05
Conventional batteries	50 - 90	0.001 - 0.01
Flow battery	70	15
Hydrogen fuel cell	40	0.05 - 1

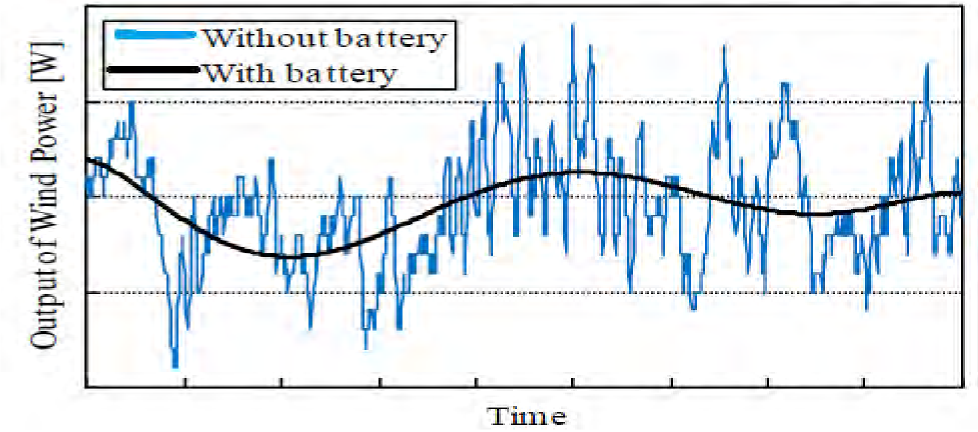


Figure 4.2: Mitigation of the output fluctuated by wind power [**175**]

The Japanese government plans to put 28 GW solar-cells on the roof of residential houses by 2020. It is expected that voltage control in the local/distributed networks will be critical unless new control action is introduced.

Optimization of location and capacity of battery

The new attempt to find optimal location and capacity of a battery is by using fractal theory which operates on the principle of a feedback loop. A simple operation can be carried out on a piece of data and then fed back in again, the process is repeated infinitely many times and limit of the process produced is the fractal. All fractals are partially self-similar as illustrated in Figure 4.3 (a) below. Battery location can be found in a distributed network by making used of this fractal concept as shown in Figure 4.3 (b).

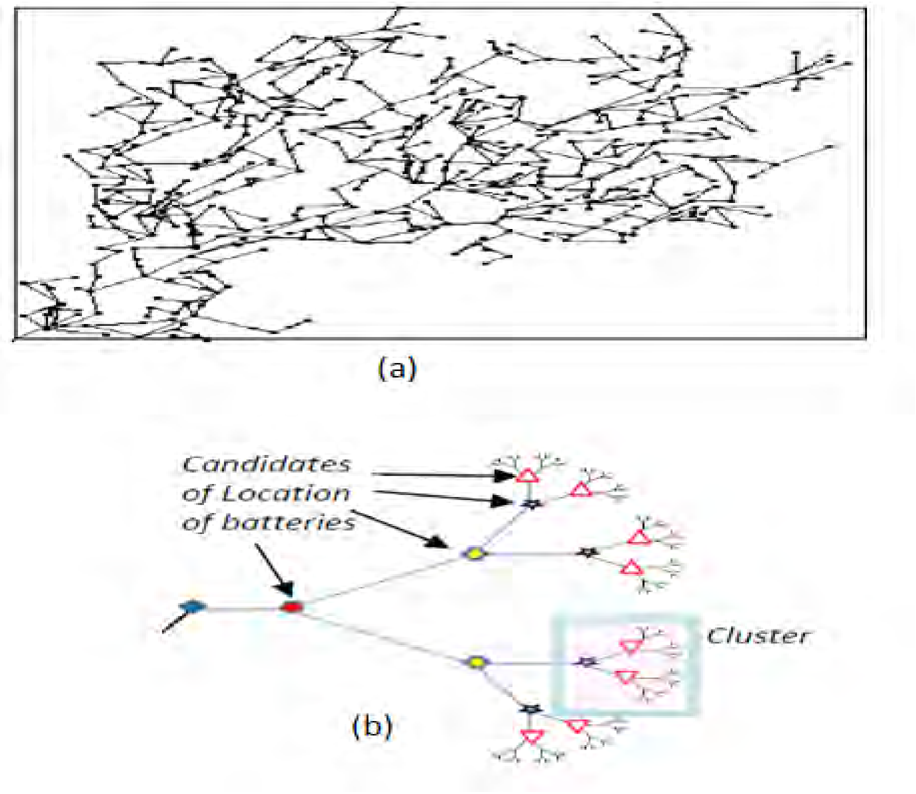


Figure 4.3: (a) Fractal concept (b) Location of batteries [**175**]

4.2.3 Power generation control [174]

Power generated by the renewable energy source can be controlled in three ways:

Exploiting storage capabilities of renewable sources of energy: Many renewable energy sources have or can be built so as to have storage capabilities. These storage capabilities can be used to adapt their power production to demand. The plant types and their energy sources are depicted in Table 4.3 below.

Downward modulation by curtailment of renewable energy: When production of electricity is higher than demand for electricity, renewable sources of energy such as wind farms or PV installations could be turned off.

Table 4.3: Storage capability [177]

Plant Type	**Energy Storage Vector**
Hydro	Water in the reservoir
Tidal	Water in the reservoir
Geothermal	Heat in the ground
Thermal Solar	Heat in the pressurized steam, concrete, molten salts
Wind	Blades that store kinetic energy
Bio-fuel	Fuel

Upwards modulation which is possible if renewable sources of energy is not operated at full power: Renewable energy sources can be invested upon to ensure that there is most of the time a surplus of capacity in such a way that when the demand for electricity increases, they could potentially be modulated upwards.

4.2.4 Demand for Energy Control (Demand side management) [174]

Demand side management modifies the demand for energy to move consumption from hours where electricity is a scarce commodity to hours where there is a surplus of electricity. Examples of electrical loads that can be shifted are: fridges, washing machines, electrical cars, heating and cooling devices. It is an old concept in power systems for ensuring a balance between production and consumption of electricity. It has long been applied to industrial loads. Day and night metering of electricity has also been used in households to transfer portions of daytime consumption to night time consumption.

Demand side management buffer is sometimes used to temporarily prevent a device that consumes electricity from taking power from the grid; instead, it's operation continues by using its own internal supply of energy. Such buffers can take the form of fly wheels (such as those used in kinetic energy recovery systems in turbines), pumped storage using gravitational potential energy and also even batteries in laptops. Devices with buffers can be designed to use grid electricity only when there is a supply surplus and not when there is a deficit [**174**]. A number of demand-side management techniques exist, e.g. Smart appliances, such as air conditioners [**177**], which either monitor the grid frequency for an instantaneous measurement of the supply-demand balance or receive information as to the current grid load via radio, internet or other means. They use this information to limit their power use in times of high demand or low supply.

4.2.5 Grid Augmentation [167]

It is augmenting the grid to increase access to renewable energy resources and share balancing resources over a wider area. This includes transmission reinforcements to relieve congestion, strengthening of tie-lines to facilitate power exchange between regions and extending the network to provide access to areas with excellent renewable resources. Since it takes time to build transmission assets, however, optimising the use of existing infrastructure using dynamic line rating, flexible alternating current transmission system devices and phase shifting transformers are suggested as a possible intermediate measure.

4.2.6 Distribution of RES to larger Geographical Area [178]

Intermittence of power generation from the RES can be controlled by distributing the RES to larger geographical area in smaller units instead of large unit concentrating in one area. For an example, the output power of a large solar PV system with a rating of tens of megawatt can be changed by 70 % in five to ten minutes of time frame by the local phenomenon like clouds passing etc. Therefore a large number of small solar PV systems should be installed in a larger geographical area. The fluctuation of total output power can be minimized because local problem can affect only small unit power not the total output power.

4.2.7 Provision of Sufficient Transmission Infrastructure [167]

Adequacy and availability of transmission lines is required for the interconnection of renewable energy to the grid. In order to prevent the possibility of cascading events, building of a new transmission line with appropriate ratings that increases the transfer capability between substations is required for enabling the interconnection of renewable generation.

4.2.8 Special Protection System (SPS) [179]

Special Protection System (SPS) otherwise known as a remedial action scheme (RAS), as defined by NERC [**179**], is an automatic protection system designed to maintain system reliability. It detects abnormal or predetermined system conditions, and takes corrective actions other than (or in addition to) the isolation of faulty components. A RAS is usually considered when other operating and construction alternatives are substantially more expensive, or cannot be implemented in time to avoid problems identified by the analytical studies. RAS senses abnormal system conditions and takes pre-designed actions to prevent these conditions from escalating into major system disturbances. The actions minimize equipment damage and prevent cascading outages, uncontrolled loss of generation, and interruptions of customer electric service.

4.2.9 Communication Systems [180]

Communication systems are crucial technologies for grid integration of renewable energy resources. Two-way communications are the fundamental infrastructure that enable the accommodation of distributed energy generation and assist in the reconfiguration of network topology for more efficient power flow. Many types of equipment in the grid which will enable important decision support systems and applications, such as supervisory control and data acquisition (SCADA), energy management system (EMS), protection, relays for high voltage lines, mobile fleet voice and data dispatch, distribution feeder automation, generating plant automation, and physical security should be monitored and controlled. These applications are vital in monitoring, operating, and protecting both renewable energy generators and power systems.

A typical electric grid communication system consists of a high-bandwidth backbone and lower-bandwidth access networks, connecting individual facilities to the backbone. Fibre optics and/or digital microwave radio are usually the technologies for the backbone, whereas the access may use alternatives such as copper twisted-pair wire lines, power line communications, and wireless systems. Types of communication technologies are:

- Power Line Communications
- Local Area Networks
- Wide Area Networks

Power Line Communications

Power line communications (PLCs) are to use existing electrical wires to transport data. Recently, new PLC technologies are available that allow high bit rates of up to 200 Mb/s. The PLC can be used in several important applications such as broadband Internet access, indoor wired local area networks, utility metering and control, real-time pricing, distributed energy generation, and so on [**180**]. The requirements for standard high speed communication devices via electric power lines up to 500 Mb/s at the physical layer are stated in IEEE 1901. This is to prevent interference when the different broadband over power lines (BPL) implementation is operated within close proximity of one another [**181**].

Wireless Local Area Networks [182]

A leading standard for the wireless home network communications is ZigBee. The Zigbee Smart Energy standard builds on top of the ZigBee Home Automation Network (HAN) standard. HAN provides a framework to automatically control lighting, appliances, and other devices at home. ZigBee Smart Energy provides a framework to connect HAN devices with smart meters and other such devices. This will enable the energy utility to directly communicate with the end consumers of energy. Wi-Fi is often used as a synonym for IEEE 802.11 wireless local area network (WLAN) technologies [**182**].

Wireless Wide Area Networks [180]

Public cell phone carriers have great interest in using wireless wide area networks to connect household smart meters directly with the utilities systems. A major advantage of this approach is the reduction of the costs (by not having to build a new network and by leveraging the expertise of the telecom world). However, since public wireless cellular networks are not specialized in the machine-to-machine area, some requirements in utilities may not be met by cellular networks. WiMAX is based on the IEEE 802.16 standard, enabling the delivery of wireless broadband communications. WiMAX uses licensed wireless spectrum, which is arguably both more secure and reliable. The primary disadvantage of using a licensed network is that it is more expensive. In addition, compared to cellular technologies, WiMAX has yet to be deployed in large scale [**180**].

4.2.10 Interoperability of Different Communication Systems [183]

It is the ability of making power system components to work together (inter-operate). Renewable energies will be very difficult to integrate into the grid without a framework of interoperable standards for communications. Many utilities and regulatory groups are collectively trying to address interoperability issues through workgroups such as the Grid Wise Architecture Council and Open Smart Grid (Subcommittee of the Utility Communications Architecture International Users Group) as well as through policy action from NIST. In June 2009, NIST announced an interoperability project via IEEE P2030, which seeks to define interoperability of energy technology and information technology operations with electric power systems and end-user applications and loads [**180**], [**183**].

4.2.11 Renewable Energy supply versus Smart Grid Concept [184]

A Smart grid is an electricity network that intelligently integrate the action of all users connected to it e.g. generators, consumers in order to ensure economically efficient, sustainable power system with low losses, high level of quality, security of supply and safety similar to an Internet, the smart grid consists of control devices, computers, automation, new technologies and equipment working together, but these technologies will work with the electrical grid to respond digitally to quickly changing electric demand. One of the smart grid objectives is to update the power system automation, which includes transmission, distribution, sub-station, individual feeder and customers using the latest technology. With the introduction of smart grid, consumers can manage their energy consumption by monitoring their voltage and power. It is to achieve reliability, efficiency and optimization in operation, planning, demand response, as well as utilization of diverse resources.

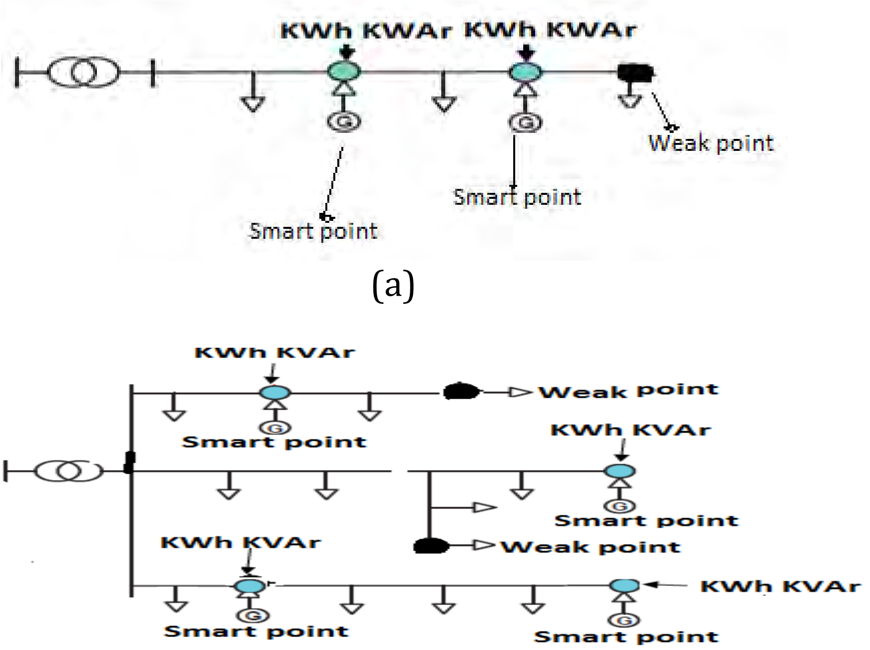
Smart grid creates the platform for deploying smart technologies which improve demand response and load management that makes the power transmission system more efficient, encourage renewable energy resources, and give consumer better control over their usages and costs. It provides a high interconnected network between electricity suppliers and consumers embracing generation, transmission and distribution. It involves real- time two- way digital communications between utilities and their consumers, it includes power delivery components, control, monitoring throughout the grid, more informed customer options, bring an improvement to resilient, and reliable electric grid. Smart grid uses sensors, monitoring, communications, automation and computers to improve the flexibility, security, reliability, efficiency, and safety of the electric system. It is an infrastructure that puts the emphasis on active rather than passive control. With the above concept of smart grid, there is a great assurance for power quality and reliability of the power system. The smart grid can provide reliability, security, safety and efficiency as well as economic, environmental friendly operation with the in-built self-healing in delivering quality electricity to consumers [**184**], [**185**], [**178**], [**186**].
If the deployment of renewable energy sources into the power system will be effective, the electric grid system must be smart. The Smart Grid secures and optimises the electricity flow across its entire journey. The grid is becoming fully dynamic, and electricity management is entering a new era, with unprecedented efficiency and stability.

The need for a Smarter Grid [187]

Digital technology that allows for two-way communication between the utility and its customers and the sensing along the transmission lines (sensor) can make the grid smarter. Electricity disruption like blackout can have a domino effect, e.g. a series of failures that can affect banking, communications, traffic, and security. This is a particular threat in the winter, when homeowners can be left without heat. A smarter grid will add resiliency to our electric power system and make it better prepared to address emergencies such as severe storms, earthquakes, large solar flares, and terrorist attacks. Because of its two-way interactive capacity, the Smart Grid will allow automatic rerouting when equipment fails or outages occur, it will minimize outages and its effects. When a power outage occurs, Smart Grid technologies will detect and isolate the outages, before it becomes large-scale blackout. The smart grid technologies will also help ensure that electricity recovery resumes quickly and strategically after an emergency, routing electricity to emergency services first, for example, the Smart Grid will take greater advantage of customer-owned power generators to produce power when it is not available from utilities, By combining these distributed generation resources, a health centre, police department, traffic lights, phone system, and grocery store can still operate during emergencies.

Renewable energy deployment brings changes into the power system distribution, the distribution network is no longer radial, power flows are no longer defined by the energy from the parent network, which flows to the end user [**187**]. Renewable energy source brings the new level of uncertainty in the development, planning and management of the distribution network. The former approach in the radial network was to monitor the current and voltage at feeding points in the substation, at the beginning of the line, this has been proven an excellent approach, and it should be used also in a network with Renewable energy source. Monitoring conditions at the beginning of the line includes monitoring conditions not only at feeding points in the parent substation at the beginning of line, but also monitoring all points of energy injection from RES connected to a line, by measuring the voltage at these points, one can recognize the status of consumption of the line relative to production.

Smart point is the node in the network with the ability of remote monitoring and controlling the network conditions. The weak point is the node with the highest voltage fluctuations in the feeder. Further increasing the amount of Renewable energy, it will result in fewer weak points, because Renewable energy will be integrated also at weak points, therefore weak points will become a smart and a weak point as shown in Figure 4.4 (a). The increase of the number of integrated Renewable energy source will eventually result in sufficient, smart points by which it will be possible to control the whole local network, at that moment local network becomes local smart zone. By further increase in the number of local smart zones, the whole network will be covered with smart zones, becoming the smart grid, creating smart distribution systems (Figure 4.4 b).



(a)

(b)

Figure 4.4 (a) Line with smart points and weak point (b) Local smart zones [187]

The benefits of Smart Grid [188]

- More efficient transmission of electricity
- Quicker restoration of electricity after power disturbances
- Reduced operations and management costs for utilities, and ultimately lower power costs for consumers
- Reduced peak demand, which will also help lower electricity rates
- Increased integration of large-scale renewable energy systems
- Better integration of customer-owned power generation systems, including renewable energy systems
- Improved security

The Smart Grid is not just about utilities and technologies; it is about giving information and tools needed to make choices about energy use. If you already manage activities such as personal banking from home, computer, imagine managing electricity in a similar way. A smarter grid will enable an unprecedented level of consumer participants. For example, one will no longer have to wait for monthly statement to know how much electricity is used. With a smarter grid, clear and timely picture of it can be easily accessed. Smart meters, and other mechanisms, will allow you to see how much electricity you use, when you use it, and its cost. Combined with real-time pricing, this will allow saving money by using less power when electricity is most expensive.

Smart Grid Deployment [189]

The Smart Grid will consist of millions of pieces and parts, controls, computers, power lines, and new technologies and equipment. It will take some time for all the technologies to be perfected, equipment installed, and systems tested before it comes fully online. It won't happen all at once, the Smart Grid is evolving, piece by piece, over the next decade. Once mature, the Smart Grid will likely bring the same kind of transformation that the Internet has already brought to the way we live, work, play, and learn.

4.3 Voltage and Stability Control [190]

Wind intermittency and fluctuations have a great consequence on the voltage fluctuation of the bus where the wind generator is connected and the load voltage fluctuation which affects the power system voltage stability. Voltage and stability control can be done at different scales. While voltage control is at a relatively slow time scale, the stability control is at a fast time scale [**191**], [**190**].

Chapter 5

Impact of DGs on power quality

Introduction

The introduction of DGs into the power system has benefits, but it makes the system to be more complicated [**160**]. For instance, with large generating units, the system operators are aware of the condition, production and security level of the system while the situation is not applicable in case of the introduction of DGs into the network; the units are completely out of control of the system operator. DGs with renewable energy sources like wind and solar, are intermittent and fluctuating with time and they are difficult to predict; which makes power system planning and operation more complicated. The primary aims of the power system are the reliability of power supply, voltage and power quality etc., in which the DGs play vital roles in achieving them. In terms of network protection, there may be no economic motivation for small DG owners in installing a control and protective device in the course of electricity production to minimize the contribution of DGs into a fault current as a result, some network operators introduce strict connection rules and requirements as regards protection and metering. In this chapter, the impact of WEC on power quality shall be discussed.

5.1 Overview of power systems change with Distributed generation

A lot changes are taking place in a power system as a result of the introduction of distributed generation. Gradually, electricity generated by fossil fuel is being replaced by electricity generated from renewable energy sources, small generator units connecting to the distribution system are replacing large generator units connected to the transmission system. The deregulation of generation, transmission, and distribution system, depending on each country has brought competition in the market [**160**]. The generation assets are no longer owned by one or a few owners, but a lot of investors have entered the electricity market. Individuals can now generate their own electricity using small combine heat and power, rooftop solar panels, and small wind energy converters to mention a few. It is obvious that all these changes have their impact on the power system.

5.2 DGs versus power quality

The challenge of maintaining appropriate frequency and voltage level is increasing due to increasing interest in DG [**192**]. Power quality determines the fitness of electrical power to consumer devices.

Synchronization of the voltage, frequency and phase allow electrical systems to function in their intended manner without significant loss of performance or life. Without the proper power quality, an electrical device or load may malfunction, fail prematurely or not operate at all. The power quality can be linked directly to the network itself, power flow and the customer connected to the distribution network. It includes:

- Voltage quality.
- Current quality.

Voltage quality

Equipment connected to the distribution network and the events in the network determines the voltage quality at the terminal of the generators. As the equipment connected to the network is affected by the voltage quality, the same way, generator unit will be affected which can cause a reduction in equipment lifetime, damage to the power system component, damage to the customer equipment, undue and forced tripping of the power system equipment or generator units is as a result of the impacts of voltage disturbance in the network [**160**]. When there are voltage quality problems in a network, maybe it has arisen as a result of fault in such a network, the energy flow may be interrupted causing an electrical machine to over speed, voltage collapse and over voltages which can damage electronic equipment. Whenever DGs are connected to a distribution network, a distinction should be made between variations, normal or abnormal voltage variations. Voltage dips and voltage rise are part of challenges associated with the voltage quality issue.

Current quality

Large single phase load connected to a network can draw large amount of unbalanced current which can cause current quality problems in the network [**160**].

5.3 Classification of DG impacts on distribution network

In Figure 5.1 below, the classifications of the distributed generation impacts on the power system are depicted.

5.3.1 Voltage dip

Voltage dips/sags are short duration under voltages. It leads to a reduction in RMS voltage for a short period of time, which can be caused by disturbance on a network, starting large loads or as a result of reactive power consumption of some of the distributed generators like induction generators. It can cause failure and malfunction of equipment and tripping of sensitive loads [**149**]. DG connection to a network can improve the voltage profiles and reduce voltage dips [**163**].

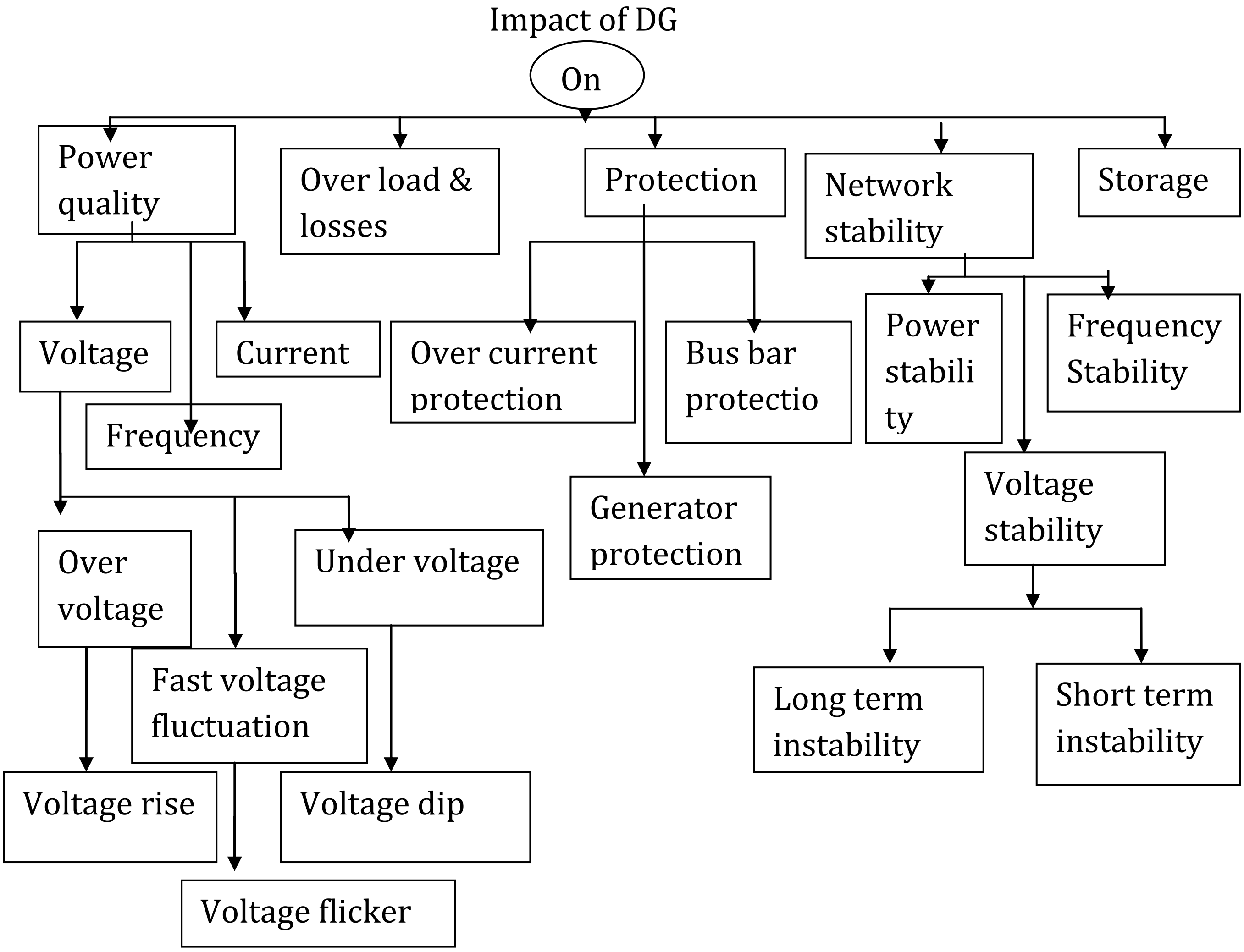


Figure 5.1: Classification of the DG impacts on the power system [**193**]

5.3.2 Voltage rise

The main limiting factor for the connection of DG is the voltage rise. With the connection of distributed generation into the distribution network, the issue of excessive voltage drops is not a concern anymore, but over voltage becomes a serious problem [**160**]. The voltage rise in a distribution network is due to the injection of active power from the DG which is proportional to the resistive part of the source impedance at the point of common coupling. It can be described as short duration over voltages or rise in voltage that occur over a long period of time, which can be caused by over generation of power, turning off of large load within a network, circuit switching, and lightning strikes [**160**].

5.3.3 Frequency change

This occurs when there is a change in the nominal frequency of a particular network, e.g. 50 Hz ± 2 % , i.e. 49 to 51 Hz [**194**]. It is usually caused by the frequency instability of the power source and overloading of a particular network, which may result in the loss of data in some sensitive equipment. It can be controlled and monitored by the installation of frequency control devices in a distribution network.

5.3.4 Voltage Flicker

Flicker is defined as the impression of fluctuating luminance or colour occurring when the frequency of the variation of the light stimulus lies between a few hertz and the fusion frequency of images [**195**], [**196**], [**197**]. It is the impression of unsteadiness of visual sensation induced by a light stimulus whose luminance or spectral distribution fluctuates with time [**198**], [**199**], [**200**], [**201**]. It is considered as one of the most severe power quality problems, flicker is induced by voltage fluctuations, which are caused by heavy loads, such as reciprocating machines or dynamic load like electric arc furnaces (EAFs) and energisation of transformers that operate periodically in a weak power distribution system, switching of capacitors, lines, cables etc. The flicker emission produced by grid connected wind turbines during continuous operation is mainly caused by fluctuations in the output power due to wind speed variation [**202**], [**203**]. A small voltage fluctuation from 0.3 % to 0.5 % in the frequency range of 6-10 Hz will cause the visible incandescent lamp flickering [**204**], [**205**].

Voltage flicker is characterized by variation of voltage magnitude in the range of 10 % of nominal voltage and with frequencies between 0.2 to 30 Hz. Many techniques have been proposed in the literature for flicker-level assessment; among them the fast Fourier transform (FFT) has been used often [**206**], [**207**].

For a short duration, a voltage flicker waveform can be described as:

$$U\ (t) = s(t)\ \sin(2\pi f_{syn} t) \ldots\ldots\ldots\ldots\ldots\ldots (5.1)$$

$$= \sqrt{2} V_{ms} f(x) = 1 + \frac{1}{2} \sum \Delta V_n\ \mathrm{Sin}(2\pi f_n t + \varphi_n) \times \sin\ (2\pi f_{syn} t) \ldots\ldots\ldots\ (5.2)$$

Where

f = Power frequency (50 or 60 Hz)

V_{rms} = Average RMS value of the voltage

ΔV_n = change in voltage

s (t) = Signal

f_n = Modulation frequency (in the rage of 0.1Hz to 30Hz)

f_{syn} = Carrier frequency

φ_n = Phase angle

The magnitude with a time dimension (T_f) that describes the flicker impression is caused by a single voltage variation. It can be calculated using the following equation [**208**]

$T_f = 2.3(\Delta.\mathrm{F})^{n}$.. (5.3)

$\Delta = \frac{\Delta V}{V}$.. (5.4)

Where

F = equivalent factor depending on the shape of the voltage fluctuation

N = 2.3 for disturbing loads matching linear part of the unity flicker curve.

Δ = Voltage change

The factor 2.3 is included in order to achieve compliance with the flicker curve

Short time flicker can also be calculated by

$P_{st} = (\frac{\sum t_f}{T_p})^{\frac{1}{n}}$..(5.5)

Where

$\sum t_f$ = sum of all the flicker times

T_P = Base of P_{st} in seconds

Addition of Flicker originating from multiple sources can be calculated by

$P_{st} = \sqrt[m]{\sum_i P_{sti}^m}$.. (5.6)

Where

P_{sti} = individual levels of flicker severity generated by each of the disturbing loads. The value of the coefficient m depends upon the characteristics of the sources of fluctuation or disturbing load

Procedures which can be used to predict flicker

Voltage flicker can be predicted in a network by making use of the following methods

- **Voltage variation**

The relative percentage voltage change, (ΔV %) for both phase voltage and line voltages are the same for a balanced three-phase load. It can be calculated approximately using the following equation.

$\Delta V = \frac{\Delta P_{max}}{S_{sc}} \times 100\ \%$.. (5.7)

ΔP_{max} = Maximum apparent power change
S_{sc} = Network short circuit power measured at the point of common coupling (PCC)

The relative voltage can be calculated more accurately using the following equation, if the active as well as the reactive part of the load change is known [**209**]

$$\Delta\,\% = \frac{R.\Delta P_{pcc1} + X.\Delta Q_{pcc2}}{V^2} \times 100 \quad (5.8)$$

Where
R = Resistive part of the network impedance
X = Reactance part of the network impedance
V = Nominal voltage
ΔP_{pcc1} = Active power change of the load at PCC
ΔQ_{pcc2} = Reactive power change of the load at PCC

- **Unity flicker severity curve method**

Short time flicker is a linear parameter with respect to the magnitude of the voltage change that causes it. In this method, the percentage relative voltage change (Δ) and the repetition rate (*r*) of this voltage change must be known. By Substituting *(r)* expressed as the number of voltage changes per minute, into the unity curve for a rectangular step provided on the ordinates gives the voltage change (Δo). If the voltage step change calculated for the load has a value (Δ), then the corresponding flicker severity can be calculated using the following equation

$$P_{st} = \frac{\Delta}{\Delta_0} \quad (5.9)$$

For many years the severity of the voltage fluctuations at a certain location has been obtained by comparing the fluctuations with a flicker curve. This flicker curve combines two curves: The lamp gain factor as a function of the frequency of the fluctuations and the smallest observable light intensity fluctuation as a function of the frequency of the fluctuations.

The latest revision in 2008 of IEC 61000-4-15 includes standard models for both 230/120V incandescent lamps. The same models are included in the current draft of IEEE standard 1453 in 2010. Both curves are obtained from the relative input voltage fluctuation that leads to one unit of perceptibility at the output [**198**].

Effects of Voltage Flicker

Flicker has an indirect effect on power system which can cause a lot of havoc to both equipment and human life [**210**].

- **Effect on equipment** [**211**]

The abrupt regulation of the utility voltage may cause objectionable light flicker, disrupt industrial and commercial processes, and adversely affect the operation of electronic apparatus, such as computers, instrumentation, and communications equipment. Also, the current flowing in traction power supply equipment can cause pulsating forces which can be of significant magnitude, and therefore, can be potentially harmful to substation equipment. Light flicker is the most common and noticeable effect of fluctuating loads, a voltage change of just 0.25 to 0.5 % will cause a noticeable change in the light output of incandescent lamps.

- **Effect on Humans** [**211**]

Light flicker perception is a physiological process in which the eye and the brain take part. There are three important mechanisms that must be taken into account in order to understand the phenomenon**:** Dynamic characteristic of the lamp**,** nonlinear frequency characteristics of the eye/brain and adaptive time of the eye/brain.

These mechanisms should be included in any flicker-measuring device in order to reproduce the human effect

Mitigation of voltage flicker [211**]**

Voltage flicker can be mitigated by FACTs devices like STATCOM, SVC etc

5.3.5 Harmonic

Harmonics are the periodic steady-state distortions of the sine wave due to equipment generating frequency other than the standard 50 or 60 cycles per second [**210**]. In other words, it is the decomposition of a non-sinusoidal, but periodic signal into a sum of sinusoidal components. Harmonics are a mathematical way of describing distortion to a voltage or current waveform. The term harmonic refers to a component of a waveform that occurs at an integer multiple of the fundamental frequency. Distortions of the fundamental sinusoid generally occur in multiples of the fundamental frequency. Thus, on a 50 Hz power system as shown in Figure 5.2 below, a harmonic wave is a sinusoid having a frequency expressed by the following formula.

$$F_{\text{harmonics}} = n \times 50\ Hz \quad (5.10)$$

Where n is an integer

Causes of harmonics

- Electronic ballasts
- Non-linear loads
- Variable frequency drives

Effect and consequences of harmonics

- Reduction in performance of equipment/appliance
- Random breakers tripping
- Hot neutrals and overheating
- Reduction in power quality

Suppose that **p** represents one waveform and **q** another, both at the same frequency but shifted 120° from each other in terms of phase and the 3rd harmonic of each waveform $\mathbf{p}^*$ and $\mathbf{q}^*$ the time-shift between $\mathbf{p}^*$ and $\mathbf{q}^*$ is equivalent to 120° at a frequency three times lower, or 360° at the frequency of $\mathbf{p}^*$ and $\mathbf{q}^*$. A phase shift of 360° is the same as a phase shift of 0°, i.e, no phase shift at all. Therefore, $\mathbf{p}^*$ and $\mathbf{q}^*$ are in phase with each other (including 6th, 9th, 12th, 15th, 18th, 21st harmonics).

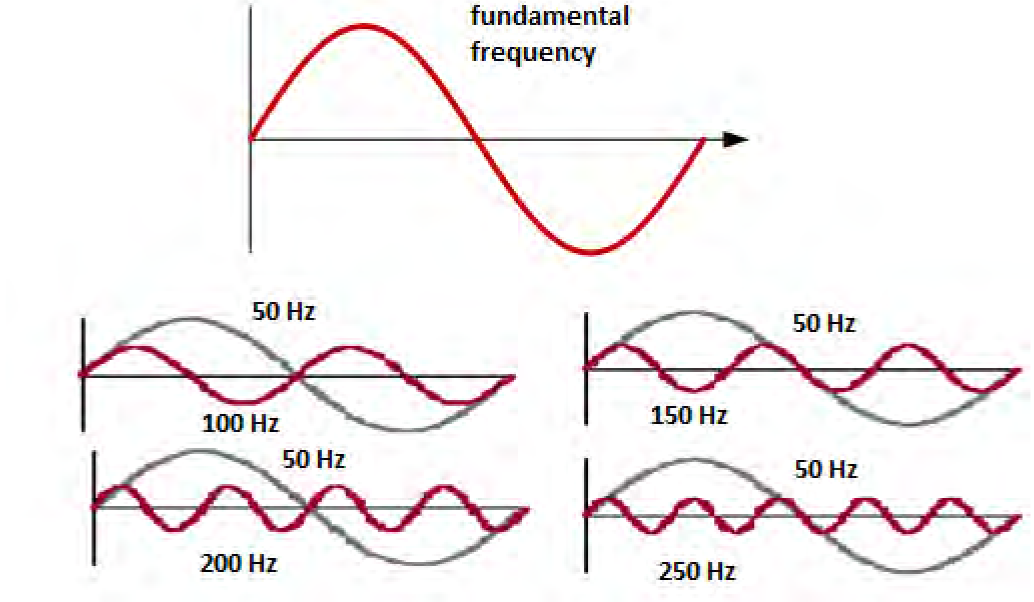


Figure 5.2: The fundamental frequency (50 Hz) sine wave and its 2nd, 3rd, 4th, and 5th harmonics

Odd harmonics occur in systems where waveform distortion is symmetrical about the centre line and it is caused by nonlinear loads which create symmetrical distortion. Even numbered multiples of the 3rd harmonic (6th, 12th, 18th, etc.) are generally not significant, only the odd-numbered multiples (3rd, 9th, 15th, 21st) contribute to neutral currents. If harmonic currents of Phases A, B, C all coincide, it means, no rotation as depicted in Table 5.1 below. The harmonic current of phases A, B and C are depicted in Figure 5.3 and the harmonic table in Table 5.2

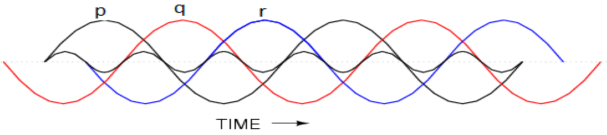


Figure 5.3: Harmonic current of phase A, B and C

Positive sequence: it is the 1st, 7th, 13th, and 19th harmonics that rotate with the same sequence as the fundamental
Negative sequence: it is the 5th, 11th, 17th and 23th harmonics that rotate in the opposite sequence as the fundamental.
Zero sequence: harmonics 3rd, 9th, 15th, and 21th shown in Table 5.1 which don't rotate at all because they're in phase with each other.

An excess of negative-sequence harmonics (5th, 11th, 17th, and 23rd) in the power supplied to a three-phase AC motor will result in a reduction in performance, random breakers tripping; hot neutrals and overheating.

Harmonic distortion is assessed for a variable speed turbine with an electronic power converter at the point of common connection. The total harmonic voltage distortion of voltage is given below

$$V_{\mathrm{THD}} = \sqrt{\sum_{\mathrm{h}=2}^{40} \frac{\mathrm{v}_{\mathrm{n}}^{2}}{v_{1}}}\,100 \ldots\ldots \quad (5.11)$$

$$I_{THD} = \sqrt{\sum_{\mathrm{h}=2}^{40} \frac{I_{\mathrm{n}}^{2}}{I_{1}}}\,100 \ldots\ldots \quad (5.12)$$

V_{THD} and I_{THD} are total harmonic voltage and current distortion respectively
V_nAnd I_n are nth harmonic voltage and current
V_1 and I_1 are fundamental frequency
THD is total harmonic distortion

How to determine harmonic voltage/current

A harmonics analyzer is the most effective instrument for performing detailed analysis of power quality to determine the wave shapes of voltage and current on respective frequency spectrums. A harmonic analyzer is also useful in instances where the lack of obvious symptoms prevents from determining if harmonics are a cause for concern [**210**].

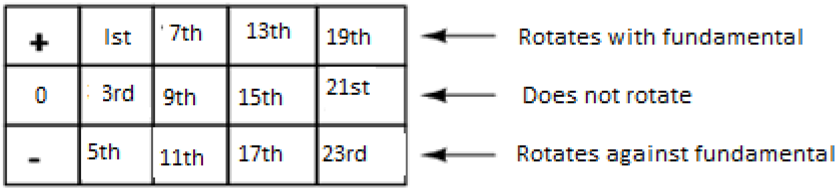
Harmonics Mitigation [210]

Filtering circuit can be connected at the points of common connection to reduce the effect of harmonics in an electrical network such as:

- Active filters
- Passive filters
- FACTS devices such as STATCOM, SVC, D-STATCOM

at the most suitable buses, locations, and the weakest buses to improve the voltage profile of the network. If a wrong bus is chosen for the integration of WEC other than the weakest point in the network, it may have a negative effect on the system or the impacts may not be seen as expected.

Table 5.1: Rotation sequences according to harmonic number



+	Ist	7th	13th	19th	← Rotates with fundamental
0	3rd	9th	15th	21st	← Does not rotate
-	5th	11th	17th	23rd	← Rotates against fundamental

Table 5.2: Harmonic formation Table

Fundamental	p 0^0	q 120^0	r 240^0	p-q-r
3rd harmonic	p* 3×0^0 0^0	q* 3×120^0 $(360^0=0^0)$	r* 3×240^0 $(720^0=0^0)$	No rotation
5th harmonic	p** 5×0^0 (0^0)	q** 5×120^0 $(600^0-720^0-120^0)$ (-120^0)	r** 5×240^0 $(1200^0-1440^0+240^0)$ (-240^0)	r-q-p
7th harmonic	p*** 7×0^0 (0^0)	q*** 7×120^0 $(840^0-720^0+120^0$ (120^0)	r*** 7×240^0 $(1680^0-1440^0+240^0)$ (240)	p-q-r
9th harmonic	p**** 9×0^0 (0^0)	q**** 9×120^0 $(1080^0=0)$	r**** 9×240^0 $(2160^0=0)$	No rotation

5.4 Tripping of generator

Depend on the protection system of a particular DG connected to a network, it is expected that the DG should trip for extreme higher voltage quality variation and severe fault occurring in the network. This can also cause tripping of multiple generators connected to the same network, which can have serious effects like large scale blackout, and loss of production of customers connected to the network [**160**].

5.5 Voltage Control

The following conditions must be met in order to have efficient, secure and reliable operation of the power system:

- Bus voltage magnitude should be within acceptable limits
- Voltage control and reactive power management should be able to improve system transient stability and voltage stability.
- The reactive power flow should be reduced so that the active and reactive power losses can be minimized [**104**]

Also the bi-product of the minimum reactive power flows can reduce the voltage drop at transmission line and transformers. Suitable control algorithms, software tools and voltage control devices such as shunt reactor, shunt capacitors, synchronous generators, SVS, and converter-based Flexible AC transmission system (FACTs) are required to determine controls settings and coordinate the control actions of all the voltage control devices sited at different locations of the system. The converter-based FACTS have excellent dynamic reactive power and voltage control capability [**104**].

5.6 The Appropriate Bus location for DG integration

Installing a DG at a faraway location to the load, the impact may be significantly small, as a result, DGs should be installed as close to the load as possible in order to capture the full benefit.

5.7 Concept of Grid code act

Introduction

A grid code is a technical specification which defines the parameters that a facility connected to a public electric network has to meet to ensure safe, secure and economic proper functioning of the electric system. The facility can be electricity generating plant, a load, or another network. The grid code is specified by an authority responsible for the system integrity and network operation.

The contents of a grid code vary depending on the transmission company's requirements. Typically a grid code will specify the required behaviour of a connected generator during system disturbances. These include voltage regulation, power factor limits and reactive power supply, response to a system fault (short-circuit), response to frequency changes in the grid, and requirement to ride through short interruptions of the connection.

Grid codes are being developed in many countries to give substance to government policy on market structure and renewable energy. A grid code establishes the relationship between the network owners and operators and the DG developer, including the right of access to the network. The primary objective of the grid connection code is to specify the minimum technical and design grid connection requirements for renewable energy connected to or seeking connection to a low voltage distribution system. The compliance with this grid connection code is applicable to the DG (Wind energy conversion WEC) depending on its rated power, and the nominal voltage at the point of connection (POC).

Technical aspects include the reliability of the networks to which the DG connects, interconnection standards, protection, voltage control, stability and operational safety procedures. Fault ride-through and reactive power requirements, which depend on the DG technology, affect the networks to which the DG is connected. Grid code development is a technical function with significant economic and regulatory consequences [**213**].

With the rapid increase in penetration of wind power in the power system, a number of transmission system operators issued grid codes imposing specific requirements concerning grid support during steady-state operation as well as grid faults or disturbances. It becomes necessary requirement for wind farms to behave as much as possible as conventional power plants to support the network voltage and frequency. Due to this requirement, the utilities in many countries have recently established or are developing grid codes for operation and grid connection of wind farms. The aim of these grid codes is to ensure that the continued growth of wind generation does not compromise the power quality as well as the security and reliability of the electric power system [**214**], [**215**], [**216**]. This is different from country to country. South Africa grid requirements for wind power integration into the grid is discussed below

5.7.1 Power Quality regulation requirement [180]

Power quality and voltage regulation impact must be monitored at the point of connection (POC) and shall include an assessment of the impact on power quality from the RPP concerning the following disturbances at the POC [**216**]

- Voltage fluctuations
- Rapid voltage changes
- Flicker
- Frequency
- Harmonics
- Unbalanced currents and voltages

Voltage variation and dips [217]

Figure 5.4 is applied to all types of faults (symmetrical and asymmetrical i.e. one-, two- or three-phase faults), If several successive fault sequences occur within the area B and evolve into area C, disconnection is allowed. In connection with symmetrical fault sequences in areas B and D, the RPP shall have the capability of controlling the reactive power. In case of Area D, the *RPP* shall stay connected to the network and provide maximum voltage support by absorbing a controlled amount of reactive current so as to ensure that the *RPP* helps to stabilise the voltage within the design capability

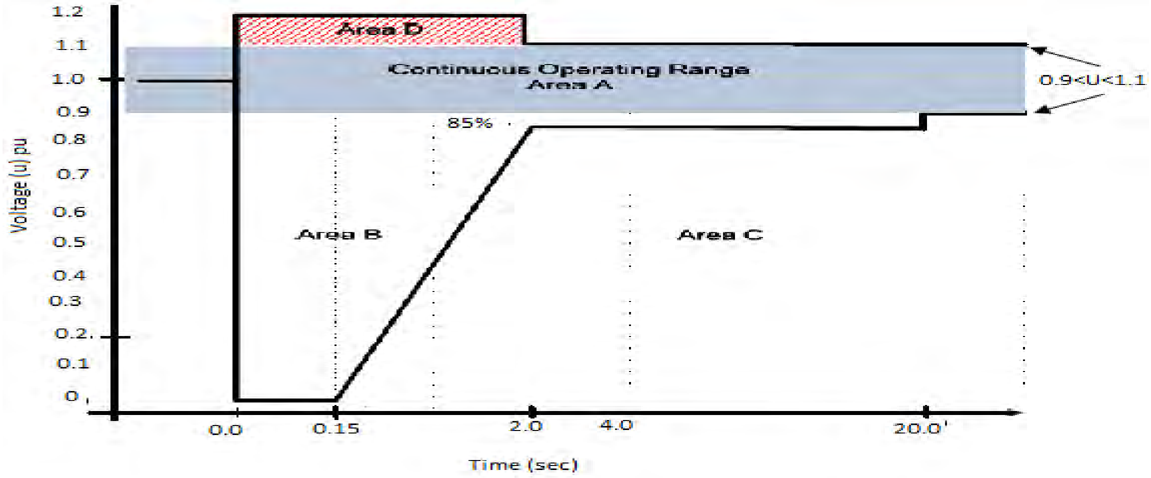


Figure 5.4: Symmetrical and asymmetrical fault requirements for South Africa [**217**]

Frequency regulation requirement

The primary objective of the grid code is to establish technical conditions for wind energy facilities (WEFs) connected to the South African electricity transmission or distribution networks. It sets out rules and obligations to which participants must comply in order to connect WEFs with the South African electricity networks [**217**]. The WEF, when in operation, must be capable of operation for specific periods as a function of system frequency in accordance with Figures 5.5. The tripping of the individual wind turbines within the wind energy facility (WEF) due to frequency excursions must be staggered and the philosophy for tripping must be approved by the system operator (SO). The WEF must remain connected to the DS or TS during rate (for falling frequencies, but not rising) of change of frequency of values up to and including 0,5 Hz per second, provided that the network frequency is still within the continuous frequency characteristic.

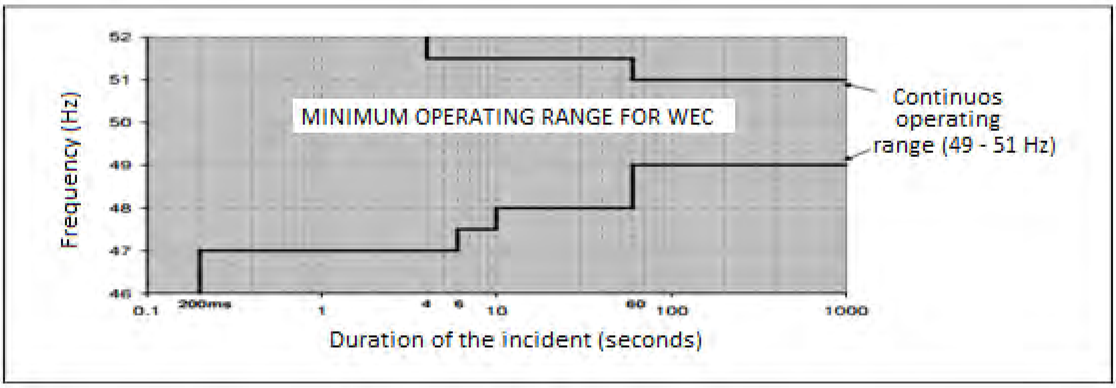


Figure 5.5: Minimum frequency operating range during a fault [**217**].

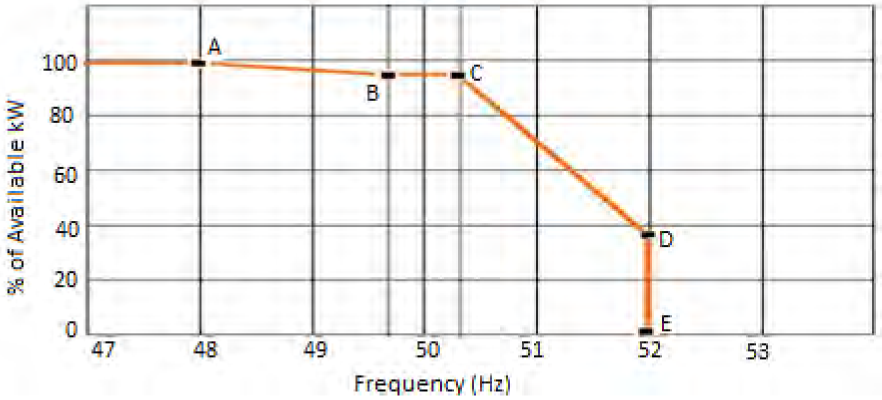


Figure 5.6: Power-Frequency Control Curve [**217**].

A frequency dead-band is capable of being set between 0 and 0.5Hz, if the frequency rises to a level above 50.5Hz, then the WEF must act to ramp down the WEF's active power output. The response rate of each available online WEF must be a minimum of 1 % of WEF rated capacity per second (MW/second), If the frequency rises to a level above the line D-E, as defined by the Power-Frequency Response Curve in Figure 5.6 above, SO recognises that WEFs must cease to generate.

Reactive power regulation requirement

The reactive power and voltage control functions are mutually exclusive, which means that only one of the three functions mentioned below can be activated at a time.

- Voltage control
- Power Factor control
- Reactive power (Q) control

Renewable power plants (RPPs) with rated power of less than 1 MVA must be designed with the capability to supply rated power (MW) for power factors ranging between 0.95 lagging and 0.98 leading. The default power factor setting must be unity power factor. Renewable power plants with plant rated power in the range equal to or greater than 1 MVA but less 20 MVA should be designed with the capability to operate at voltage (V), power factor or reactive power (Q or Mvar) control modes [**217**]. The actual operating mode (V, power factor or Q control) as well as the operating point can be agreed with the network service provider. Point A is equivalent (in MVar) to −5 % rated MW output and point B is equivalent (in MVar) to 5 % rated MW output, and point C is equivalent (in MW) to 5 % rated MW output as shown in Figures 5.7 and 5.8

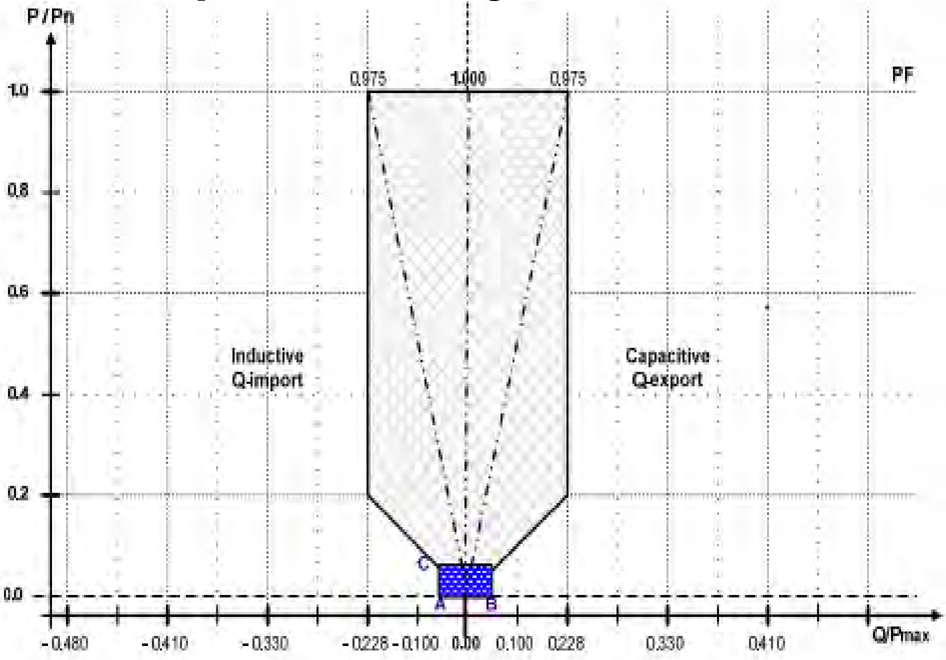


Figure 5.7: Reactive power requirements for Renewable power plants 1 MVA ≤ x ≤ 20 MVA [**217**].

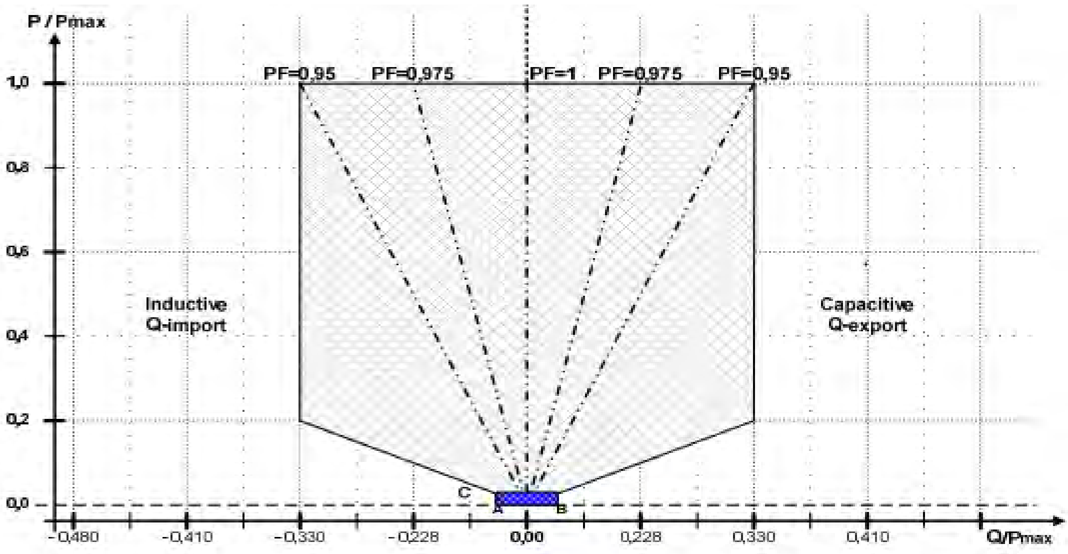


Figure 5.8: Reactive power requirements for RPPs ≥20 MVA [217].

5.7.2 Classification by Category

Sizes of WEC or DG to be integrated into the South Africa distribution network are classified into three categories based on size of the facility and the connection voltage). According to the South Africa grid code rules, subcategories of WEC with rated power in the range of 0 to 13.8 kVA are referred to as category A1. Subcategories of WEC with rated power in the range of 13.8 kVA to 100 kVA are referred to as category A2. Subcategories of WEC with rated power in the range of 100 kVA to 1 MVA are referred to as category A3, where A1 to A3 are to integrate into the low voltage distribution network, B and C are to integrate on the medium and high voltage network as depicted in Table 5.3 below

WEC synchronization to the interconnected power system

The voltage at the point of connection of WEC into the grid according to the South African grid connection code for renewable power plants connected to the distribution network must be in the range of -15 % to +10 % (0.85 to 1.1 voltages per unit) for low voltage and ± 10 % for medium and high voltage around nominal voltage. This condition is put into consideration in this dissertation, Table 5.4 below show the details.

Table 5.3: WEC classification for distribution network connection [**217**]

Sub – categories of REF	Power Range	Connection Voltage	Voltage Limits
A1	$0 < x \leq 13.8$ kVA	LV	-15+10 %
A2	13.8 kVA < x < 100 kVA	LV	-15+10 %
A3	100 kVA ≤ x < 1 MVA	LV	-15+10 %
B	1 MVA ≤ x ≤ 20 MVA, 0 < x <1 MVA	MV and HV	±10 %
C	≥ 20 MVA	HV	±10 %

WEC connection and penetration level

DFIG interacts with the grid through the rotor and stator terminals. The bases for choosing WEC rated power and penetration level shall be according to the WEC categories mentioned in section 5.7.2 above. For an example, if the rated power of the WEC to be integrated into the network is equal to 13.8 kVA at a power factor of 0.98, and the total load demanded in a network is equal to 4.3 MVA, by calculation, the wind penetration to such network is equal to 0.3 % WEC penetration level. Wind penetration level can be defined thus:

$$\text{Wind capacity penetration level} = \frac{\text{IWC (MVA)}}{\text{TLD(MVA)}} \times 100 \ldots\ldots\ldots\ldots \quad (5.13)$$

Where
IWC = Installed wind energy capacity
TLD = Total load demanded

In a network with total loading of 4.3 MVA, WEC rated power of 100 kVA will be equal to the 2.3 % penetration level in the network, while the rated power of 300 kVA will have 7 % WEC penetration on the network. More WECs rated power and penetration levels (600 kVA=14 % WEC penetration level, 1 MVA=23.3 % WEC penetration level, and 2 MVA=47 % penetration level) are considered in this dissertation to determine the amount of the penetration level of WECs that the network can accommodate without violation of the grid code act and the normal international standard network permissive voltage drop of the nominal value (±10 %).

Chapter 6

WEC integration, analysis and its impacts on the voltage profile of a distribution network under normal operation

Introduction

Research work and investigation in proffering solutions to most of the power system challenges and problems encountered in a real case are mostly carried out on a standard test system and involves in network design, modelling, testing and simulation before a reasonable contribution and a recommendation can be given to a particular or identified problem. In this chapter, an overview of the softwares used, the description, validation and modification of the test system used are discussed. The impacts of WEC location, the effects of WEC on the point of common coupling, maximum penetration level of WEC with different power rating in kVA and MVA without grid code violation are investigated using MATLAB/SIMULINK and PSCAD/EMTDC. These software packages are used so that the results obtained can be compared.

6.1. Overview of the Software Used

Simulation is a powerful analytical tool that allows for prediction of system behaviour in response to operator actions and events. System operators and engineers must have instant access to online information and analysis tools that allow them to predict an outcome before system actions are taken. The ability to simulate the sequence-of-operation is of fundamental importance. Design is an iterative process, in which simulation results will suggest ways that the design should be modified to increase safety, reliability, and serviceability. At the conclusion of the design effort, organizations will enjoy a far higher degree of confidence in the integrity of their power systems infrastructure than with manually drawn schematics. The software packages used for this dissertation are MATLAB/SIMULINK and PSCAD/EMTDC.

6.1.1 MATLAB

The name MATLAB stands for matrix laboratory, it was originally written to provide easy access to matrix software developed by the LINPACK and EISPACK projects. The MATLAB software can be described as a high- level performance language for technical computing integrates computation, data analysis, exploration, visualization, algorithm development and programming in an easy-to-use environment where problems and solutions are expressed in familiar mathematical notation. The uses of MATLAB can be found in the following:

- Math and computation
- Algorithm development
- Data acquisition
- Modelling, simulation, and prototyping
- Data analysis, exploration, and visualization
- Scientific and engineering graphics
- Application development, including graphical user interface building

6.1.2 SIMULINK Software

The Simulink software model simulates, and analyses dynamic systems. It enables a question to be posed about a system, model the system, and simulate to see the outcome. A model can be built with SIMULINK from the scratch and the existing model can be modified to suit one's purpose. It supports linear and nonlinear systems, modelled in continuous time, sampled time, or a hybrid of the two. Simulink can move beyond idealized linear models to explore more realistic nonlinear models, factoring in friction, air resistance, gear slippage, hard stops, and the other things that describe real-world phenomena. Simulink provides tools to model and simulate almost any real-world problem. It is a tool for model-based design, simulation and analysis. It provides a graphical user interface (GUI) for building models as block diagrams and also provides demos that model a wide variety of real-world phenomena. Simulink turns a computer into a laboratory for modelling and analysing systems [**217**].

6.1.3 Interaction of Simulink Software with the MATLAB Environment

Simulink software is tightly integrated with the MATLAB environment. It requires MATLAB to run, depending on it to define and evaluate the model and block parameters. It uses the MATLAB environment to define model inputs, store model outputs for analysis and visualization, and perform functions within a model, through integrated calls to MATLAB operators and functions. Model analysis tools include linearization and trimming tools, which can be accessed from the MATLAB command line, and its application toolboxes. MATLAB and Simulink are integrated, it is possible to simulate, analyse, and revise models in either environment at any point. A model can be simulated, using a choice of mathematical integration methods, either from the Simulink menus or by entering commands in the MATLAB Command Window. The menus are convenient for interactive work, while the command line is useful for running a batch of simulations

[**217**]. Using scopes and other display blocks, the simulation results can be viewed while the simulation runs, many parameters can be changed to see what happens for "what if" exploration. The simulation results can be put in the MATLAB workspace for post processing and visualization.

6.1.4 MATLAB/SIMULINK tool boxes

MATLAB consists of add-on application-specific solutions which are called toolboxes. The toolboxes allow learning and apply specialized technology. It is a comprehensive collection of MATLAB functions that extend the MATLAB environment to solve particular classes of problems, e.g. Signal processing toolbox, control systems toolbox, neural networks toolbox, fuzzy logic toolbox, simpowersystems toolbox and many other areas.

There are many tool boxes in MATLAB/SIMULINK that can be used for different kinds of applications, modellings, and simulations which depend on the area of research and interest such as signal processing toolbox, control systems toolbox, neural networks toolbox, fuzzy logic toolbox, simpower systems toolbox, vehicle network toolbox and robust control toolbox, etc. The simpowersystem tool box is used in this dissertation [**217**].

6.1.5 Simpowersystem toolbox

SimPowerSystems software and other tool boxes of the Physical Modelling product family work together with Simulink software to model electrical, mechanical, and control systems. It operates in the Simulink environment. SimPowerSystems software is a modern design tool that allows scientists and engineers to rapidly and easily build models that simulate power systems. It allows building a model using simple click and drag procedures, it allows drawing a circuit topology rapidly, which may include its interactions with mechanical, thermal, control, and other disciplines. This is possible because all the electrical parts of the simulation interact with the extensive Simulink modelling library. Simulink uses the MATLAB computational engine; designers can also use MATLAB toolboxes and Simulink block sets. SimPowerSystems software belongs to the Physical Modelling product family and uses similar block and connection line interface [**217**].

SimPowerSystems Libraries

SimPowerSystems libraries contain models of typical power equipment such as transformers, lines, machines, and power electronics. These models are proven ones coming from textbooks, and their validity is based on the experience of the Power Systems Testing and Simulation. The

SimPowerSystems main library, powerlib, organizes its blocks into libraries according to their behaviour. The powerlib library window displays the block library icons and names. A library icon is double-clicked to open the library and access the blocks. The main powerlib library window also contains the Powergui block that opens a graphical user interface for the steady-state analysis of electrical circuits. The step by step details of MATLAB/SIMULINK is discussed in Appendix B [**217**].

6.2 PSCAD/EMTDC software

PSCAD is a powerful electromagnetic time domain transient simulation tool. With proper design of the simulation model, power system problems can be analysed. Various electric power researchers use PSCAD, for example, transmission system design, power quality studies, power electronics design, electric machine performance study, control system design and optimization [**217**].

6.2.1 Master Library Models

There is a master library model in PSCAD, which consists of all components such as Two Winding DC Machine, Wind Turbine, Wind Source, active and passive components, transformers, etc; it is from this library that components of the network design are taken. The desired components can be copied from the master library or dragged and dropped into the workspace for network building or modelling

6.3 The Test System Description

To investigate the impacts of WEC on a low Voltage distribution network, the wind energy converter to be considered in this dissertation is a doubly fed induction generator (DFIG). This wind energy generator (DFIG) is considered because of easy control and robustness. DFIG is a wound rotor induction generator with voltage source converter connected to the slip-rings of the rotor; it interacts with the grid through the rotor and stator terminals. This type of wind turbine has been designed to increase the aerodynamic efficiency in various ranges of wind speeds. Their electrical system is more complex than the fixed-speed wind turbines [**219**]. Better power quality, higher amount of energy extracted and less mechanical stress on the turbines are the main benefits.

IEEE 13-bus test system is considered as a standard test system to be used [**220**], which has challenging voltage management feature, as it exhibits extreme voltage issues. It is made of medium (1 kV to 44 kV) and low voltage (50 V to 1 kV), it is one of four standard distribution models developed by the IEEE Power Engineering Society's Power System Analysis, Computing and Economics Committee [**221**]; the test feeder is short and relatively highly loaded for a 4.160 kV feeder and the total loading of the network is 4.054 MVA. It has several key distribution system components such as overhead lines, spot and distributed loads, substation transformers, Wye and delta connected loads, mixture of constant kW, kVar, constant impedance and current, shunt capacitor at buses and voltage regulator, etc. It is very indicative of the types of distribution systems in use today and is a standard test system. A step down transformer is connected to buses 633 and 634 which stepped down 4.16 kV to 480 V. Only bus 634 is at 480 V, all other buses receive 4.16 kV, this unbalanced multiphase feeder consists of three phases (buses 632, 633, 634, 671, 692, and 675), two phases (buses 645, 646 and 684) and single phase (buses 611 and 652) sections.

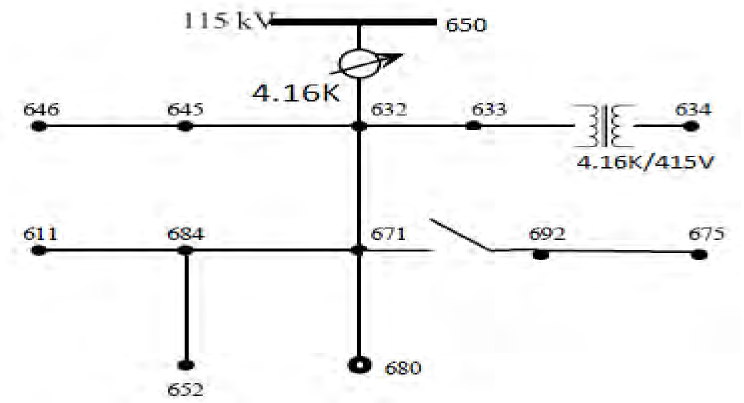


Figure 6.1: IEEE 13 Node feeder test system [220]

6.3.1 Case I: Unbalanced IEEE 13-bus test system

The test system was modelled and simulated in MATLAB/SIMULINK; all the underground lines are modelled as overhead lines because there is no underground cable in the simpower systems library, the simulation results are shown in Table 6.0 and Figure 6.2 below which are obtained by taking the voltage measurements at each bus in the network and the values were plotted. The comparison tables in Appendix A (Tables A6 to A8) show the differences between the simulation results obtained and those published in the IEEE document and CYME International T&D power engineering software and solution document [**222**]. The maximum voltage deviation obtained in the simulation performed compared to IEEE are 0.02 %, 0.06 % and 0.02 % for phase A, B and C, while that of CYME international T&D for A, B and C are 0.05 %, 0.03 % and 0.05 %.

Table 6.0: Measured voltage of the IEEE 13-bus test system

Bus No	Phase A	Phase B	Phase C
632	1.0025	1.0013	1.0004
633	1.0071	1.0013	1.0008
634	0.9747	0.9999	0.9999
645	0	1.0008	1.0004
646	0	1.0004	1.0008
671	0.9992	1.0037	0.9867
692	0.9908	1.0008	0.9808
675	0.9904	1.0021	0.9792
684	0.9971	0	0.9863
611	0	0	0.9863
652	0.9958	0	0
680	0.9992	1.0037	0.9867

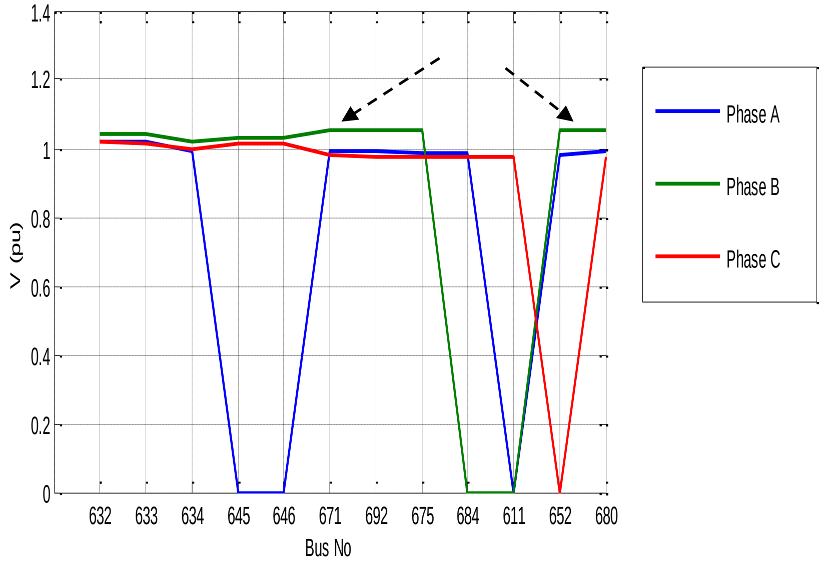


Figure 6.2 Simulation graph for IEEE 13-bus test system

6.3.2 Case II: Unbalanced IEEE 13-bus test system (with capacitor and voltage regulator removed without WEC)

After validating the test system used without any modification as shown in the section 6.3.1 above, to investigate the impacts of WECs on an unbalanced network, the regulator between buses 650 and 632 and the compensating capacitors at the buses 634 and 611 were removed. The reason why they were removed is that, with the regulator and capacitor, the network voltage profile is already at the maximum allowed limit as indicated by the arrow in Figure 6.2 above. The network is simulated and the voltage profiles are plotted using the measured voltages of each phase at the bus bar as shown in Table 6.1 and Figure 6.3 below, there is a smooth voltage profile from the substation to the farthest bus except that a low voltage occurred at bus 634 compared to other buses.

Table 6.1: Measured voltage of the base case

Bus no	Phase A	Phase B	Phase C
632	0.9912	0.9951	0.9964
633	0.9909	0.9949	0.9962
634	0.8909	0.9103	0.9116
645	0	0.9912	0.9948
646	0	0.9913	0.9944
671	0.9753	0.993	0.9985
692	0.9698	0.9851	0.9958
675	0.9681	0.9844	0.9969
684	0.9748	0	0.9911
611	0	0	0.9743
652	0.9899	0	0
680	0.9753	0.993	0.9985

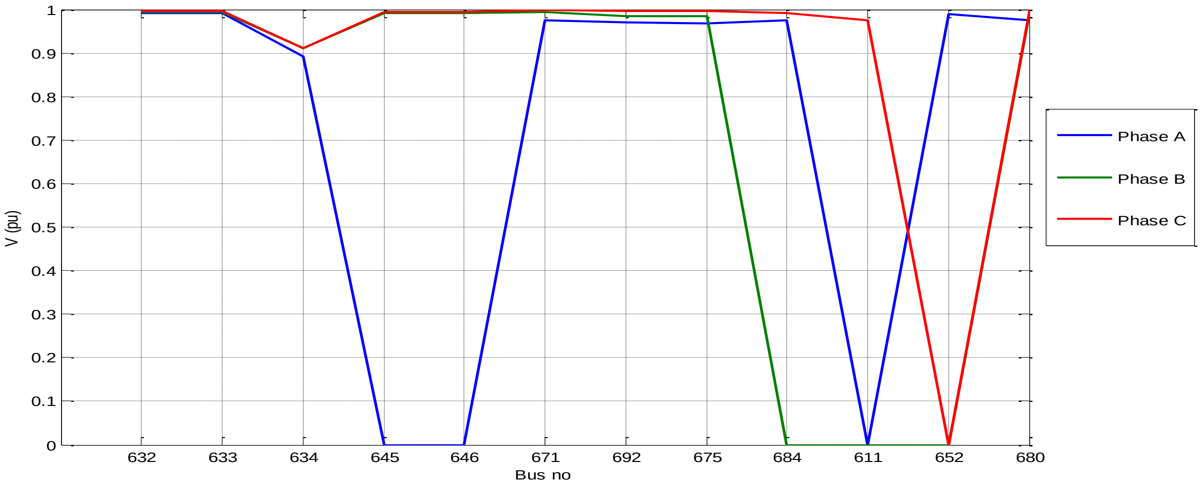


Figure 6.3: Voltage profiles without regulator and compensation capacitor

6.3.3 Case III: Unbalanced IEEE 13-bus test system (with capacitor and voltage regulator removed with WEC)

Buses 671, 675 and 634 are considered for WECs connection, this is because the output of WECs is balanced three-phase, and can only be connected where there is a complete three phases (three wires) in the network, buses 646 and 645 are two phases, buses 611, 684 and 652 are single phase, bus 632 is three-phase, but it is very close to the substation, it cannot be considered for WEC connection, bus 680 is also not considered because there is no load connected to the bus. Bus 692 is not the best point of WEC connection because only one single phase light load is connected to the bus.

When bus 671 is considered as the point of WECs connection ranging from 13.8 k VA, 100 kVA, 300 kVA, 600 kVA, 1 MVA and 2 MVA at a power factor of 0.98 and the network is simulated, the measured voltages in Tables 6.2 and 6.3 from each phase is plotted as depicted in Figure 6.4 below, the impacts of WECs improved the voltage profile of the network, bus 671 can only take less than 47 % WECs penetration levels, if it is equal to or more than that, the grid code act will be violated i.e., the voltage will go beyond 1.1 pu, especially at the point of common coupling.

When WEC is integrated at the bus 675 with the same power range, at 23 % penetration level of WEC, red phase violated the grid code act at the point of common coupling, while other two phases are within an acceptable limit, further increasing the penetration level, all the three phases violated the grid code act at the point of common coupling as indicated in Tables 6.2 and 6.7 by red colour and by an arrow in Figure 6.5. The last location for WEC integration is the bus 634 which is the only low voltage arm in the network, in-line transformer is connected near the bus that stepped down the voltage from 4.16 kV to 480V. A 7 % WEC penetration level is still acceptable on the bus 634, 14 % penetration caused a voltage rise beyond an acceptable range, this is due to the fact that the load on that bus is a light load (494 kVA) and if the power of the WEC is more than the load, there will be an excess generation which may lead to voltage rise as shown in Tables 6.6, 6.7, Figure 6.6

Table 6.2: Measured voltages when WEC is connected to bus 671

Penetration levels	0.3 %			2.3 %			7 %		
Bus no	**Phase A**	**Phase B**	**Phase C**	**Phase A**	**Phase B**	**Phase C**	**Phase A**	**Phase B**	**Phase C**
632	0.9911	0.9951	0.9964	0.9941	0.9982	0.9993	1.0148	1.0179	1.0191
633	0.9909	0.9949	0.9962	0.9939	0.9979	0.9991	1.0145	1.0183	1.0188
634	0.8909	0.9103	0.9116	0.8936	0.913	0.9143	0.912	0.9319	0.9334
645	0	0.9912	0.9948	0	0.9942	0.9978	0	1.0122	1.0172
646	0	0.9913	0.9948	0	0.9943	0.9974	0	1.0139	1.0171
671	0.9753	0.993	0.9985	0.9792	0.997	1.0026	1.0055	1.0222	1.0296
692	0.9698	0.9851	0.9958	0.9737	0.989	0.9999	0.9983	1.0143	1.0255
675	0.9681	0.9844	0.9969	0.972	0.9884	1.001	0.9969	1.0147	1.0267
684	0.9748	0	0.9911	0.9787	0	0.9951	1.0035	0	1.0206
611	0.9743	0	0	0	0	0.9783	0	0	1.003
652	0	0	0.9899	0.9939	0	0	1.0183	0	0
680	0.9753	0.993	0.9985	0.9792	0.997	1.0026	1.0043	1.0225	1.028

Table 6.3: Measured voltages when WEC is connected to bus 671

Penetration levels	14 %			23.3 %			47 %		
Bus no	**Phase A**	**Phase B**	**Phase C**	**Phase A**	**Phase B**	**Phase C**	**Phase A**	**Phase B**	**Phase C**
632	1.0367	1.0411	1.0422	1.061	1.0656	1.0667	1.1004	1.1053	1.1064
633	1.0364	1.0408	1.042	1.0607	1.0653	1.0664	1.1002	1.105	1.1061
634	0.9319	0.9521	0.9536	0.9538	0.9745	0.976	0.9892	1.0107	1.0124
645	0	1.0361	1.0407	0	1.0611	1.0651	0	1.1005	1.1049
646	0	1.0365	1.04	0	1.0612	1.0648	0	1.1006	1.1045
671	1.0334	1.0524	1.0585	1.0648	1.0841	1.0904	1.1153	1.1354	1.1421
692	1.0276	1.044	1.0556	1.0588	1.0754	1.0874	1.109	1.1264	1.139
675	1.0261	1.0434	1.0501	1.0569	1.0747	1.0886	1.107	1.1256	1.1403
684	1.0315	0	1.0501	1.0643	0	1.082	1.1147	0	1.1333
611	0	0	1.031	0	0	1.0637	0	0	1.1142
652	1.0489	0	0	1.0807	0	0	1.1319	0	0
680	1.0337	1.0524	1.0585	1.0648	1.0841	1.0904	1.1153	1.1354	1.1421

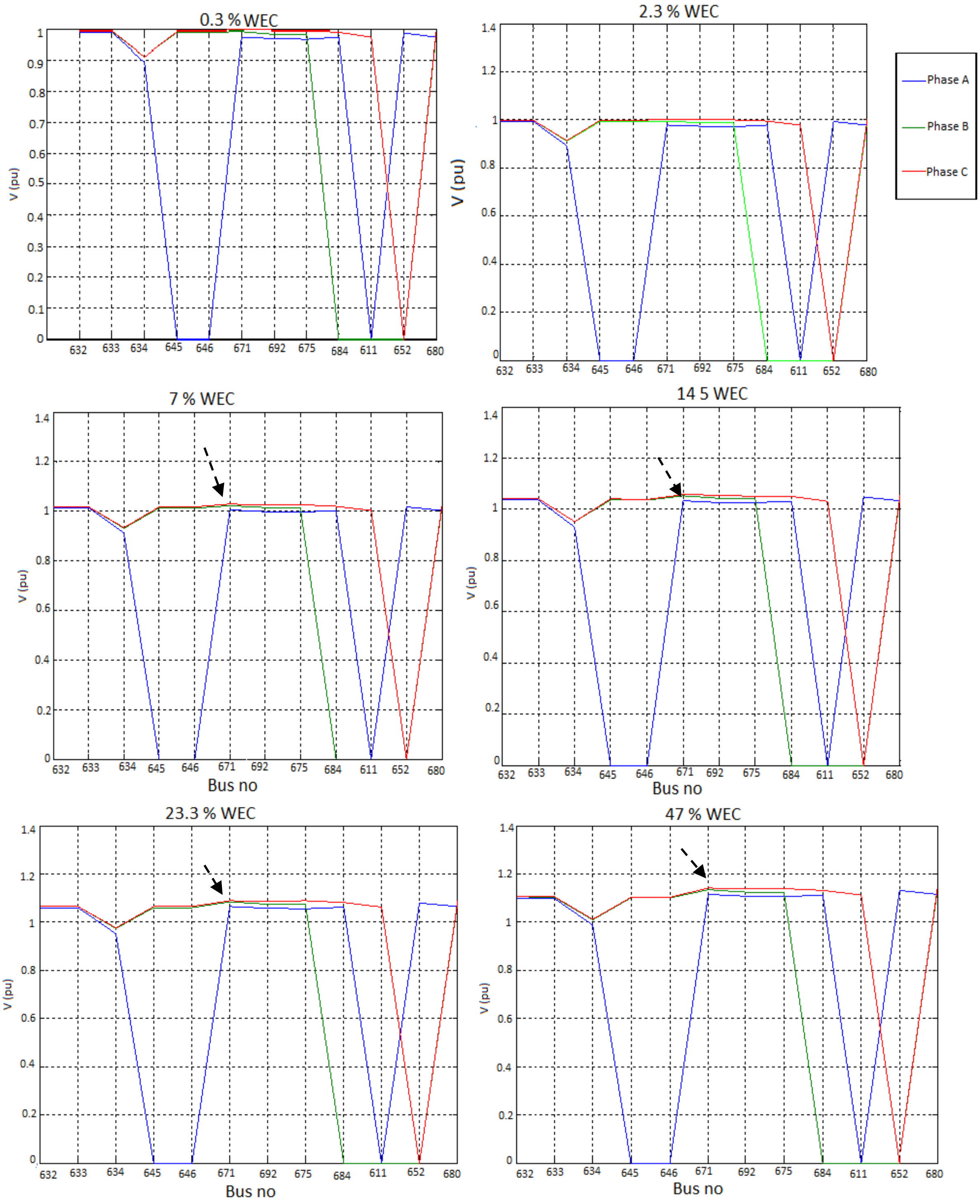


Figure 6.4: Network voltage profiles when of WEC is connected to bus 671

Table 6.4: Measured voltages at bus 675 for WEC penetration level

Penetration levels	0.3 %			2.3 %			7 %		
Bus no	**Phase A**	**Phase B**	**Phase C**	**Phase A**	**Phase B**	**Phase C**	**Phase A**	**Phase B**	**Phase C**
632	0.9935	0.9978	0.9988	1.0132	1.0154	1.0167	1.0293	1.034	1.0348
633	0.9933	0.9975	0.9985	1.013	1.0172	1.0184	1.029	1.0337	1.0345
634	0.8932	0.9125	0.9139	0.9108	0.9306	0.9303	0.9254	0.9453	0.947
645	0	0.9936	0.9974	0	1.0114	1.0152	0	1.0293	1.0325
646	0	0.9937	0.997	0	1.0112	1.0139	0	1.0293	1.0303
671	0.9785	0.9962	1.0021	1.0034	1.0219	1.0276	1.024	1.043	1.0495
692	0.9759	0.9912	1.0022	1.0147	1.0277	1.042	1.0487	1.0647	1.0771
675	0.9745	0.9909	1.0036	1.0118	1.0314	1.0449	1.0498	1.0673	1.0813
684	0.978	0	0.9943	1.0006	0	1.0168	1.0222	0	1.0395
611	0	0	0.9776	0	0	1.0001	0	0	1.0216
652	0.9931	0	0	1.0158	0	0	1.0382	0	0
680	0.9785	0.9962	1.0021	1.0034	1.0216	1.0276	1.024	1.043	1.0495

Table 6.5: Measured voltages at bus 675 for WEC penetration level

Penetration levels	14 %			23.3 %			47 %		
Bus no	**Phase A**	**Phase B**	**Phase C**	**Phase A**	**Phase B**	**Phase C**	**Phase A**	**Phase B**	**Phase C**
632	1.0469	1.0518	1.0526	1.0469	1.0518	1.0526	1.0736	1.0788	1.0797
633	1.0466	1.0515	1.0524	1.0466	1.0515	1.0524	1.0734	1.0785	1.0794
634	0.9412	0.9616	0.9634	0.9412	0.9616	0.9634	0.9652	0.9862	0.9882
645	0	1.0469	1.0514	0	1.0469	1.0514	0	1.0737	1.0784
646	0	1.047	1.051	0	1.047	1.051	0	1.0738	1.078
671	1.0464	1.066	1.0727	1.0464	1.066	1.0727	1.0804	1.1011	1.1078
692	1.0838	1.1007	1.1133	1.0838	1.1007	1.1133	1.1372	1.1549	1.1681
675	1.0862	1.1043	1.1188	1.0862	1.1043	1.1188	1.1414	1.1603	1.1757
684	1.0459	0	1.0626	1.0459	0	1.0626	1.0798	0	1.099
611	0	0	1.0454	0	0	1.0454	0	0	1.0793
652	1.0627	0	0	1.0627	0	0	1.0976	0	0
680	1.0464	1.066	1.0727	1.0464	1.066	1.0727	1.0804	1.1011	1.1078

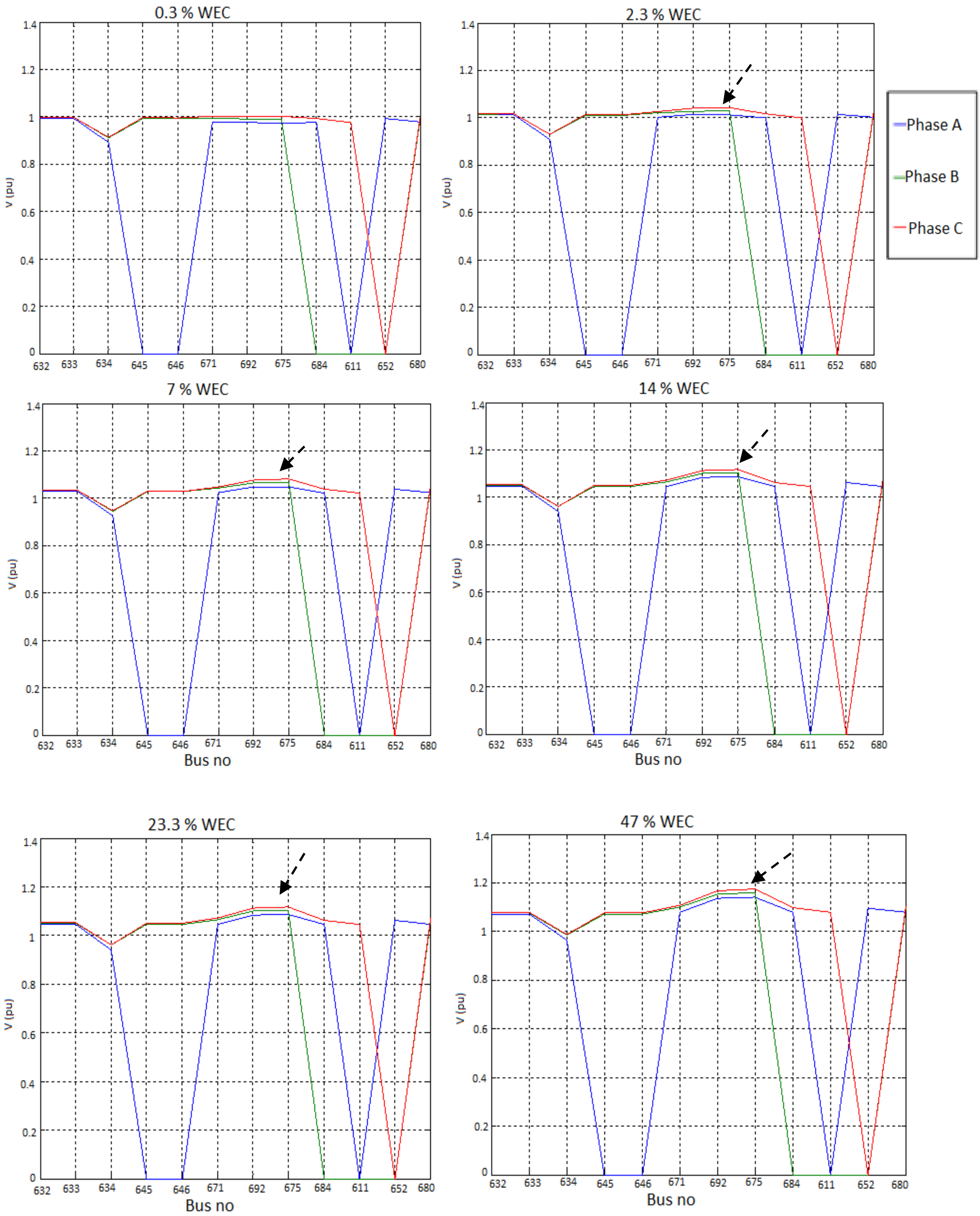


Figure 6.5: Network voltage profiles when of WEC is connected to bus 675

Table 6.6: Measured voltages at bus 634 for WEC penetration level

Penetration levels	0.3 %			2.3 %		
Bus no	**Phase A**	**Phase B**	**Phase C**	**Phase A**	**Phase B**	**Phase C**
632	0.9922	0.9962	0.9974	0.9966	1.0006	1.0018
633	0.9921	0.996	0.9973	0.9968	1.0007	1.002
634	0.8906	0.9186	0.9269	0.9918	1.0233	1.0323
645	0	0.9919	0.9955	0	0.9949	0.9984
646	0	0.992	0.9951	0	0.995	0.998
671	0.9764	0.9941	0.9996	0.9807	0.9984	1.004
692	0.9709	0.9861	0.9969	0.9752	0.9904	1.0012
675	0.9691	0.9855	0.998	0.9734	0.9898	1.0024
684	0.9755	0	0.9918	0.9785	0	0.9947
611	0	0	0.975	0	0	0.9779
652	0.9906	0	0	0.9935	0	0
680	0.9764	0.9941	0.9996	0.9807	0.9984	1.004

Table 6.7: Measured voltages at bus 634 for WEC penetration level

Penetration levels	7 %			14 %		
Bus no	**Phase A**	**Phase B**	**Phase C**	**Phase A**	**Phase B**	**Phase C**
632	0.9996	1.0034	1.0047	1.0049	1.0088	1.0101
633	0.9999	1.0038	1.0051	1.0057	1.0095	1.0109
634	1.0476	1.081	1.0904	1.1707	1.2083	1.2188
645	0	0.9954	0.9989	0	0.9948	0.9983
646	0	0.9955	0.9985	0	0.9949	0.9979
671	0.9836	1.0013	1.0069	0.9889	1.0067	1.0122
692	0.978	0.9933	1.0041	0.9833	0.9986	1.0094
675	0.9763	0.9927	1.0052	0.9816	0.998	1.0106
684	0.9789	0	0.9952	0.9783	0	0.9946
611	0	0	0.9784	0	0	0.9778
652	0.994	0	0	0.9934	0	0
680	0.9836	1.0013	1.0069	0.9889	1.0067	1.0122

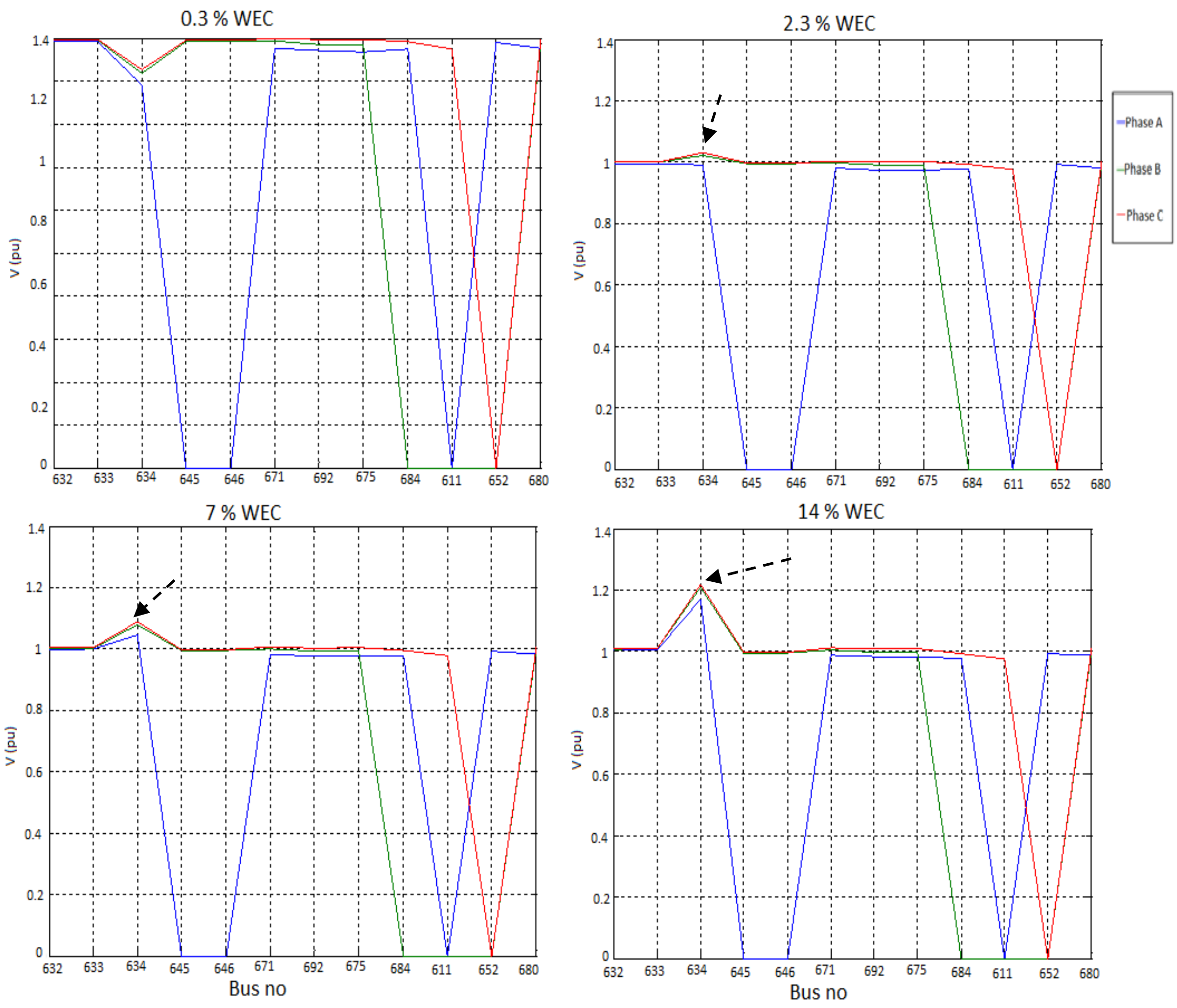


Figure 6.6: Network voltage profiles when of WEC is connected to bus 634

6.3.4 Case IV: Modified IEEE (with capacitor and voltage regulator removed and load balanced without WEC)

For the simulation work presented in this section, IEEE 13-bus Test Feeder system is modified as follows:

- The unbalanced loads were made balanced (balanced network), this was achieved by extending the total loading 3.5 MW, 2.1 MVAr (total loading of 4.1 MVA) to 3.561 MW, 2.310 MVAr (total loading of 4.3 MVA) and making each load balanced.
- The underground cables are modelled as overhead lines and bus 634 is made overloaded since it is the only low voltage bus, so that WEC can be connected to the bus.
- Single and double phase lines were replaced with three-phase lines,
- The network loading is extended to ensure that loads are connected into all the buses that have no load before.

- To draw the voltage profile without the coupling capacitors and regulator

Network design and implementation in MATLAB/SIMULINK

The modified network shown in Figure 6.7 below is implemented in MATLAB/SIMULINK, the layout is in Appendix A, in Figure A2, the network loads are all balanced loads and all the details of the network parameters can be found in Appendix A, in Table A1.

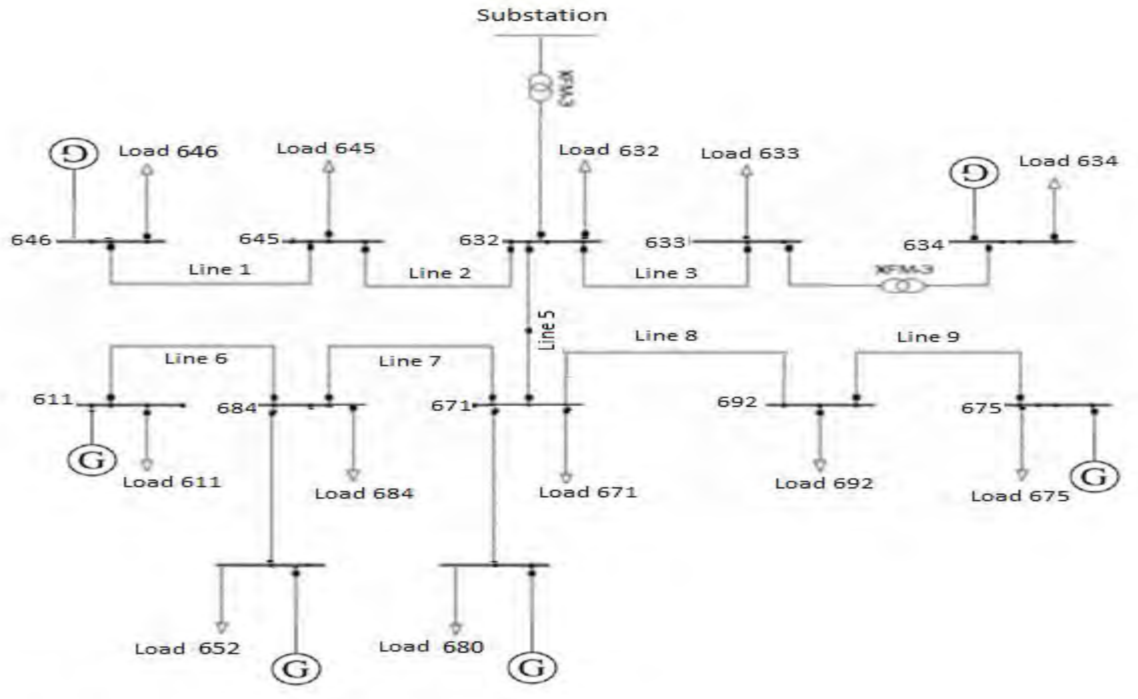


Figure 6.7: Modified IEEE 13 bus test system

- **Voltage profile of the modified IEEE 13 node test system**

The network is designed, tested and simulated in the MATLAB/SIMULINK; the voltages are measured at each bus of the network, the results obtained are depicted in Table 6.8, and are used to plot the network voltage profile in Figure 6.10 and the voltage drop in Figure 6.9. From the voltage profile plotted (see Figure 6.8), the power flow through the feeder results in a smooth voltage drop from the beginning to the end of the feeder, i.e., the voltage drops along the feeder are within an acceptable limit in compliance with the normal permissive (±10 %) drop in the nominal voltage of any standard network and with South African Grid code for distribution network i.e. the acceptable voltage distribution network in South Africa is between 0.85 to 1.1 pu or – 15 to +10 % for low voltage and 0.9 to 1.1 pu or ±10 % for medium voltage network, except that there is a voltage dip at bus 634 which is the weakest bus, the transformer located at the bus is a step down transformer which stepped down the voltage from 4.160 kV to 480 V (the load on the bus is the only load that is supplied by 480 V), the transformer was overloaded, the power of the transformer is 500 kVA while the load connected to the bus is 550.7 kVA. The voltage obtained at the bus is 0.8359 V i.e. it has voltage drop of 13.41 % per unit which is not acceptable (less than acceptable range) according to the normal standard network permissively voltage (-15 to +10 %) and South African grid code act.

More also, there is a voltage drop at the bus 652 which is the second weakest bus as compared to other buses in the network, this is because, the bus 652 is connected to a huge amount of load about 1.2 MVA that is almost two times that of any other bus in the network. Also, the voltage drop at bus 652 may be related to the line length and load current. When the length of the network line increases, the percentage of the voltage drop will also increase, this is due to the increase in the voltage drops along the network as the power flows from the source to the terminal end of the network. Bus 680 may be assumed to be the weakest bus of the network, but it is not so because the load connected to the bus is not huge, it is a very light load, which draws little current from the network compared to buses 634 and 652 that have peak loads and draw more current in the network.

Table 6.8: Bus voltage

Bus Number	Base Voltage	Voltage drop (%)
632	0.9242	7.58
633	0.9232	7.68
634	0.8359	16.41
645	0.9107	8.93
646	0.9101	8.99
671	0.9076	9.24
692	0.9076	9.24
675	0.9070	9.30
684	0.9061	9.39
611	0.9060	9.4
652	0.9030	9.7
680	0.9071	9.29

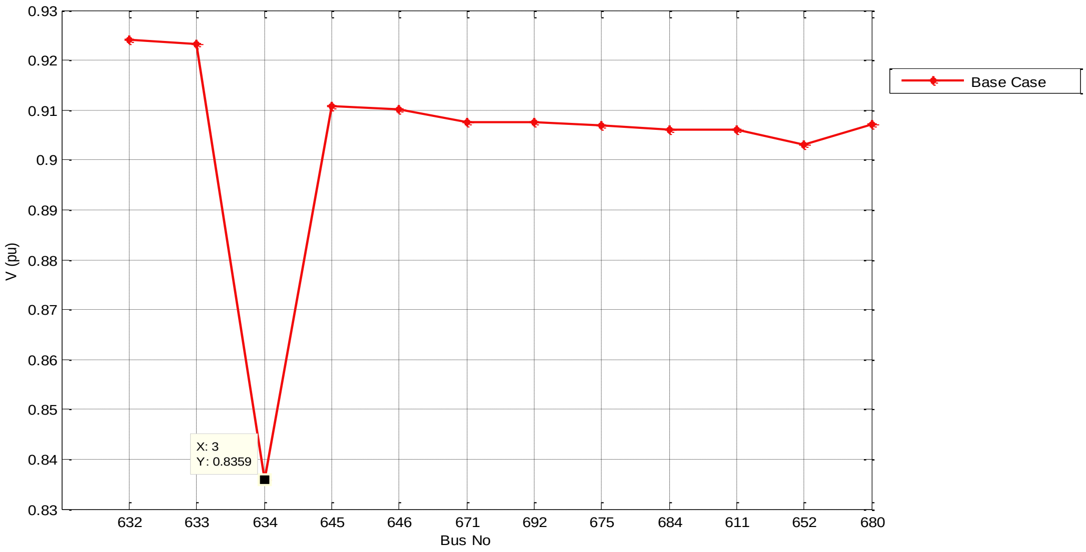


Figure 6.8: Voltage profile of the modified IEEE 13-bus test system without WEC

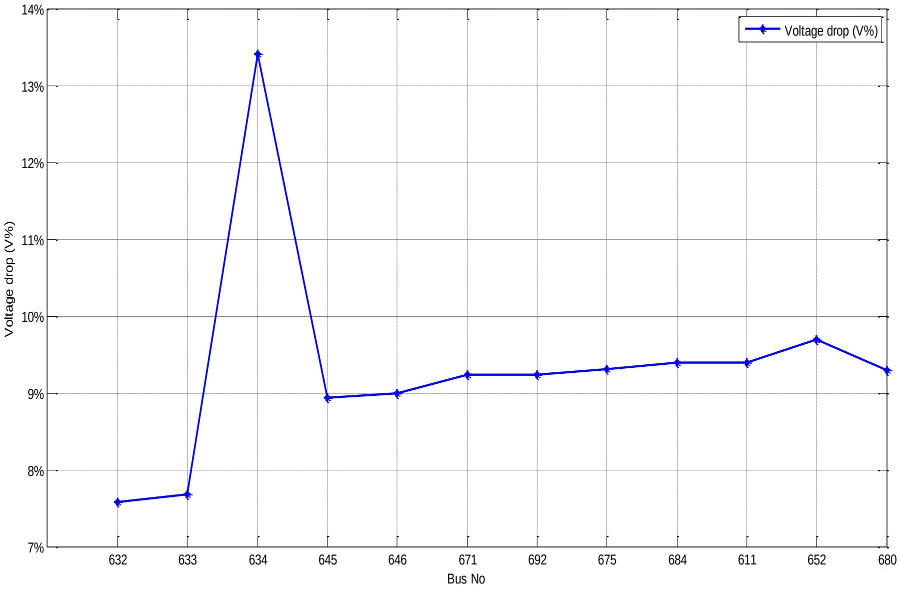


Figure 6.9: Distribution system Voltage drop without WEC

6.3.5 Case V: Modified IEEE (with capacitor and voltage regulator removed and load balanced with WEC)

The quality of power delivered to the consumers by the utility determines the functionality and performance of the most sensitive equipment or appliance. For these equipment or appliances to function and perform well, the voltage level of the distribution network must not exceed the acceptable limit or range i.e., must not exceed the grid code specification. Distribution network confronts with varying loads, thereby changing of current through the resistance and reactance of the feeder, causing a voltage drop across the network, the impact of DGs on a network may depend on the power flow and the location of such DGs in the network. The voltage profile of a network may not be influenced if the DG's power injected into the network is very small compared to the load, otherwise, if the injected power by the DG is more than the loads connected to the network, the grid voltage can exceed an acceptable range which may violate the grid code act or international standard.

Connection to the farthest bus

The impacts of the wind energy integration on the voltage profile of a distribution network are demonstrated in the simulation of a modified 4.160 kV test feeder. Different generation scenarios (WEC range of 13.8 kVA, 100 kVA, 300 kVA, 600 kVA, 1 MVA, 2 MVA and 2.8 MVA) are considered to show the impacts of WEC on the network, to investigate the maximum penetration level of the WEC in the network without grid code act violation (±10 %) as stated in the section 5.7.2 and to determine the impacts of WEC on the voltage profile along the feeder. Bus 680 is considered to be the point of integration into the network; this location is chosen because it is very far from the substation.

When a 13.8 kVA wind power (0.3 % penetration level) is injected into the network at the bus 680 in relation to the category B as mentioned in Table 5.2, section 5.6.2.2 above, to supply the local load, the impact on the network voltage profile is insignificant, i.e., the voltage profile of the network remains the same as shown in Table 6.9 and Figure 6.10 below. This is because the ratio of the 13.8 kVA wind power integrated into the network that has a total load of 4.3 MVA is 1:312, therefore, more wind power is required for the network voltage profile to be improved. At a 2.3 % WEC penetration level, the network voltage profile increased slightly, but a voltage dip is still noticed on the bus 634. From 7 % WEC penetration level, the voltage dip improved which brought about the increasing of voltage profile of the network. Further increasing WEC (14 %, 23.3 %, 47 %, 58 % and 65 %) penetration levels, the network voltage profile improved; at bus 680 with 58 % injection scenario, the voltage increased from 1 to 1.0929 pu, (a 9.29 % increase) which is within an acceptable range in relation to the grid code act and is the best simulation result for the bus 680. Injection of WEC to 65 % penetration, the additional voltage on that bus is 0.1041 or +10.41 %, which is not acceptable in relation to the grid code act (±10 %), i.e., the bus voltage is more than 1.1 pu volts required. But this over voltage is only noticed at the POCC of the WEC (bus

680), while other voltages are still within an acceptable range, meanwhile, the penetration level cannot be increased further beyond this point.

Table 6.9: Network voltages when WEC is connected at bus 680

Bus	Base Voltage	WEC 0.3 %	WEC 2.3 %	WEC 7 %	WEC 14 %	WEC 23.3 %	WEC 47 %	WEC 58 %	WEC 65 %
632	0.9242	0.9242	0.9264	0.9555	0.9771	1.0003	1.0382	1.0518	1.0598
633	0.9232	0.9232	0.9254	0.9538	0.9764	0.9992	1.0361	1.0507	1.0586
634	0.8359	0.8359	0.8379	0.8632	0.8837	0.9047	0.9392	0.9513	0.9585
645	0.9107	0.9108	0.9129	0.9411	0.9629	0.9857	1.0233	1.0365	1.0443
646	0.9101	0.9101	0.9122	0.9404	0.9622	0.985	1.0225	1.0357	1.0435
671	0.9076	0.9076	0.9109	0.9474	0.9763	1.006	1.0548	1.073	1.0831
692	0.9076	0.9076	0.9109	0.9474	0.9763	1.0061	1.0546	1.073	1.0831
675	0.907	0.9071	0.9103	0.9467	0.9758	1.0054	1.0543	1.0724	1.0825
684	0.9061	0.9061	0.9094	0.9458	0.9749	1.0044	1.053	1.0713	1.0814
611	0.906	0.906	0.9093	0.9456	0.9746	1.0043	1.0529	1.0711	1.0812
652	0.903	0.903	0.9062	0.9425	0.9714	1.001	1.0495	1.0676	1.0776
680	0.9071	0.9072	0.9111	0.9517	0.9844	1.0177	1.0721	1.0929	1.1041

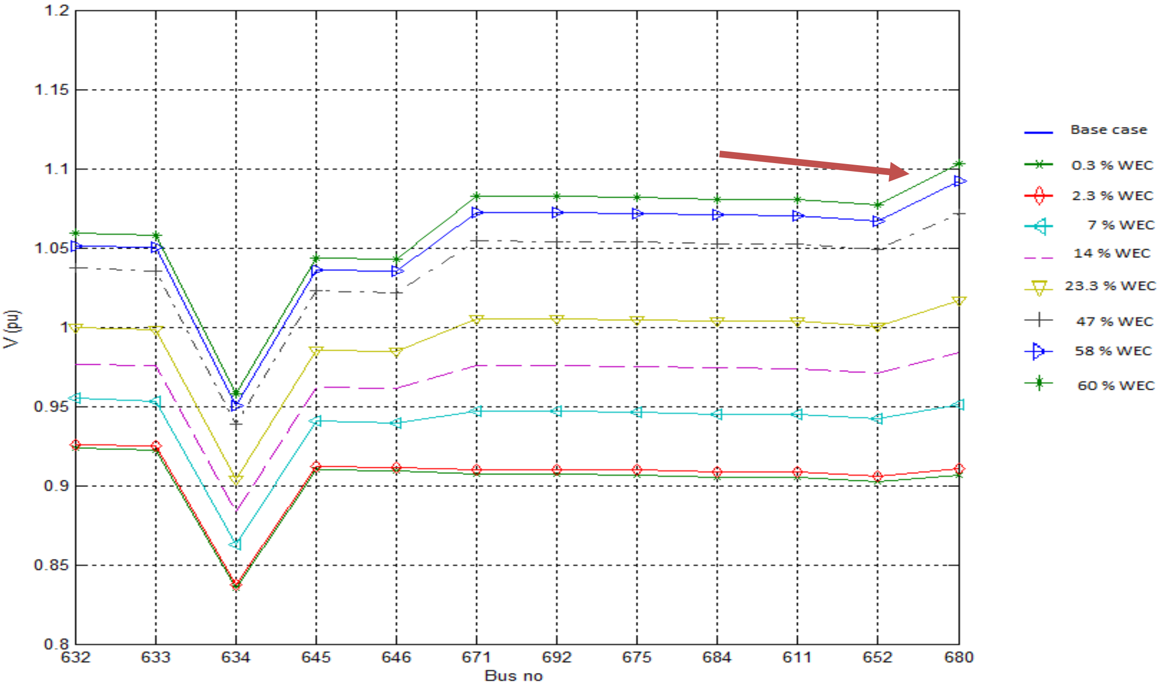


Figure 6.10: Voltage profiles with WEC connection to bus 680

Comparison of the maximum penetration level on the selected buses (buses 633, 652, 675, 646, 671, 680, and 611) without/with the grid code act violation

Having shown in the previous section that WEC can improve the voltage profile of a distribution network, it is necessary now to compare the integration of WEC into different buses of the network to really know the bus that can take the highest WEC penetration level without violating the grid code act. The simulation results are depicted in Figures 6.11 to 6.16 and Tables 6.10 to 6.16 below. Bus 652 takes 93 % WECs penetration level, which is more than any other bus in the network without grid code act violation. Bus 633 takes up to 81 % WEC integration due to the fact that the load connected to bus 634 is also a huge load, but it is the only load connected to 480V in the network and is very near to bus 633. Buses 675, 646, 671 and 611 accept 70 % WECs penetration level (Figures 6.13, 6.14, 6.16 and 6.17); any attempt to increase the penetration level may lead to the grid code act violation. Bus 680 takes 65 % WEC penetration level (Figure 6.15), further increasing the penetration level may lead to grid code act violations. Its penetration level is smaller compared to buses 675, 646, 611,652 and 633, although it is the farthest from the substation. It may be as a result of light load that is connected to the bus.

Integration of WEC to a distribution network by selecting a different location within the network bus confirm that its voltage profile can be improved, meanwhile, the penetration level may vary depending on the type of load connected to a particular bus (light or heavy load), and the distance of the bus bar that the load is connected from the substation location.

Some of the benefits of choosing the weakest point or location for WEC integration in any network is that, voltage dips can be minimized, voltage drop can be reduced, more WECs penetration can be attained without the fear of an over voltage and the weaker network can be strengthened. Buses 633 and 652 (Figures 6.11 and 6.12) have the highest and maximum penetration levels of the WEC in the network while bus 680 has the lowest penetration

Table 6.10: Network voltages when WEC is connected at bus 633

Bus No	Base Voltage	WEC 0.3 %	WEC 2.3 %	WEC 7 %	WEC 14 %	WEC 23.3 %	WEC 47 %	WEC 58 %	WEC 65 %	WEC 70 %	WEC 81 %
632	0.9242	0.9242	0.9269	0.9553	0.9807	1.0068	1.0534	1.0701	1.0795	1.0846	1.0901
633	0.9232	0.9232	0.9262	0.9569	0.9838	1.0123	1.0624	1.0804	1.0903	1.096	1.1019
634	0.8659	0.8659	0.8697	0.8741	0.8798	0.8827	0.9265	0.9422	0.9509	0.9558	0.961
645	0.9107	0.9108	0.9134	0.9416	0.9664	0.9922	1.0381	1.0546	1.0638	1.0687	1.0742
646	0.9101	0.9101	0.9127	0.9407	0.9657	0.9914	1.0373	1.0538	1.063	1.068	1.0734
671	0.9076	0.9076	0.9102	0.9381	0.963	0.9887	1.0345	1.0509	1.0601	1.065	1.0705
692	0.9076	0.9076	0.9102	0.9381	0.963	0.9887	1.0345	1.0509	1.0601	1.065	1.0705
675	0.907	0.907	0.9097	0.9377	0.9625	0.9881	1.0339	1.0502	1.0594	1.0644	1.0699
684	0.9061	0.9061	0.9087	0.9368	0.9613	0.9871	1.0328	1.0492	1.0584	1.0633	1.0688
611	0.906	0.906	0.9086	0.9366	0.9613	0.987	1.0326	1.049	1.0582	1.0632	1.0686
652	0.903	0.903	0.9056	0.9333	0.958	0.9837	1.0292	1.0455	1.0547	1.0596	1.065
680	0.9071	0.9071	0.9097	0.9376	0.9825	0.9899	1.034	1.0503	1.0595	1.0645	1.07

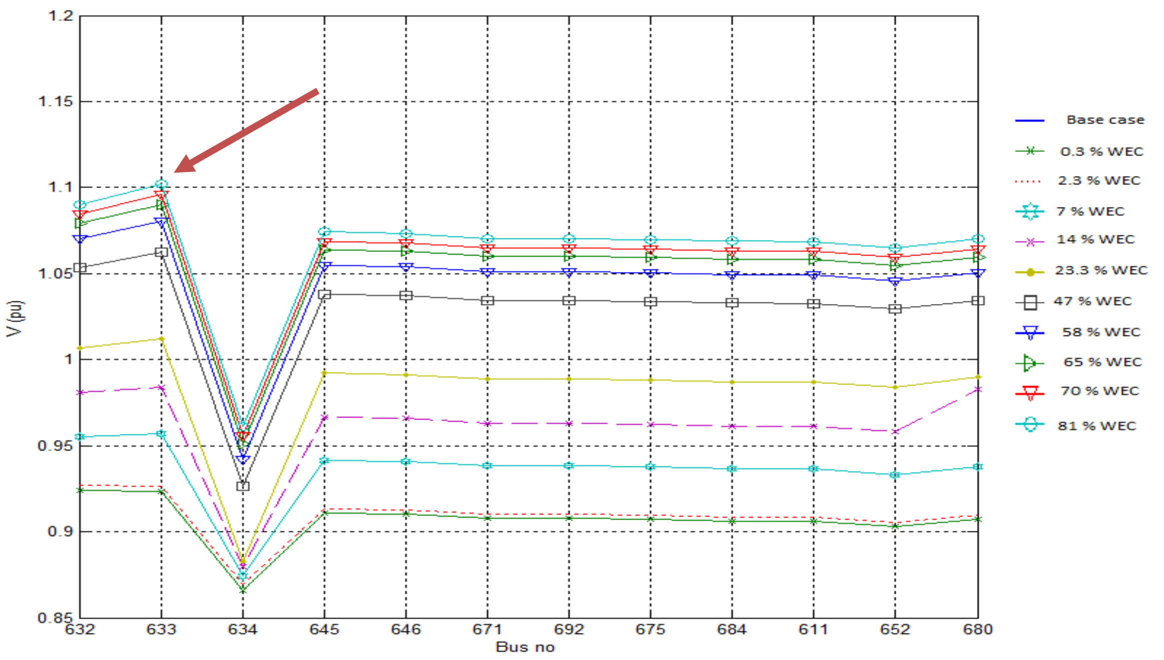


Figure 6.11: Voltage profiles with WEC connection to bus 633

Table 6.11: Network measured voltages with WEC connected to bus 652

Bus No	Base Voltage	WEC 0.3 %	WEC 2.3 %	WEC 14 %	WEC 23.3 %	WEC 47 %	WEC 58 %	WEC 70 %	WEC 81 %	WEC 93 %
632	0.9242	0.9243	0.9263	0.955	0.9777	1.0004	1.0381	1.0518	1.0598	1.0644
633	0.9232	0.9232	0.9252	0.954	0.9766	0.9993	1.0368	1.0506	1.0575	1.0633
634	0.8359	0.8359	0.8377	0.8637	0.8842	0.9048	0.939	0.9513	0.9584	0.9627
645	0.9107	0.9108	0.9128	0.9412	0.9635	0.9858	1.0231	1.0365	1.0443	1.049
646	0.9101	0.9101	0.9121	0.9402	0.9627	0.9851	1.0224	1.0357	1.0435	1.0482
671	0.9076	0.9076	0.9107	0.9477	0.9768	1.0062	1.0546	1.0729	1.0829	1.089
692	0.9076	0.9076	0.9107	0.9477	0.9768	1.0062	1.0546	1.0729	1.0829	1.089
675	0.9070	0.9071	0.9102	0.947	0.9762	1.0056	1.054	1.0723	1.0823	1.0883
684	0.9061	0.9061	0.9094	0.9476	0.9777	1.0081	1.0583	1.0772	1.0876	1.0939
611	0.9060	0.906	0.9093	0.9474	0.9776	1.0081	1.0581	1.0771	1.0875	1.0937
652	0.9030	0.903	0.9067	0.9482	0.9806	1.0144	1.0689	1.0889	1.101	1.1078
680	0.9071	0.9072	0.9102	0.9469	0.9763	1.0057	1.0541	1.0724	1.0824	1.0884

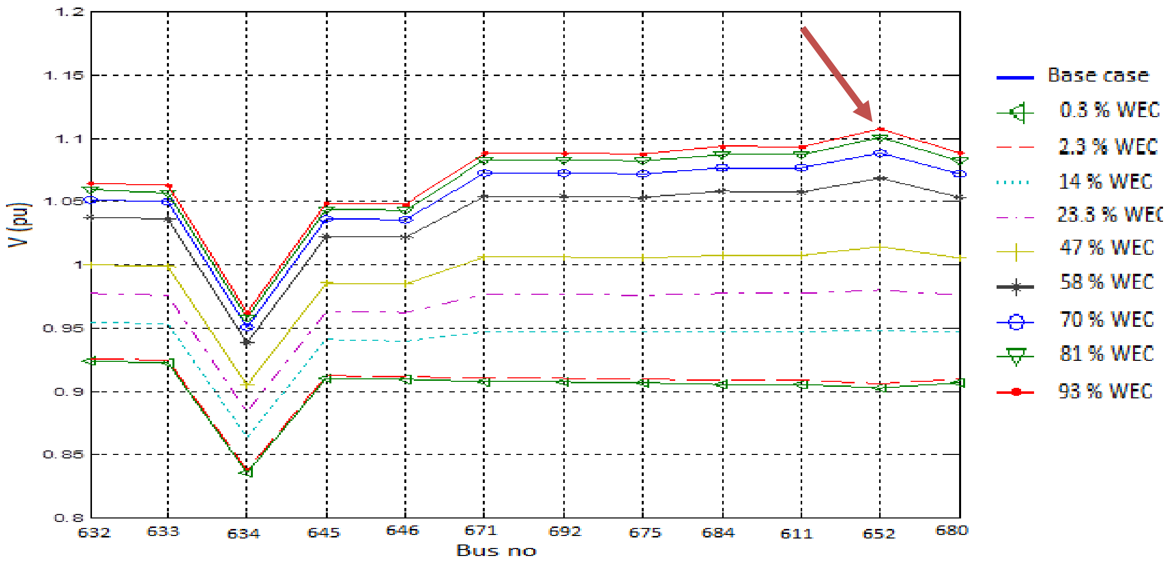


Figure 6.12 Voltage profiles with WEC connected to bus 652

Table 6.12: Network measured voltages with WEC connected to bus 675

Bus No	Base Voltage	WEC 0.3 %	WEC 2.3 %	WEC 7 %	WEC 14 %	WEC 23.3 %	WEC 47 %	WEC 58 %	WEC 65 %	WEC 70 %
632	0.9242	0.9243	0.9264	0.9541	0.9783	1.0022	1.0411	1.056	1.0643	1.0688
633	0.9232	0.9232	0.9253	0.9542	0.9773	1.001	1.0399	1.0549	1.0631	1.0676
634	0.8359	0.8359	0.8378	0.864	0.8848	0.9064	0.9416	0.9551	0.9625	0.9666
645	0.9107	0.9108	0.9129	0.9411	0.9641	0.9876	1.0259	1.0406	1.0488	1.0532
646	0.9101	0.9101	0.9122	0.9406	0.9631	0.9868	1.0251	1.0399	1.048	1.0524
671	0.9076	0.9076	0.9108	0.9478	0.9776	1.0084	1.0587	1.0781	1.0885	1.0945
692	0.9076	0.9076	0.9108	0.9477	0.9775	1.0084	1.0587	1.0781	1.0885	1.0945
675	0.907	0.9071	0.9106	0.9477	0.9812	1.0139	1.0674	1.0879	1.0989	1.1052
684	0.9061	0.9061	0.9094	0.9463	0.9759	1.0067	1.057	1.0764	1.0868	1.0927
611	0.906	0.906	0.9092	0.9461	0.9759	1.0066	1.0569	1.0762	1.0866	1.0926
652	0.903	0.903	0.9062	0.9432	0.9725	1.0032	1.0534	1.0726	1.083	1.0889
680	0.9071	0.9072	0.9104	0.9467	0.977	1.0079	1.0582	1.0776	1.088	1.0939

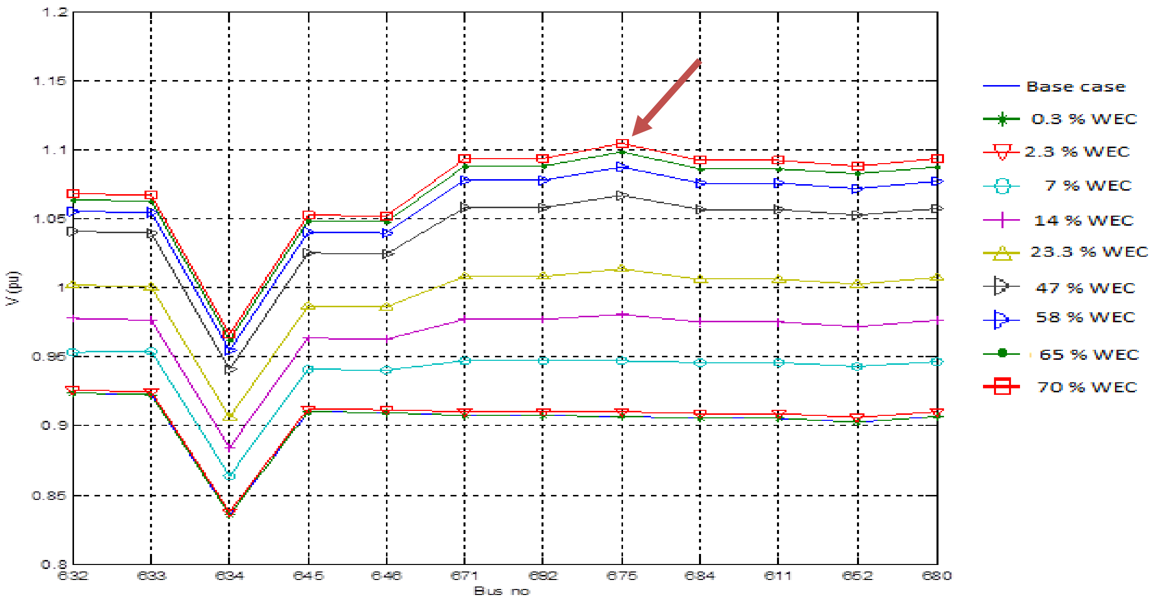


Figure 6.13: Voltage profiles with WEC connected to bus 675

Table 6.13: Network measured voltage with WEC connected to bus 646

Bus No	Base Voltage	WEC 0.3 %	WEC 2.3 %	WEC 7 %	WEC 14 %	WEC 23.3 %	WEC 47 %	WEC 58 %	WEC 65 %	WEC 70 %	WEC 81 %
632	0.9242	0.9243	0.9242	0.9518	0.9736	1.0195	1.0388	1.0507	1.0579	1.0754	1.0904
633	0.9232	0.9232	0.9232	0.9508	0.9722	1.0183	1.0376	1.0495	1.0568	1.0742	1.0892
634	0.8359	0.8364	0.8404	0.8685	0.891	0.9378	0.9581	0.969	0.9761	0.994	1.0099
645	0.9107	0.9111	0.9174	0.9529	0.976	1.026	1.0467	1.0597	1.0676	1.0863	1.1025
646	0.9101	0.9104	0.917	0.9541	0.9782	1.0303	1.0516	1.0656	1.0739	1.0933	1.1103
671	0.9076	0.9076	0.9076	0.9362	0.9572	1.0026	1.0216	1.0333	1.0405	1.0576	1.0724
692	0.9076	0.9076	0.9076	0.936	0.9576	1.0026	1.0216	1.0333	1.0405	1.0576	1.0724
675	0.907	0.9071	0.9071	0.9357	0.9567	1.0021	1.0211	1.0306	1.0399	1.057	1.0718
684	0.9061	0.9061	0.9061	0.9346	0.9562	1.0011	1.0201	1.0318	1.039	1.056	1.0708
611	0.906	0.906	0.906	0.9346	0.9557	1.001	1.0194	1.0316	1.0388	1.0559	1.0706
652	0.903	0.903	0.903	0.9318	0.9531	0.9979	1.0162	1.0285	1.0356	1.05526	1.0673
680	0.9071	0.9072	0.9072	0.9358	0.9572	1.0022	1.0211	1.0328	1.04	1.0571	1.0719

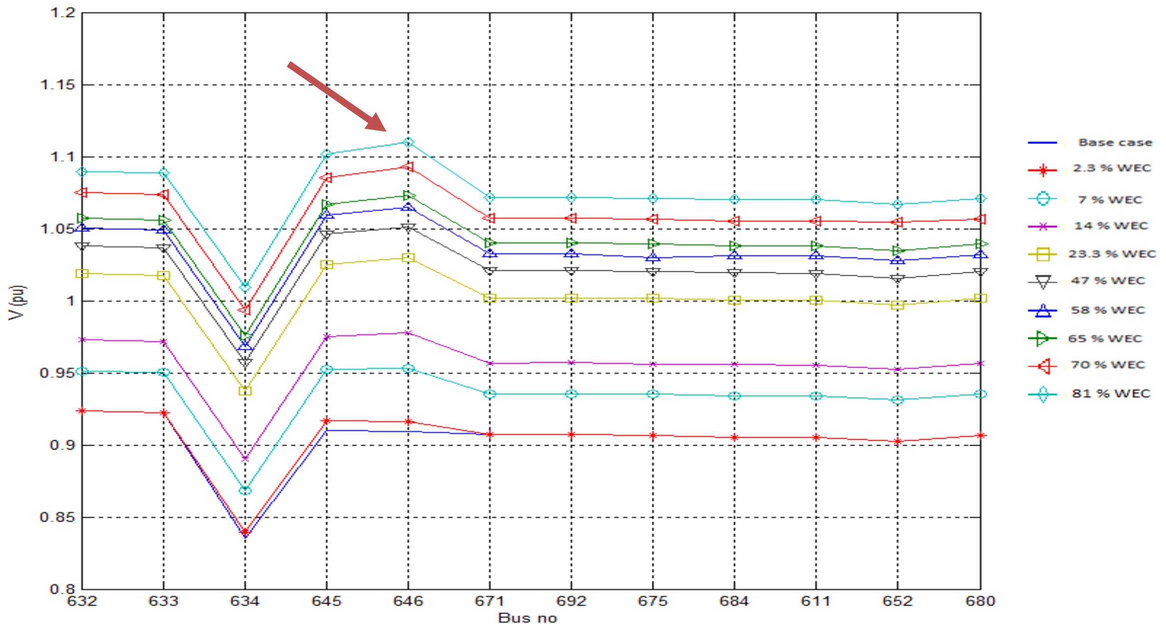


Figure 6.14: Voltage profiles with WEC connected to bus 646

Table 6.14 Voltage profiles with WEC connected to bus 680

Bus No	Base Voltage	WEC 0.3 %	WEC 2.3 %	WEC 7 %	WEC 14 %	WEC 23.3 %	WEC 47 %	WEC 58 %	WEC 65 %
632	0.9242	0.9242	0.9264	0.9555	0.9771	1.0003	1.0382	1.0518	1.0598
633	0.9232	0.9232	0.9254	0.9538	0.9764	0.9992	1.0361	1.0507	1.0586
634	0.8359	0.8359	0.8379	0.8632	0.8837	0.9047	0.9392	0.9513	0.9585
645	0.9107	0.9108	0.9129	0.9411	0.9629	0.9857	1.0233	1.0365	1.0443
646	0.9101	0.9101	0.9122	0.9404	0.9622	0.985	1.0225	1.0357	1.0435
671	0.9076	0.9076	0.9109	0.9474	0.9763	1.006	1.0548	1.073	1.0831
692	0.9076	0.9076	0.9109	0.9474	0.9763	1.0061	1.0546	1.073	1.0831
675	0.907	0.9071	0.9103	0.9467	0.9758	1.0054	1.0543	1.0724	1.0825
684	0.9061	0.9061	0.9094	0.9458	0.9749	1.0044	1.053	1.0713	1.0814
611	0.906	0.906	0.9093	0.9456	0.9746	1.0043	1.0529	1.0711	1.0812
652	0.903	0.903	0.9062	0.9425	0.9714	1.001	1.0495	1.0676	1.0776
680	0.9071	0.9072	0.9111	0.9517	0.9844	1.0177	1.0721	1.0929	1.1041

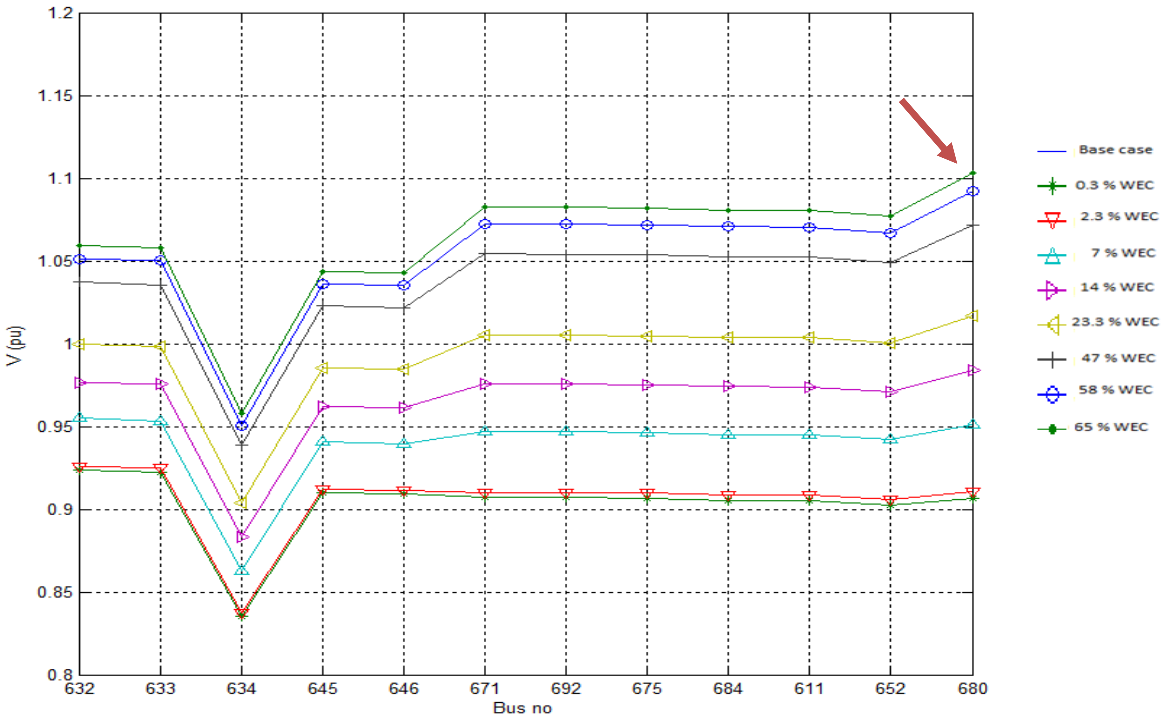


Figure 6.15: Voltage profiles with WEC connected to bus 680

Table 6.15: Voltage profile with WEC connected to bus 611

Bus No	Base Voltage	WEC 0.3 %	WEC 2.3 %	WEC 7 %	WEC 14 %	WEC 23.3 %	WEC 47 %	WEC 58 %	WEC 65 %	WEC 70 %
632	0.9242	0.9243	0.9263	0.9552	0.978	1.0019	1.0407	1.0553	1.0634	1.068
633	0.9232	0.9232	0.9253	0.9541	0.9769	1.0008	1.0396	1.0541	1.0622	1.0668
634	0.8359	0.8359	0.8378	0.8639	0.8847	0.9061	0.9413	0.9544	0.9617	0.9659
645	0.9107	0.9108	0.9129	0.9413	0.9638	0.9873	1.0256	1.0399	1.0479	1.0524
646	0.9101	0.9101	0.9122	0.9405	0.963	0.9866	1.0248	1.0391	1.0471	1.0517
671	0.9076	0.9076	0.9108	0.9476	0.9774	1.008	1.0578	1.0772	1.0875	1.0935
692	0.9076	0.9076	0.9108	0.9476	0.9773	1.008	1.0578	1.0772	1.0875	1.0935
675	0.907	0.9071	0.9102	0.947	0.9768	1.0074	1.0572	1.0766	1.0868	1.0929
684	0.9061	0.9061	0.9095	0.9476	0.9784	1.0101	1.0616	1.0817	1.0923	1.0986
611	0.906	0.906	0.9096	0.9489	0.9808	1.0136	1.0669	1.0878	1.0987	1.1052
652	0.903	0.903	0.9063	0.9444	0.975	1.0049	1.0579	1.078	1.0885	1.0948
680	0.9071	0.9072	0.9103	0.9467	0.9769	1.0075	1.0573	1.0767	1.0869	1.093

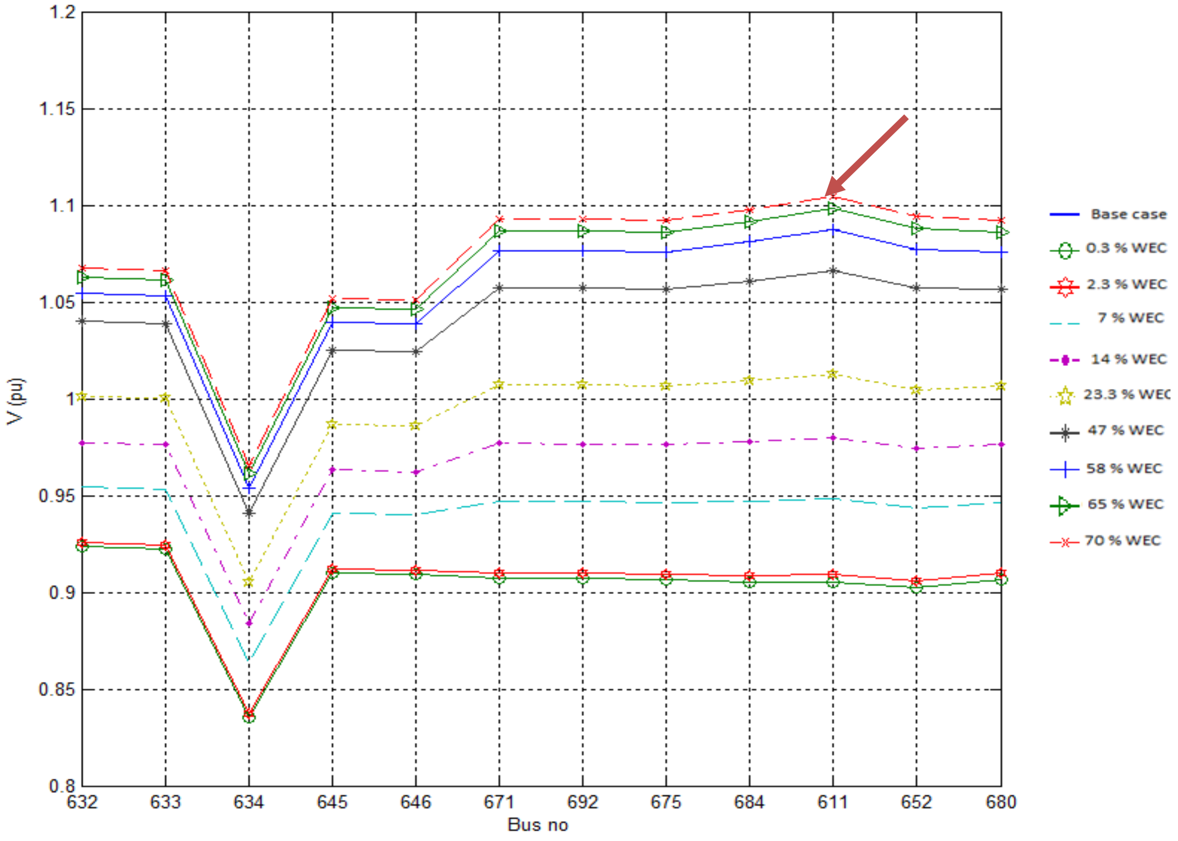


Figure 6.16: Network voltage profiles with WEC connected to bus 611

Table 6.16: Voltage profile with WEC connected to bus 671

Bus No	Base Voltage	WEC 0.3 %	WEC 2.3 %	WEC 7 %	WEC 14 %	WEC 23.3 %	WEC 47 %	WEC 58 %	WEC 65 %	WEC 70 %
632	0.9242	0.9243	0.9264	0.9541	0.9783	1.0022	1.0411	1.056	1.0643	1.0688
633	0.9232	0.9232	0.9253	0.9542	0.9773	1.001	1.0399	1.0549	1.0631	1.0676
634	0.8359	0.8359	0.8378	0.864	0.8848	0.9064	0.9416	0.9551	0.9625	0.9666
645	0.9107	0.9108	0.9129	0.9411	0.9641	0.9876	1.0259	1.0406	1.0488	1.0532
646	0.9101	0.9101	0.9122	0.9406	0.9631	0.9868	1.0251	1.0399	1.048	1.0524
671	0.907	0.9071	0.9106	0.9477	0.9812	1.0139	1.0674	1.0879	1.0989	1.1052
692	0.9076	0.9076	0.9108	0.9477	0.9775	1.0084	1.0587	1.0781	1.0885	1.0945
671	0.9076	0.9076	0.9108	0.9478	0.9776	1.0084	1.0587	1.0781	1.0885	1.0945
684	0.9061	0.9061	0.9094	0.9463	0.9759	1.0067	1.057	1.0764	1.0868	1.0927
611	0.906	0.906	0.9092	0.9461	0.9759	1.0066	1.0569	1.0762	1.0866	1.0926
652	0.903	0.903	0.9062	0.9432	0.9725	1.0032	1.0534	1.0726	1.083	1.0889
680	0.9071	0.9072	0.9104	0.9467	0.977	1.0079	1.0582	1.0776	1.088	1.0939

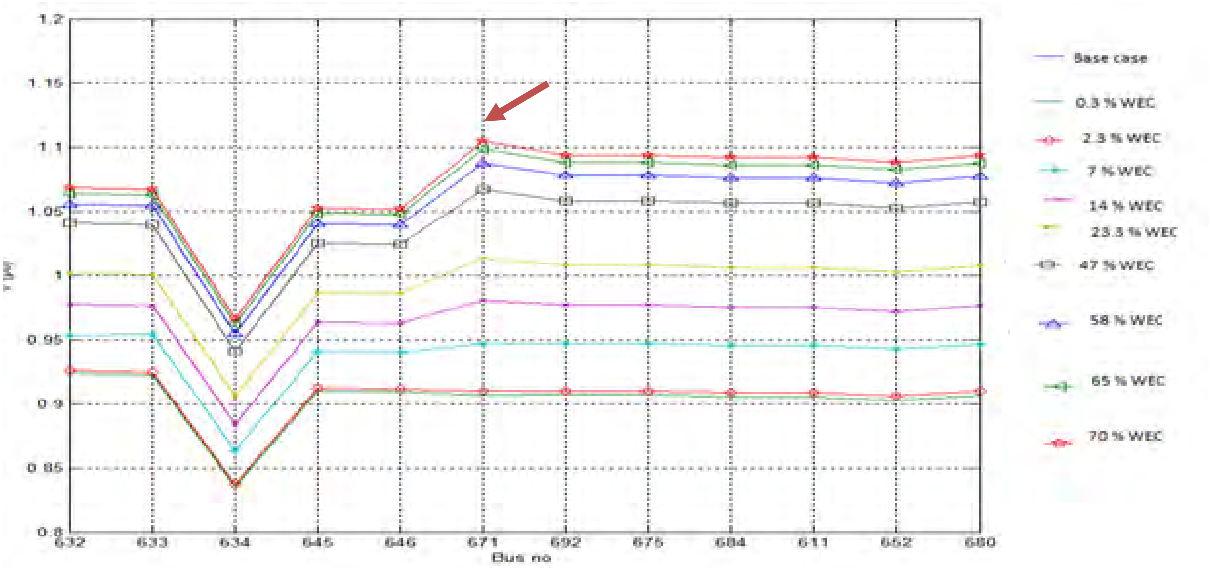


Figure 6.17: Network voltage profiles with WEC connected to bus 671

Impact and effect of WEC location and penetration level on bus loading at low voltage

The previous section showed in details the WEC penetration level comparison in selecting different buses for integration. In this section, the investigation of the impacts of WEC on a low voltage network of choosing the best and the wrong locations and their possible effects shall be considered. Bus 634 has the total load of 550.7 kVA and highest voltage drops 13.41 % according to the voltage profile in Figure 6.8 and Table 6.8, which can be regarded as the weakest bus in the network and the bus is a low voltage bus bar (480 V). When WEC of different power rating (13.8 kVA, 100 kVA, 300 kVA, 600 kVA) is connected to the bus, 7 % penetration level is accepted. When the penetration exceeds the 7 % penetration level, voltage rise occurs. The receiving end voltage on the bus is more than the sending voltage therefore, the load connected to the bus will behave as a capacitive load, between buses 633 and 634 which result in an unacceptable voltage profile and the grid code act is violated as shown in Table 6.16 and Figure 6.18 indicated by the green arrow, while all other bus voltages in the network remained unaffected. This occurs as a result of reversed power flow, which is a function of the power generated by the WEC and the short-circuit power of the network at the point of interconnection. This reversed power flow effect gets stronger as the WEC injects more active power into the network, by this investigation, which means that the power of WEC should not be more than the load connected to bus 634. Bus 652 can be considered to be a very good location of WEC integration because it can take more WEC penetration level without the fear of over voltage as indicated in Figure 6.14 above. Also buses 633, 675, 671, 680, 646 and 611 can also be considered as point of WEC connection to the network, if more than one wind generators are to be connected to the network either by the utility or independent power producers.

If bus 634 is considered as a location of WEC integration, the rated power of such WEC must be less than 500 kVA, for any wind power more than that, a voltage rise may occur which can cause an unnecessary damage to the power equipment and any load connected to the network.

Connection of WEC to a lightly loaded network can cause reverse power flow, which can cause the voltage at the WEC connection point to rise, the supply voltage for customers connected nearby WEC units start to rise as well. As a result of this effect, power flow may be interrupted, leading to machine over speed, large over voltage and tripping of multiple generators can occur when there is high level of the voltage quality variation. This voltage rise is a steady state effect that depends on the resistance and the reactance ratio, load feeder and the power injection by the WEC units. Furthermore, a higher level of over voltage can cause faster power component aging, immediate disconnection of the generation from the network and damage to the customer equipment [**223**], [**224**], [**225**].

Causes of voltage rise in the bus 634

- Inability of the power to flow back to the rest of the network because there is step down transformer between buses 633 and 634 (it stepped down the voltage from 4.160 kV to 480V)
- The WEC power injected into the bus is more than the load demanded or connected to the bus

Table 6.17: Network measured voltages with WEC connected to bus 634

Bus No	Base Voltage	WEC 0.3 %	WEC 2.3 %	WEC 7 %	WEC 14 %	WEC 23.3 %	WEC 47 %
632	0.9242	0.9253	0.9301	0.9369	0.9389	0.9457	0.9746
633	0.9232	0.9244	0.9296	0.9368	0.9389	0.9463	0.9776
634	0.8359	0.8212	0.8911	0.9806	1.0242	1.1223	1.5926
645	0.9107	0.9118	0.9166	0.9232	0.9252	0.9319	0.9605
646	0.9101	0.9111	0.9159	0.9225	0.9245	0.9312	0.9597
671	0.9076	0.9086	0.9134	0.92	0.9219	0.9287	0.9571
692	0.9076	0.9086	0.9134	0.92	0.9219	0.9287	0.9571
675	0.907	0.9081	0.9129	0.9194	0.9214	0.9281	0.9565
684	0.9061	0.9072	0.9119	0.9185	0.9205	0.9272	0.9555
611	0.906	0.907	0.9118	0.9184	0.9203	0.927	0.9554
652	0.903	0.904	0.9088	0.9153	0.9173	0.9239	0.9522
680	0.9071	0.9082	0.9129	0.9195	0.9215	0.9282	0.9566

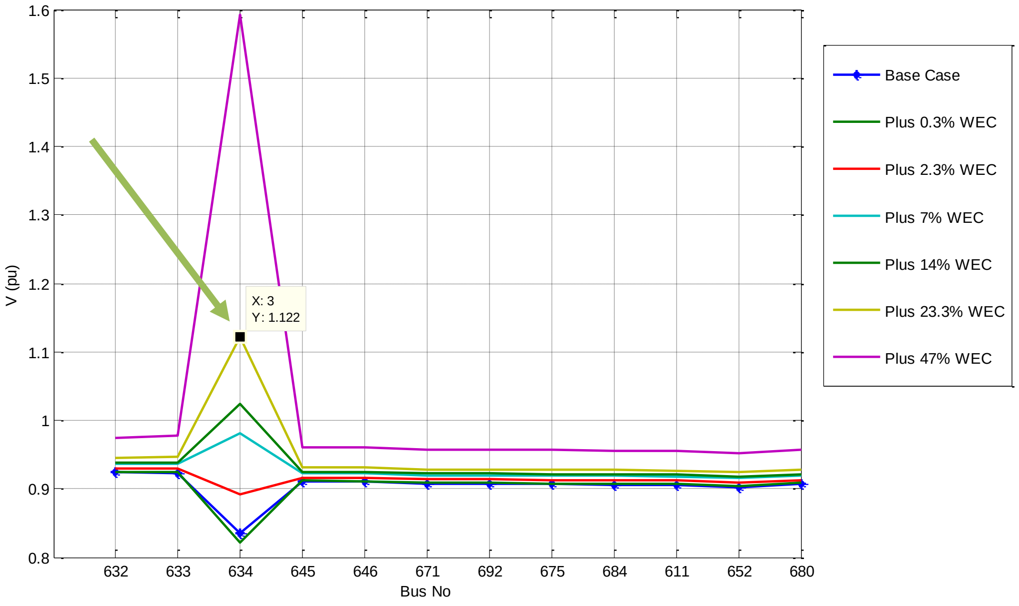


Figure 6.18: Network voltage profiles with WEC connected to bus 634

The impact of WEC at the point of common coupling in the distribution network

The impacts of WEC of different power ratings on the voltage profile of a distribution network has been successfully investigated in the previous section, the comparison has been made between different buses in relation to the penetration level and the grid code act violation, and the implications of choosing the weakest and wrong location for WEC integration into the network. This section investigates the impact of WEC at the point of common coupling of WECs into the network. From the simulation results, in Figures 6.10 to 6.17 shown above, it can be noticed that the voltage on the bus where WEC is connected is slightly increased or higher than any other voltage of the buses in the network as indicated by a red coloured arrow in each graph. It can also be seen from Tables 6.8 to 6.16 as indicated by the colour red in each of the Tables.

When a WEC is connected to a particular bus in a network, increase in the penetration level of the WEC will bring about an increase in voltage (since there is an existing voltage on the bus before) and the active power generated on such a bus, as a result, it will turn the weak bus to an active bus or weak network to an active more than any other bus on the network.

6.3.6 WEC penetration level comparison in unbalanced and balanced modified IEEE 13-bus test system

The comparisons between unbalanced IEEE 13-bus test system when voltage regulator and the coupling capacitor were removed with WEC connection and the balanced modified network are discussed in this section. Based on the simulation results in Tables 6.2 to 6.17 and Figures 6.4 to 6.18, balanced network takes more WEC penetration level than unbalanced network. The details analyses are depicted in Table 6.18 below.

Table 6.18: WEC penetration level comparison

Bus no	Unbalanced network %	Balanced network %
671	47	70
675	47	70
634	7	14

6.3.7 Summary

It has been shown that the simulation result of the IEEE 13-bus test system is similar to the CYME and IEEE published results [**222**] . The impacts of WEC on the unbalanced network is to improve the voltage profiles, but the network cannot take more than 47 % WEC penetration level even at the farthest bus. Three-phase WEC can only be connected to the network at three different locations because there are only three buses that have balanced three phases, three wires in the network, other buses are made up of two and single phases.

In general, it can be seen that the connection of WEC to a distribution network has the potential benefits of improving and supporting the voltage profile of the network. It also shows negative impacts that the ranges of WEC's (wind power ratings) penetration levels can have on the distribution network. The voltage profile graphs and the measured voltages in these tables also revealed that at any point of WEC integration into a network, the voltage of that point is usually higher than the voltage of all other buses in the network. It was also observed that a small amount of WEC penetration level, e.g., below 14 % (500kVA) installed in the wrong location (Figures 6.17) can cause unacceptable voltage profiles at the same time, very large amount of WEC that is close to 93 % penetration level installed with adequate strategy improved voltage profile without grid code act violation and enable acceptable operating condition (see Figure 6.12). Also, balanced network can take more WEC penetration level than unbalanced network.

It was found that the surplus or higher penetration level of WEC in a localized area can cause an overvoltage or a voltage rise, which may cause the tripping of the network protection. The point of connection or the location of WEC integration on any network can be chosen in such a way that the voltage profile of a particular network should be first plotted to study the weakest point and sufficient information should be given to the individuals connecting their WEC into the network. The original voltage profile of any network should be a guide and strictly followed by the utility before DGs are considered for integration, which requires the cooperation between the network operator and the independent power producers.

6.4 Distribution network design, modelling of DFIG and component parameters in PSCAD/EMTDC

Introduction

In this section, the modified network in Figure 6.7 is designed and simulated in power system computer aided design/Electromagnetic Transient Domain Package (PSCAD/EMTD) with the WEC integration, similar simulation scenarios investigated in sections 6.3.4 to 6.3.5 are repeated to compare and analyse the results obtained in both packages.

6.4.1 Case I: Modified IEEE (with capacitor and voltage regulator removed and load balanced without WEC) using PSCAD/EMTDC

The detailed model of DFIG was developed using software package PSCAD/EMTDC. Figure 6.19 below shows the connection of WEC to a distribution network, the network layout consists of a typical 4.160 kV distribution network configured downstream of one 115/4.160 kV substation except the voltage at bus 634 that is stepped down to 480 V. The network parameters used here are the same as the ones used in Figure 6.7 which can be found in Table A1 in Appendix A. The machine is started in speed control mode with the input set to the rated per unit speed and switched over to torque control after the initial transients of the machine die out or after it reaches the steady state. The DFIG is being driven by a wind turbine, the turbine is controlled by a wind governor, the wind source is used to model wind speed fluctuation. The measured bus voltages are plotted in excel package, and the results without WEC integration are shown in Table 6.19 and Figure 6.20 below. The voltage profile shows that there is a voltage dip at the bus 634 (0.8472 pu) which is not acceptable in relation to the grid code act (-15 +10 % or 0.85 to 1.1 pu), the stepped down transformer that stepped 4.160 kV to 480V is connected between buses 633 and 634.

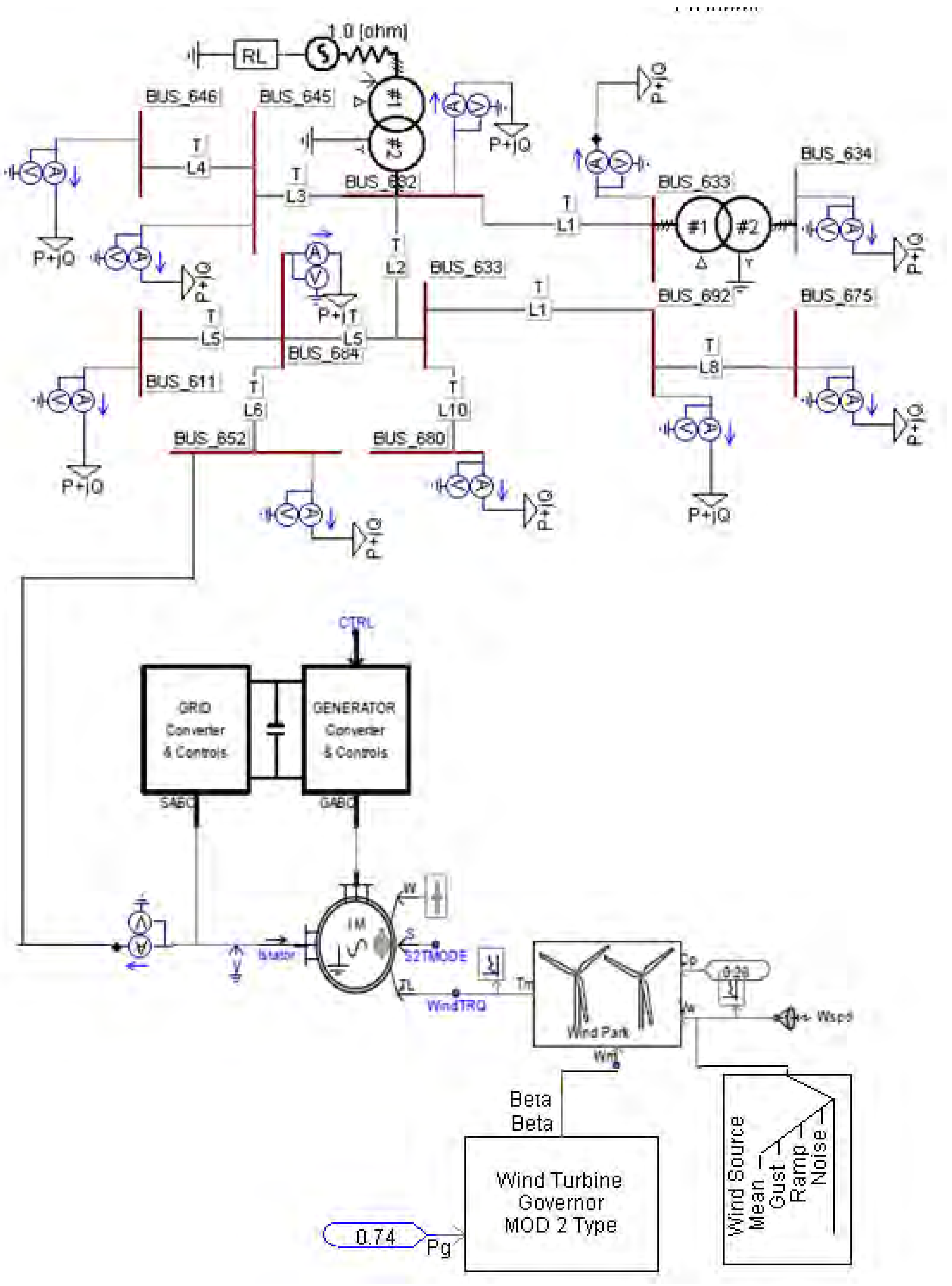


Figure 6.19: Network layout in PSCAD

Table 6.19: Measured network voltage without WEC

Bus no	Base voltage (p.u.)	% drop
632	0.9479	5.21
633	0.9416	5.84
634	0.8472	15.28
645	0.9235	7.65
646	0.9231	7.69
671	0.9214	7.86
692	0.9213	7.87
675	0.9213	7.87
684	0.9205	7.95
611	0.9204	7.96
652	0.918	8.2
680	0.9211	7.89

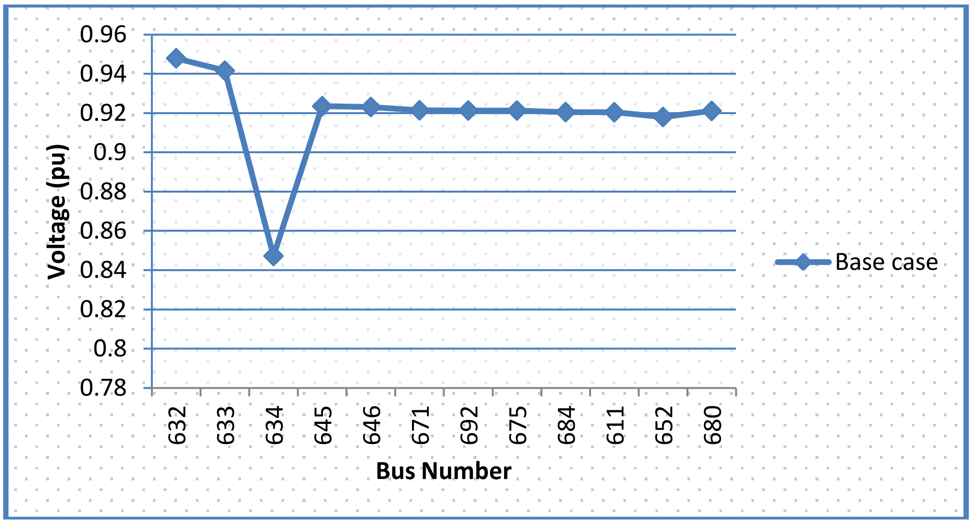


Figure 6.20: Base case voltage profiles in PSCAD

6.4.2 Case II: Modified IEEE (with capacitor and voltage regulator removed and load balanced with WEC)

To investigate the impacts of WEC integration on the voltage profile of a distribution network, bus 680 is chosen, being the farthest to the substation. The WEC power integrated into the network at that point are 13.8 kVA or 0.3 % penetration level, 100 kVA or 2.3 % penetration level, 300 kVA or 14 % penetration level, 600 kVA or 23.3 penetration level, 1 MVA or 47 % penetration level, 2.5 MVA or 58 % penetration level, 2.8 MVA or 65 % penetration level, and 3 MVA or 70 % penetration level with 0.98 power factor where the maximum total network loading is 4.3 MVA. It can be observed in Table 6.20 and Figure 6.21 below that the integration of WEC into the network improved the voltage profile, the network can take up to 70 % WEC penetration level without grid code act violation, if this penetration level is exceeded, the grid code act may be violated

Table 6.20: Network measured voltages with WEC connected to bus 680

Bus No	Base VOLTAGE	WEC 0.3 %	WEC 2.3 %	WEC 7 %	WEC 14 %	WEC 23.3 %	WEC 47 %	WEC 58 %	WEC 65 %	WEC 70 %
632	0.9479	0.948	0.9488	0.9497	0.9501	0.9755	0.9963	1.0187	1.0428	1.0621
633	0.9416	0.9417	0.9424	0.9433	0.9438	0.969	0.9897	1.0119	1.0358	1.055
634	0.8872	0.8873	0.888	0.8889	0.8893	0.9131	0.9325	0.9534	0.9758	0.9939
645	0.9235	0.9236	0.9243	0.9252	0.9256	0.9504	0.9706	0.9924	1.0159	1.0347
646	0.9231	0.9232	0.9239	0.9248	0.9252	0.9499	0.9702	0.992	1.0154	1.0342
671	0.9214	0.9217	0.9229	0.9244	0.9253	0.9671	1.0013	1.038	1.078	1.1093
692	0.9213	0.9216	0.9228	0.9243	0.9253	0.967	1.0012	1.0379	1.0774	1.1091
675	0.9213	0.9216	0.9228	0.9243	0.9252	0.967	1.0011	1.0379	1.0774	1.1091
684	0.9205	0.9208	0.922	0.9235	0.9245	0.9662	1.0003	1.037	1.0765	1.1082
611	0.9204	0.9206	0.9218	0.9233	0.9243	0.9666	1.0001	1.0368	1.0763	1.108
652	0.918	0.9183	0.9195	0.921	0.9219	0.9635	0.9976	1.0342	1.07356	1.1051
680	0.9211	0.9213	0.9226	0.9242	0.9253	0.9698	1.0062	1.0454	1.0876	1.1214

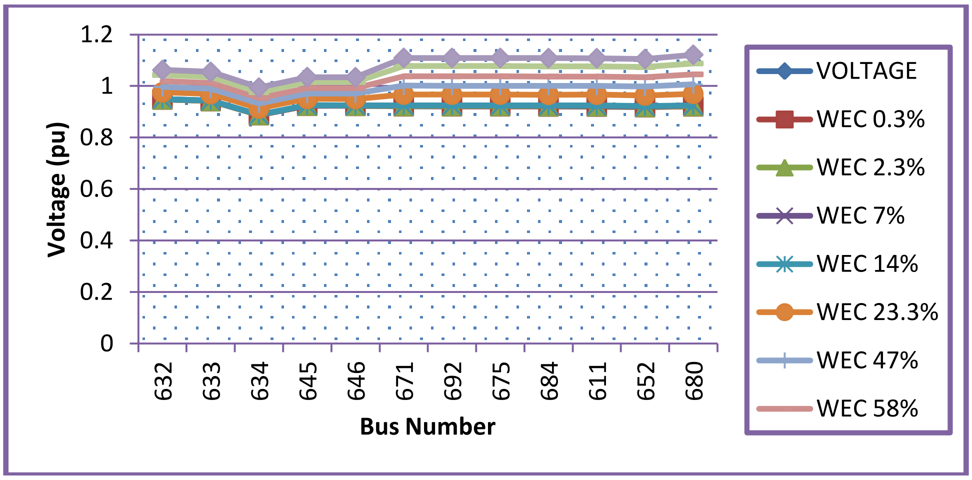


Figure 6.21: Distribution network voltage profiles with WEC integration at bus 680

Maximum penetration level determination between some selected buses with varying WEC power in a distribution network

To investigate and determine the maximum penetration level of WEC that the network can take in relation to its location, some buses are chosen (buses 633, 652, 675, 646, 680, and 611) as the point of common coupling between the network and the WEC. Figures 6.22 to 6.27 and Table 6.21 to 6.26 shows the voltage profile graphs, it can be seen from the simulation results that bus 652 accepted maximum WEC penetration level of about 93 %, while bus 634 took the least WEC penetration level of 47 %; bus 633 took 81 % WEC penetration level, all other selected buses took the same amount of WECs penetration level 70 %. Bus 634 cannot take more WEC penetration than 14 % because if the power of the WEC to be integrated at the bus is more than the load connected to the bus, it leads to an unacceptable voltage profile which violates the grid code act since the voltage cannot flow back to the rest of the network, step down transformer is located on the bus (4.160 kV/480V) which means bus 633 is preferable as a point of WEC integration instead of bus 634. Bus 652 took the highest WEC penetration level because the load connected to the bus is a heavy load and the bus is very far from the substation location.

Table 6.21: Network measured voltages with WEC connected to bus 633

Bus No	Base Voltage	WEC 0.3 %	WEC 2.3 %	WEC 7 %	WEC 14 %	WEC 23.3 %	WEC 47 %	WEC 58 %	WEC 65 %	WEC 70 %	WEC 81 %
632	0.9479	0.948	0.9487	0.9496	0.9498	0.9755	0.995	1.0141	1.0319	1.044	1.0549
633	0.9416	0.9476	0.9494	0.9583	0.9699	0.9769	0.9984	1.0273	1.0625	1.0871	1.1079
634	0.8872	0.8875	0.888	0.8889	0.9291	0.9577	0.9712	0.9889	0.9954	1.0011	1.0017
645	0.9235	0.9266	0.9274	0.9285	0.9359	0.9618	0.9757	0.9839	0.9859	1.0006	1.0111
646	0.9231	0.9262	0.9272	0.9284	0.9358	0.9649	0.9814	0.9922	0.9968	1.0009	1.0108
671	0.9214	0.9215	0.9222	0.9231	0.9234	0.9482	0.9672	0.9857	1.0029	1.0148	1.0254
692	0.9213	0.9214	0.9221	0.923	0.9233	0.9481	0.9671	0.9856	1.0029	1.0147	1.0253
675	0.9213	0.9213	0.922	0.923	0.9232	0.9481	0.9671	0.9856	1.0029	1.0147	1.0252
684	0.9205	0.9205	0.9213	0.9222	0.9224	0.9473	0.9663	0.9847	1.002	1.0138	1.0244
611	0.9204	0.9204	0.9211	0.922	0.9223	0.9471	0.9661	0.9846	1.0018	1.0136	1.0242
652	0.918	0.918	0.9188	0.9197	0.9199	0.9447	0.9636	0.9821	0.9993	1.011	1.0216
680	0.9211	0.9211	0.9218	0.9227	0.923	0.9478	0.9668	0.9853	1.0026	1.0144	1.0249

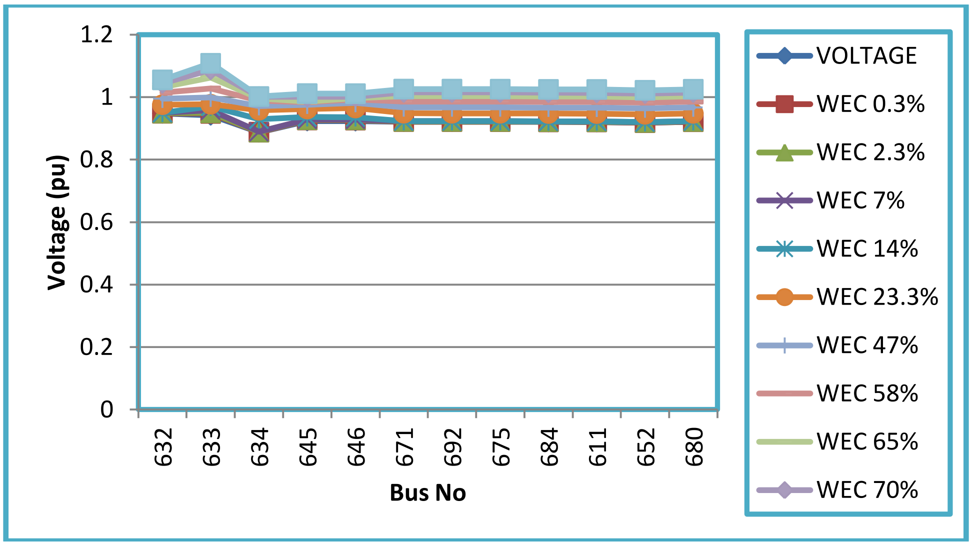


Figure 6.22: Network voltage profile with WEC connected to bus 633

Table 6.22: Network voltage with WEC connected to bus 652

Bus No	Base Voltage	WEC 0.3 %	WEC 2.3 %	WEC 7 %	WEC 14 %	WEC 23.3%	WEC 47 %	WEC 58 %	WEC 65 %	WEC 70 %	WEC 81 %	WEC 93 %
632	0.9479	0.948	0.9487	0.9496	0.9499	0.9755	0.995	1.0141	1.0319	1.044	1.0549	1.0904
633	0.9416	0.9416	0.9424	0.9433	0.9436	0.969	0.9884	1.0073	1.025	1.0371	1.0479	1.0892
634	0.8872	0.8873	0.888	0.8889	0.8891	0.913	0.9312	0.9489	0.9654	0.9767	0.9867	1.0099
645	0.9235	0.9266	0.9274	0.9285	0.9359	0.9618	0.9757	0.9839	0.9859	0.9831	0.9768	1.0087
646	0.9231	0.9262	0.9272	0.9284	0.9358	0.9649	0.9814	0.9922	0.9968	0.9959	0.9914	1.0083
671	0.9214	0.9215	0.9222	0.9231	0.9234	0.9482	0.9672	0.9857	1.0029	1.0148	1.0254	1.0724
692	0.9213	0.9214	0.9221	0.923	0.9233	0.9481	0.9671	0.9856	1.0029	1.0147	1.0253	1.0724
675	0.9213	0.9213	0.922	0.923	0.9232	0.9481	0.9671	0.9856	1.0029	1.0147	1.0252	1.0718
684	0.9205	0.9205	0.9213	0.9222	0.9224	0.9473	0.9663	0.9847	1.002	1.0138	1.0244	1.0708
611	0.9204	0.9204	0.9211	0.922	0.9223	0.9471	0.9661	0.9846	1.0018	1.0136	1.0242	1.0706
652	0.918	0.918	0.9188	0.9197	0.9199	0.9647	0.9936	1.0321	1.0503	1.0611	1.0716	1.0999
680	0.9211	0.9211	0.9218	0.9227	0.923	0.9478	0.9668	0.9853	1.0026	1.0144	1.0249	1.0719

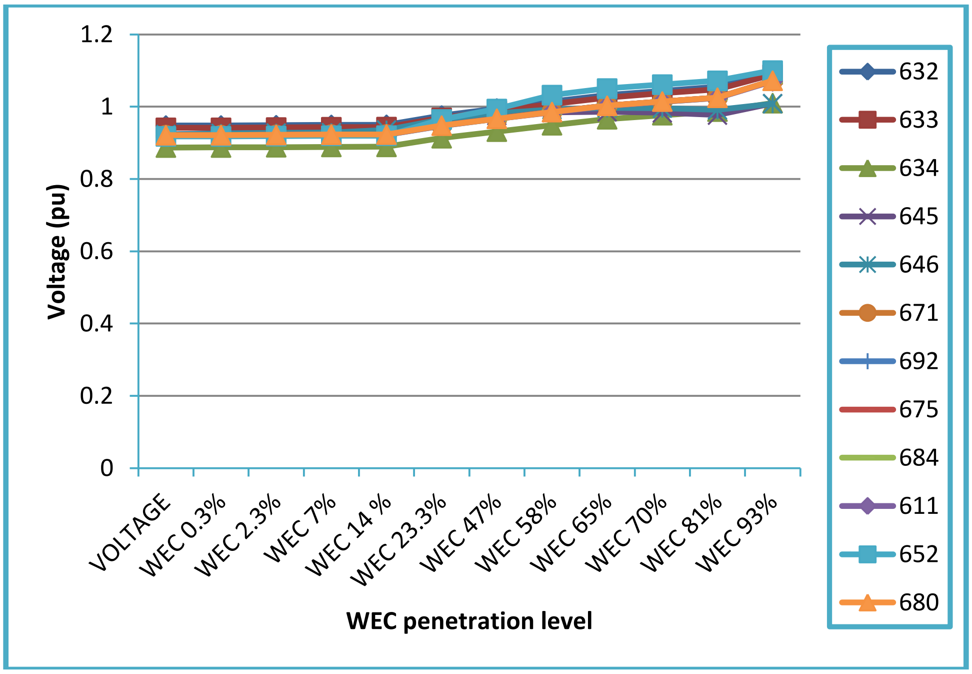


Figure 6.23: Network voltage profiles with WEC connected to Bus 652

Table 6.23: Network voltages with WEC connected to bus 675

Bus No	Bse Voltage	WEC 0.3 %	WEC 2.3 %	WEC 7 %	WEC 14 %	WEC 23.3 %	WEC 47 %	WEC 58 %	WEC 65 %	WEC 70 %
632	0.9479	0.948	0.9488	0.9497	0.9501	0.9755	0.9961	1.0183	1.042	1.0609
633	0.9416	0.9417	0.9424	0.9433	0.9438	0.969	0.9895	1.0115	1.035	1.0539
634	0.8872	0.8873	0.888	0.8889	0.8893	0.913	0.9323	0.953	0.9751	0.9928
645	0.9235	0.9236	0.9243	0.9252	0.9256	0.9503	0.9705	0.992	1.0151	1.0336
646	0.9231	0.9232	0.9239	0.9248	0.9252	0.9499	0.97	0.9916	1.0147	1.0331
671	0.9214	0.9217	0.9229	0.9244	0.9254	0.9671	1.001	1.0373	1.0763	1.1075
692	0.9213	0.9216	0.9228	0.9243	0.9253	0.967	1.001	1.0374	1.0764	1.1075
675	0.9213	0.9216	0.9228	0.9243	0.9253	0.9673	1.0014	1.038	1.0773	1.1086
684	0.9205	0.9208	0.922	0.9235	0.9246	0.9661	1	1.0363	1.0753	1.1064
611	0.9204	0.9206	0.9218	0.9233	0.9243	0.9659	0.9998	1.0361	1.0751	1.1062
652	0.918	0.9183	0.9195	0.921	0.9219	0.9635	0.9973	1.0335	1.0723	1.1034
680	0.9211	0.9213	0.9225	0.924	0.925	0.9667	1.0006	1.0369	1.0759	1.107

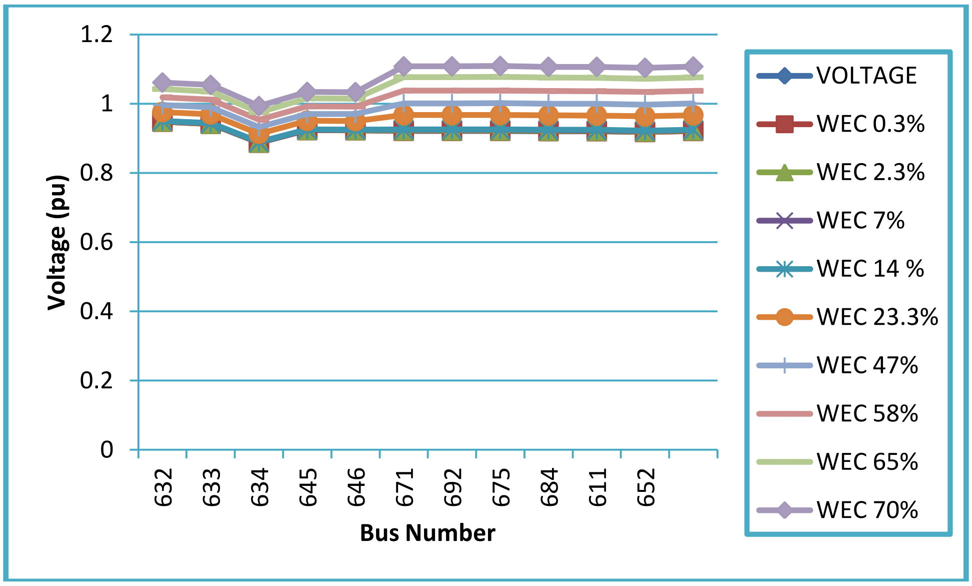


Figure 6.24: Network voltage profile with WEC connected to Bus 675

Table 6.24: Network voltages with WEC connected to bus 646

Bus No	Base Voltage	WEC 0.3 %	WEC 2.3 %	WEC 7 %	WEC 14 %	WEC 23.3 %	WEC 47 %	WEC 58 %	WEC 65 %	WEC 70 %
632	0.9479	0.948	0.9487	0.9496	0.9499	0.9755	0.995	1.0141	1.0319	1.044
633	0.9416	0.9416	0.9424	0.9433	0.9436	0.969	0.9884	1.0073	1.025	1.0371
634	0.8872	0.8873	0.888	0.8889	0.8891	0.913	0.9312	0.9489	0.9654	0.9767
645	0.9235	0.9266	0.9274	0.9285	0.9359	0.9618	0.9757	0.9839	0.9859	0.9831
646	0.9231	0.9262	0.9272	0.9284	0.9358	0.9759	0.9957	1.0142	1.0106	1.1009
671	0.9214	0.9215	0.9222	0.9231	0.9234	0.9482	0.9672	0.9857	1.0029	1.0148
692	0.9213	0.9214	0.9221	0.923	0.9233	0.9481	0.9671	0.9856	1.0029	1.0147
675	0.9213	0.9213	0.922	0.923	0.9232	0.9481	0.9671	0.9856	1.0029	1.0147
684	0.9205	0.9205	0.9213	0.9222	0.9224	0.9473	0.9663	0.9847	1.002	1.0138
611	0.9204	0.9204	0.9211	0.922	0.9223	0.9471	0.9661	0.9846	1.0018	1.0136
652	0.918	0.918	0.9188	0.9197	0.9199	0.9447	0.9636	0.9821	0.9993	1.011
680	0.9211	0.9211	0.9218	0.9227	0.923	0.9478	0.9668	0.9853	1.0026	1.0144

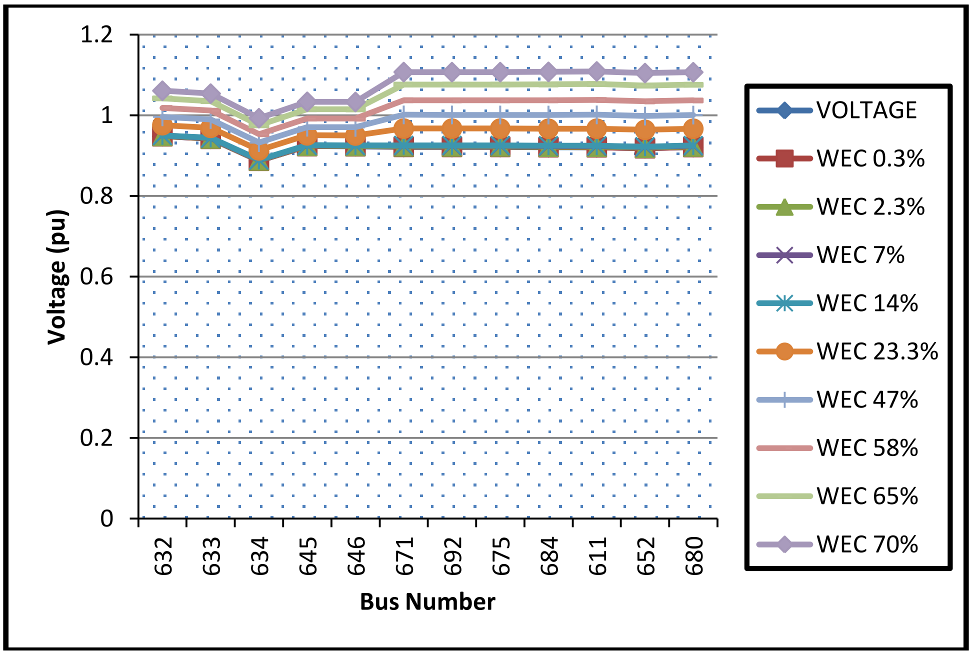


Figure 6.25: Voltage profiles with WEC connected to Bus 646

Table 6.25: Network voltages with WEC connected to bus 680

Bus No	Base Voltage	WEC 0.3 %	WEC 2.3 %	WEC 7 %	WEC 14 %	WEC 23.3 %	WEC 47 %	WEC 58 %	WEC 65 %	WEC 70 %
632	0.9479	0.948	0.9488	0.9497	0.9501	0.9755	0.9963	1.0187	1.0428	1.0621
633	0.9416	0.9417	0.9424	0.9433	0.9438	0.969	0.9897	1.0119	1.0358	1.055
634	0.8872	0.8873	0.888	0.8889	0.8893	0.9131	0.9325	0.9534	0.9758	0.9939
645	0.9235	0.9236	0.9243	0.9252	0.9256	0.9504	0.9706	0.9924	1.0159	1.0347
646	0.9231	0.9232	0.9239	0.9248	0.9252	0.9499	0.9702	0.992	1.0154	1.0342
671	0.9214	0.9217	0.9229	0.9244	0.9253	0.9671	1.0013	1.038	1.078	1.1093
692	0.9213	0.9216	0.9228	0.9243	0.9253	0.967	1.0012	1.0379	1.0774	1.1091
675	0.9213	0.9216	0.9228	0.9243	0.9252	0.967	1.0011	1.0379	1.0774	1.1091
684	0.9205	0.9208	0.922	0.9235	0.9245	0.9662	1.0003	1.037	1.0765	1.1082
611	0.9204	0.9206	0.9218	0.9233	0.9243	0.9666	1.0001	1.0368	1.0763	1.108
652	0.918	0.9183	0.9195	0.921	0.9219	0.9635	0.9976	1.0342	1.07356	1.1051
680	0.9211	0.9213	0.9226	0.9242	0.9253	0.9698	1.0062	1.0454	1.0876	1.1214

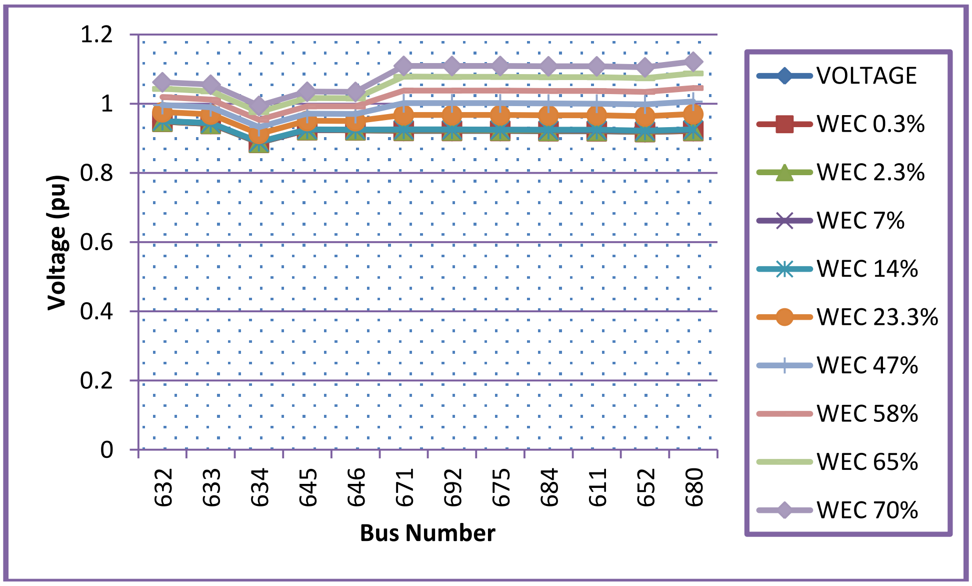


Figure 6.26: Voltage profiles with WEC connected to Bus 680

Table 6.26: Network voltages with WEC connected to bus 611

Bus No	Base Voltage	WEC 0.3 %	WEC 2.3 %	WEC 7 %	WEC 14 %	WEC 23.3 %	WEC 47 %	WEC 58 %	WEC 65 %	WEC 70 %
632	0.9479	0.948	0.9488	0.9497	0.9501	0.9755	0.9961	1.0182	1.0419	1.0608
633	0.9416	0.9417	0.9424	0.9433	0.9438	0.9689	0.9894	1.0114	1.0349	1.0537
634	0.8872	0.8873	0.888	0.8889	0.8893	0.913	0.9322	0.9529	0.975	0.9927
645	0.9235	0.9236	0.9243	0.9252	0.9256	0.9503	0.9704	0.9919	1.015	1.0334
646	0.9231	0.9232	0.9239	0.9248	0.9252	0.9499	0.97	0.9915	1.0146	1.033
671	0.9214	0.9217	0.9229	0.9244	0.9254	0.967	1.0009	1.0372	1.0761	1.1071
692	0.9213	0.9216	0.9228	0.9243	0.9253	0.9669	1.0008	1.037	1.076	1.107
675	0.9213	0.9216	0.9228	0.9243	0.9252	0.9669	1.0007	1.037	1.076	1.107
684	0.9205	0.9208	0.922	0.9235	0.9245	0.9665	1.0006	1.0371	1.0763	1.1076
611	0.9204	0.9207	0.9219	0.9234	0.9245	0.9667	1.001	1.0378	1.0772	1.1087
652	0.918	0.9183	0.9195	0.921	0.9221	0.9639	0.9979	1.0343	1.0734	1.1046
680	0.9211	0.9213	0.9225	0.924	0.925	0.9666	1.0005	1.0367	1.0756	1.1067

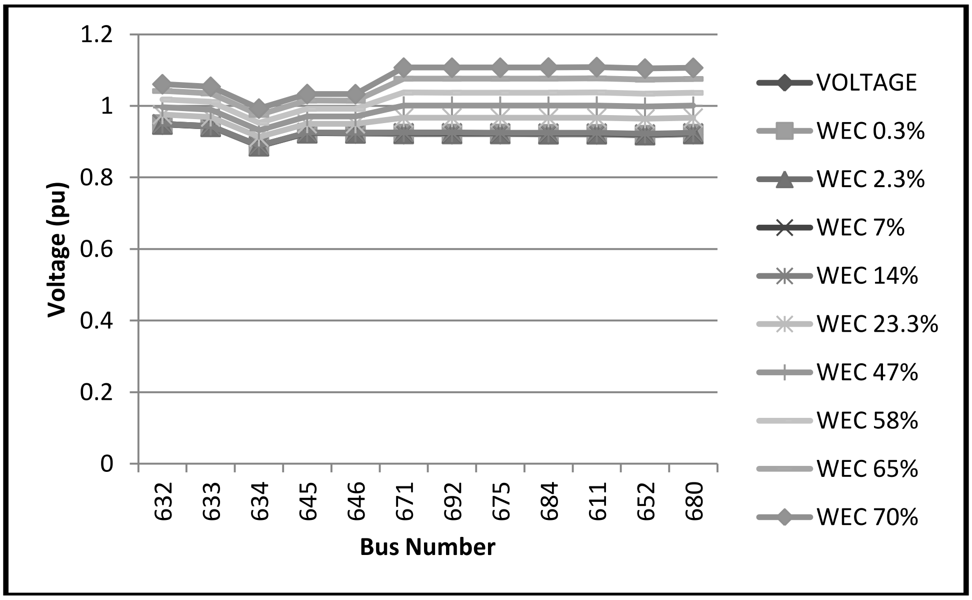


Figure 6.27: Voltage profiles with WEC connected to Bus 611

Investigation and determination of the suitable location (impact of WEC location), as well as the wrong location

DGs are to be connected at the most suitable buses, weakest buses to improve the voltage profile of a distribution network and decrease the voltage dip as well as to reduce the voltage drops across the network. When bus 634 is considered as a point of WEC integration, it is discovered that at

14 % WEC penetration level, there is a voltage rise at that particular bus as shown in Figure 6.28 and Table 6.27 below, this may be as a result of integrated WEC power (600 kVA) being more than the load connected to the bus. The load power (550 kVA) is more than the power of the transformer (500 kVA) at that point. Another reason to be considered is that bus 634 is the only bus in the network that is at 480 V voltage, it is impossible for the power to flow to the rest of the bus since a step down transfer is located at the bus, which means if the bus is to be considered as a point of WEC integration, the power of such WEC must not be greater than the load connected to the bus. Also, the transformer connected to that bus must be replaced due to overloading. Instead of considering bus 634 which cannot take more WEC penetration level, bus 633 can be considered which can take up to 81 % WEC penetration level.

Bus 652 takes high WEC penetration level (Figure 6.23), this may be as a result of the location of the bus, or the load that is connected to the bus. Also, buses 611, 675, 633, 646 and 680 can be considered as suitable locations for WEC integration in case two or more WECs are to be integrated into the network either by the utility or independent power producer.

Table 6.27: Network voltages with WEC connected to bus 634

Bus No	VOLTAGE	WEC 0.3 %	WEC 2.3 %	WEC 7 %	WEC 14 %	WEC 23.3 %	WEC 47 %
632	0.9479	0.948	0.948	0.9584	0.9585	0.9588	0.9591
633	0.9416	0.9417	0.9417	0.9501	0.9501	0.9506	0.9508
634	0.8872	0.8876	0.8877	1.0212	1.0217	1.0263	1.1298
645	0.9235	0.9235	0.9235	0.9337	0.9338	0.9341	0.9344
646	0.9231	0.9231	0.9231	0.9333	0.9333	0.9337	0.934
671	0.9214	0.9215	0.9215	0.9316	0.9317	0.932	0.9323
692	0.9213	0.9214	0.9214	0.9315	0.9316	0.9319	0.9322
675	0.9213	0.9213	0.9214	0.9315	0.9315	0.9319	0.9322
684	0.9205	0.9206	0.9206	0.9307	0.9307	0.9311	0.9314
611	0.9204	0.9204	0.9204	0.9305	0.9306	0.9309	0.9312
652	0.918	0.9181	0.9181	0.9282	0.9282	0.9286	0.9288
680	0.9211	0.9211	0.9211	0.9312	0.9313	0.9316	0.9319

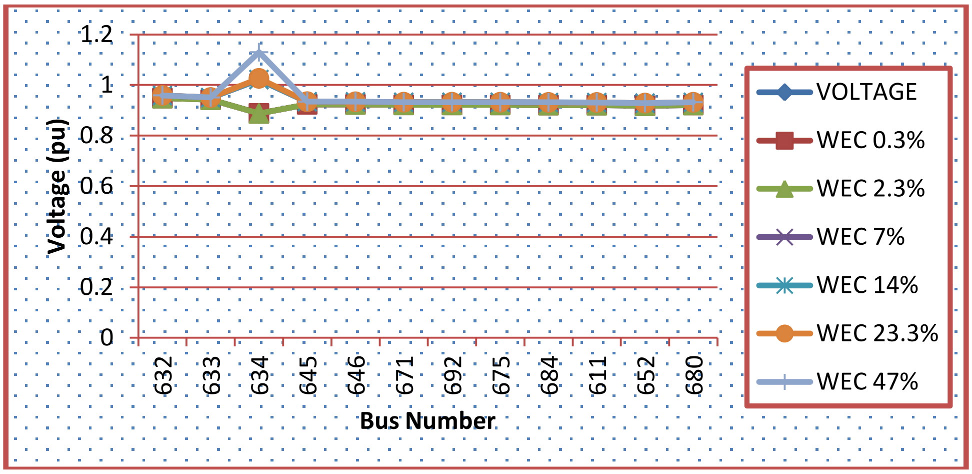


Figure 6.28: Voltage profiles with WEC connected to Bus 634

Impact of WEC at the point of common coupling into a low voltage distribution network

The point of common coupling (PCC) can be described as a point where WEC is connected or integrated into a particular network. It can be examined from the Figures 6.21 to 6.28 and Table 6.19 to 6.26 (all the rows with highlighted with red colour) that the voltage at the buses which the WEC is integrated into the network are slightly higher than all other voltages in the network this is due to the injection of the active power of the WEC at that particular bus which make the bus to be more active than any other bus in the network.

Summary

The impacts of WEC on a distribution network voltage profile may be strongly influenced by the location of WEC in the network, varying WECs power and its penetration levels. This dissertation investigated and established in MATLAB/SIMULINK and PSCAD that integration of WEC into a distribution network can reduce the voltage dip, decrease the voltage drop and improve the voltage profile of such network. Also, integration of large amounts of WECs at a wrong location or where the WEC power is more than the load can cause unacceptable voltage profile. It is therefore advisable to draw and study the voltage profile of any network, the weakest buses should be noted before WEC is to be integrated into such network either by the utility or by the generator owner.

Chapter 7

WEC integration, analysis under fault conditions and comparison using MATLAB/SIMULINK and PSCAD/EMTD in a distribution network

Introduction

This chapter investigates the behaviour of a distribution network using MATLAB/SIMULINK and PSCAD/EMTDC under a fault condition without WEC integration, under steady state condition with WEC integration and comparisons between the simulations results obtained are discussed**.**

7.1 Distribution network behaviour during fault without WEC integration

The circuit layout in MATLAB/SIMULINK is shown in Figure 7.1 and the simulation result when WEC has not been integrated into the network is shown in Figure 7.2. The grid voltages for the buses are within an acceptable range in compliance with the grid code (-15 % to +10 %, i.e., 0.85 to 1.1). The current at bus 634 is more than that at the other buses this is because of the large load connected to the bus which draw more current in the network. Figure 7.3 shows the grid voltage and current when there is a three-phase fault between 5 to 10 seconds on the bus 634 without WEC integration into the network. It was observed within this time frame that, there is voltage dip, the voltages at bus 634 reduced to zero and higher current flows in the network especially at bus 634 which is the fault location. But after the fault is cleared, the voltages and the currents returned back to normal and maintained their stability

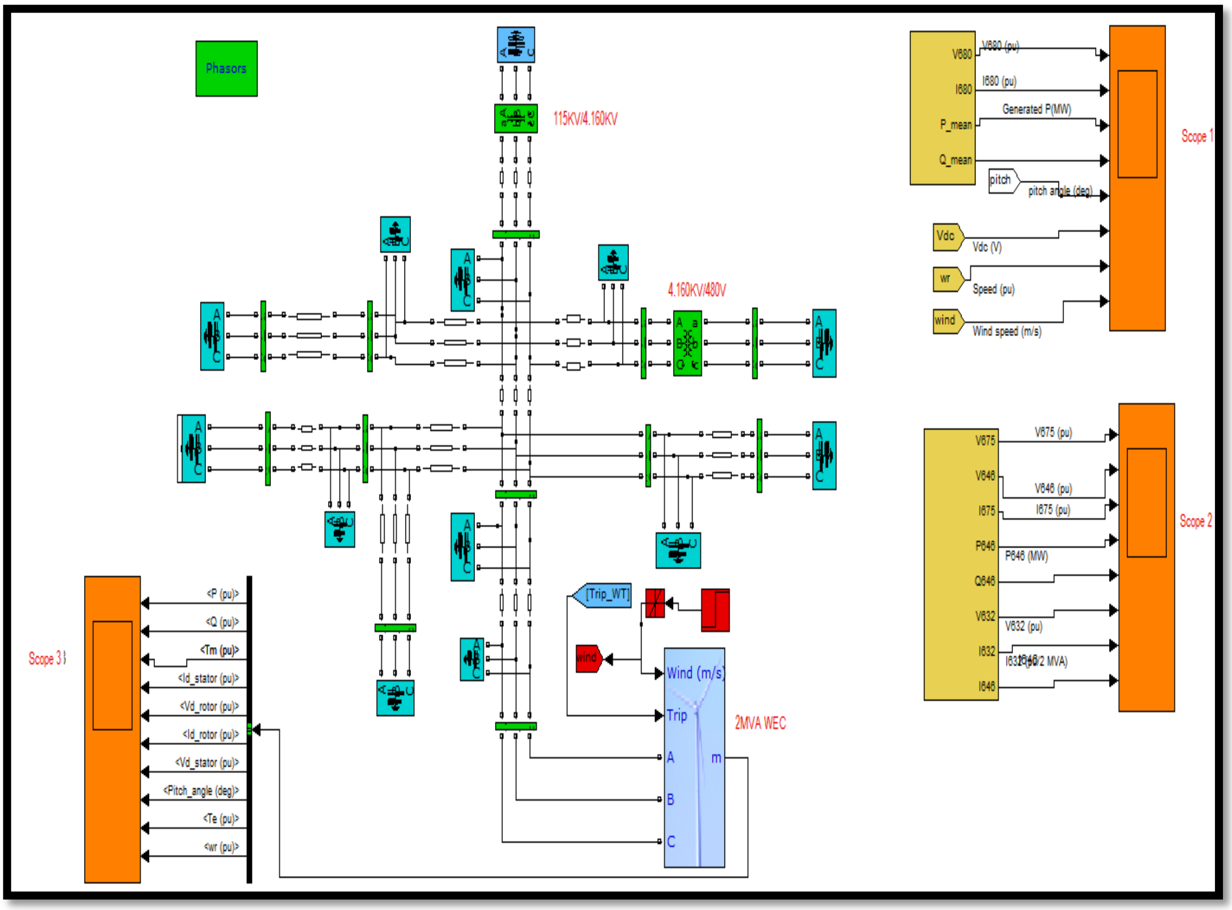


Figure 7.1: SimPowerSystems diagram of the WEC

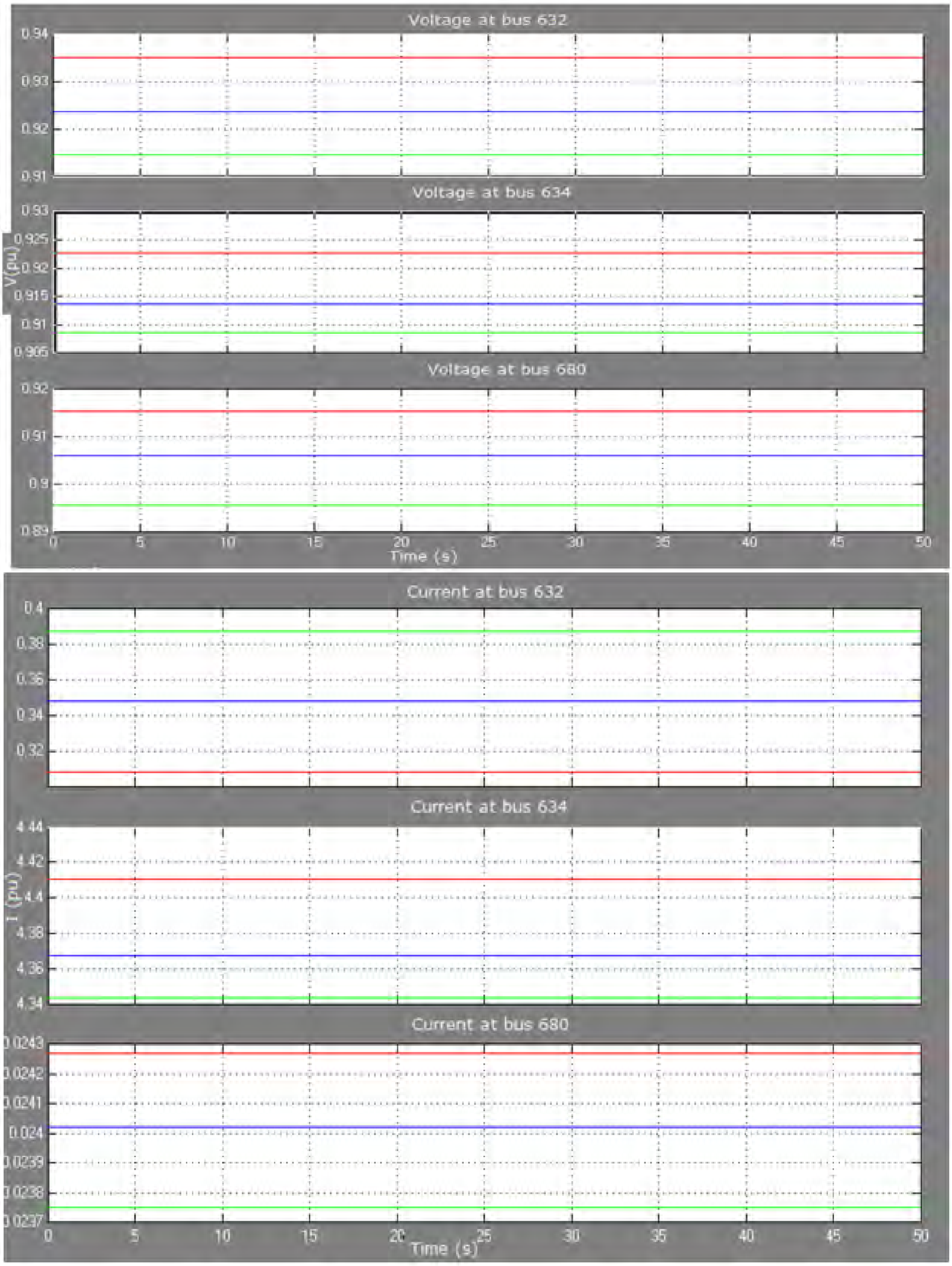


Figure 7.2: Three-phase voltages and currents at different buses without disturbance and WEC connection

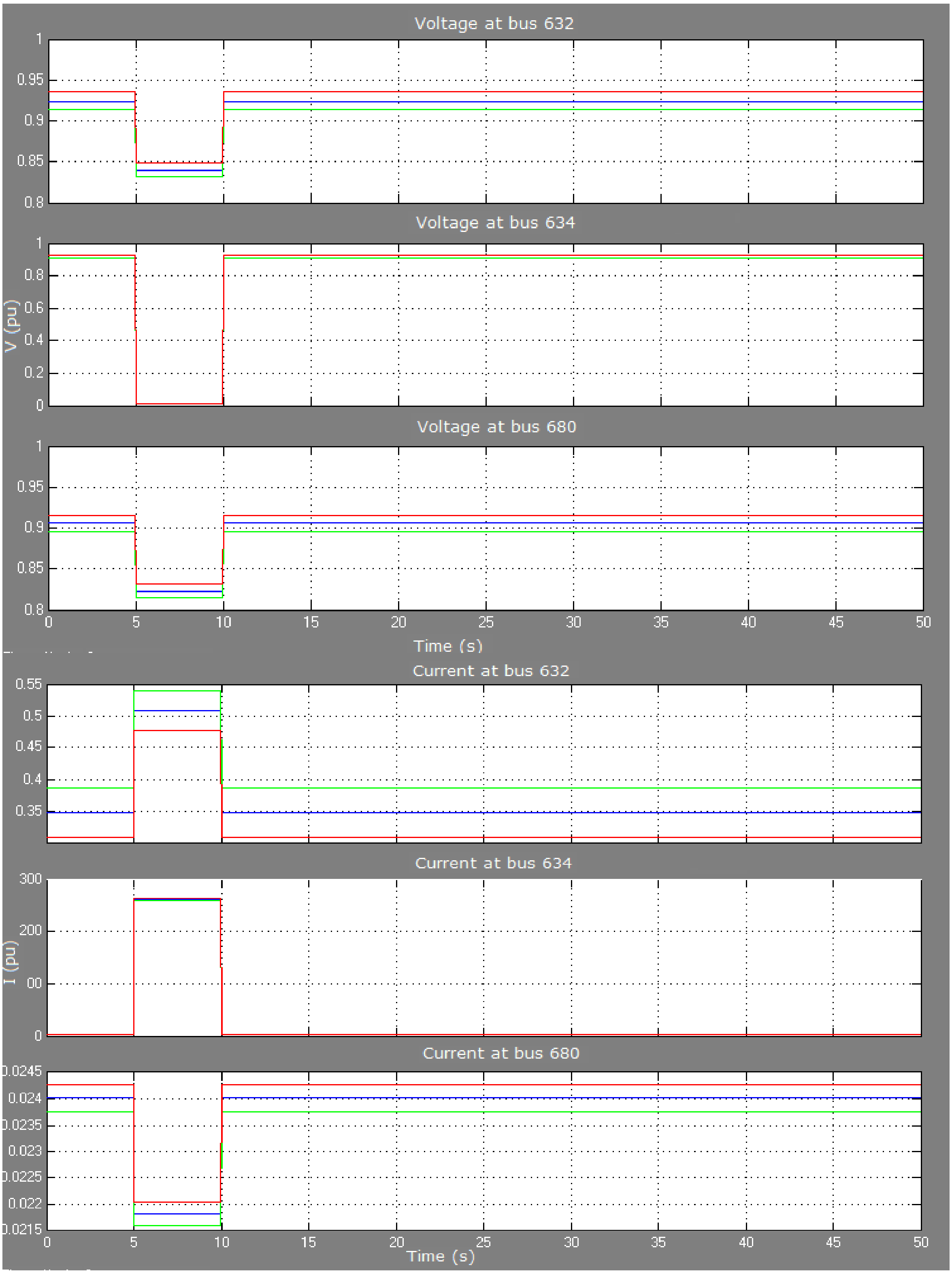


Figure 7.3: Three-phase voltages and currents at different buses with disturbance without WEC connection to the network

7.2 The impacts of WEC under steady state condition in a distribution network

The impacts of WEC on a distribution network under steady state are investigated in this section. The network design and layout is implemented in MATLAB/SIMULINK as shown in Figure 7.1. The details of the network parameters can be found in Table 1 in Appendix A. The network is simulated for 0.50 seconds; the simulation results (buses 675, 646 and 632) are shown in Figures 7.4 and 7.6 below. Figure 7.4 depicts the WEC generated active and the reactive power, voltage and current under steady state, the wind speed is set to 9 m/s as the initial setting, at t = 0.05 s, there is an increase in wind speed from 0.05 s to 0.1 s, it maintained 14 m/s and the turbine speed is maintained at 1.2 pu as shown in Figure 7.5 (a), at t = 0.03s, the generated active power starts to increase smoothly and reaches its rated value 1.96 MW. The pitch angle (angle of attack) increases from zero degree at 0.14 s to 30 degrees at 27 s, and maintains its stability in 0.45 s at 19.8 degree to limit the mechanical power. The turbine speed increases from 0.8 pu at 0.04 s to 1.2 pu at 0.2 s and maintained the speed at 1.02 pu (see Figure 7.4), the turbine Vdc voltage is maintained at 6 kV. It is shown that the impact of WEC under steady state condition increases the grid voltage profile from 0.93 pu in Figure 7.2 above to 1.0 pu as depicted in Figure 7.6 and the oscillations that occurred between 0 to 0.02 s, are as a result of switching of the generator before a steady state is maintained.

7.3 The turbine power characteristics

The turbine speed optimization is obtained between points B and C on the curve shown in Figure 7.5 (a) below, the DFIG is controlled to follow the ABCD curve in the turbine data menu and the turbine power characteristics

7.3.1 Pitch Angle Control System

The pitch angle is kept constant at zero degree as shown in Figure 7.5 (b) until the speed reaches point D of the tracking characteristic. Beyond the point D the pitch angle is proportional to the speed deviation from point D speed

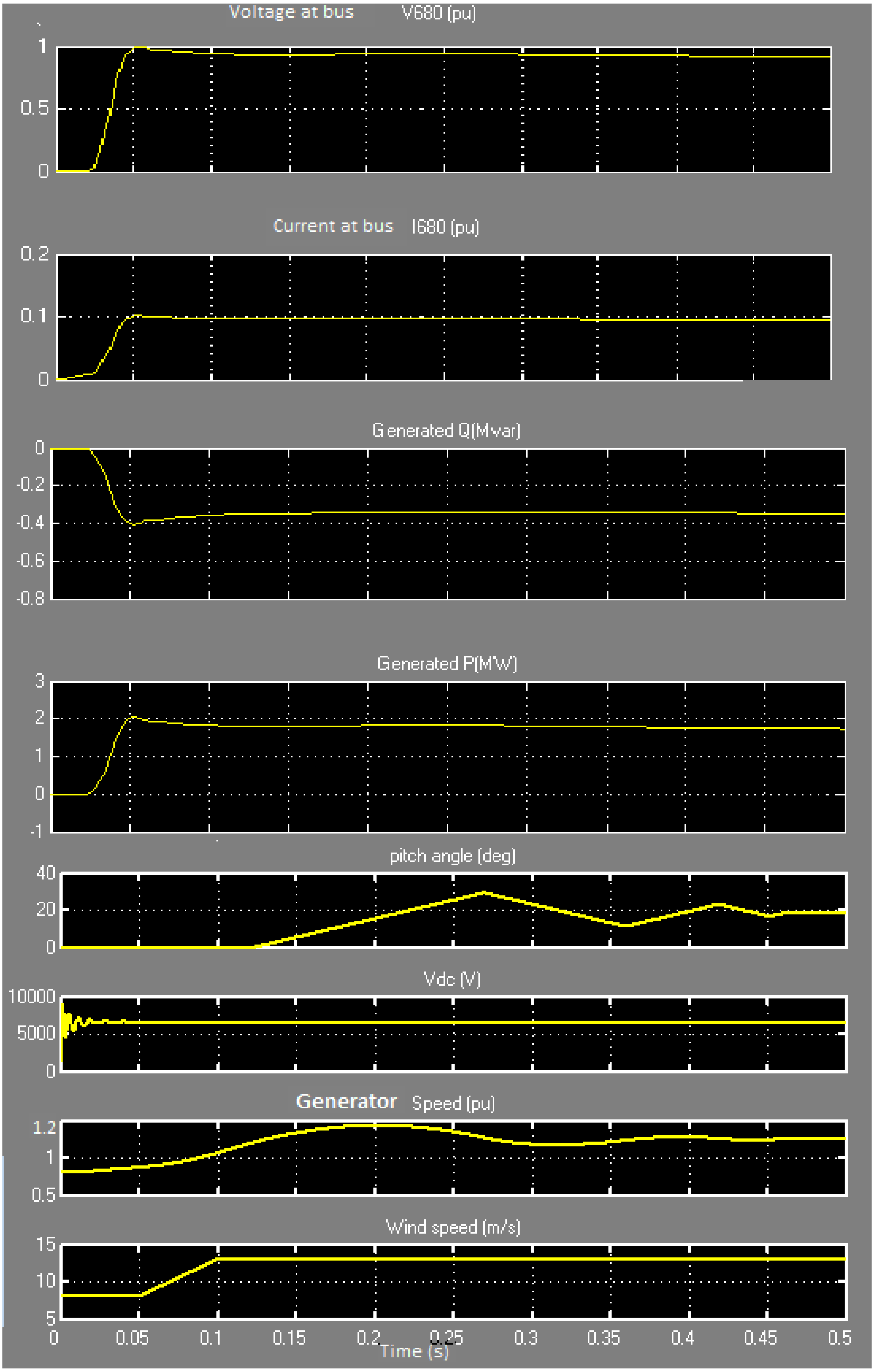
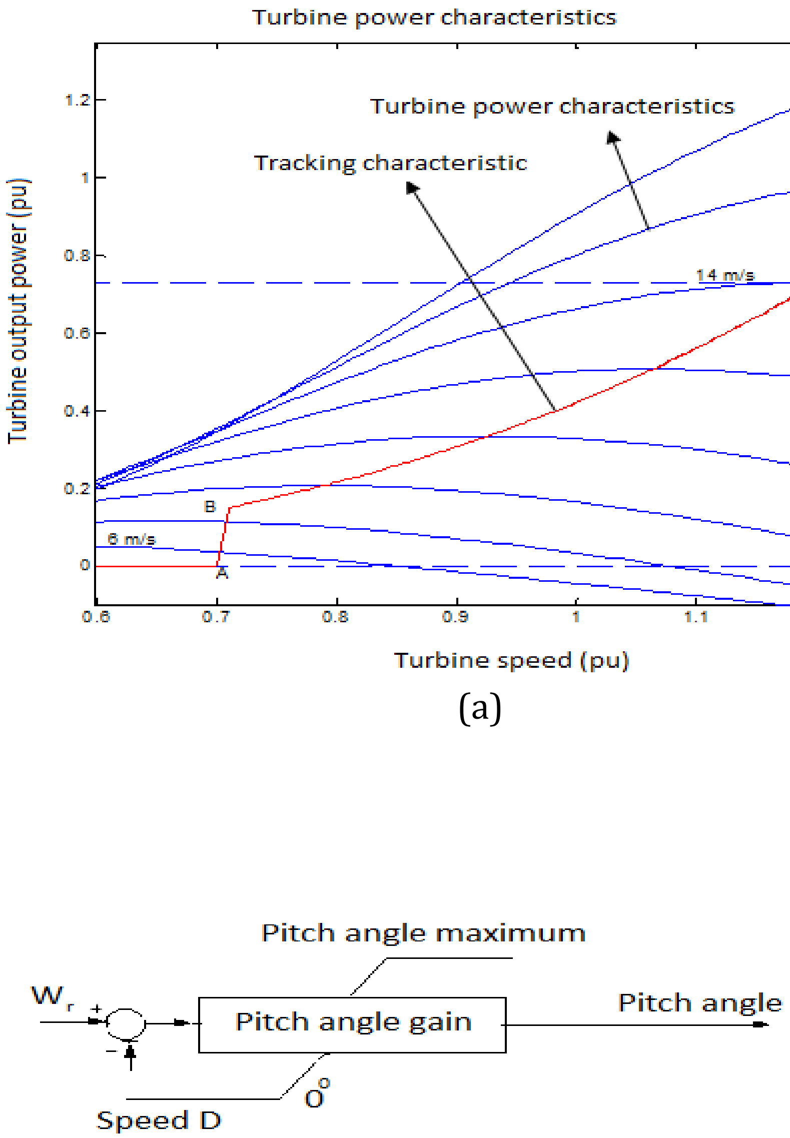


Figure 7.4: WEC generated voltage, current, active and reactive power under steady state conditions



(a)

(b)

Figure 7.5: (a) Pitch control system and (b) the turbine power characteristics

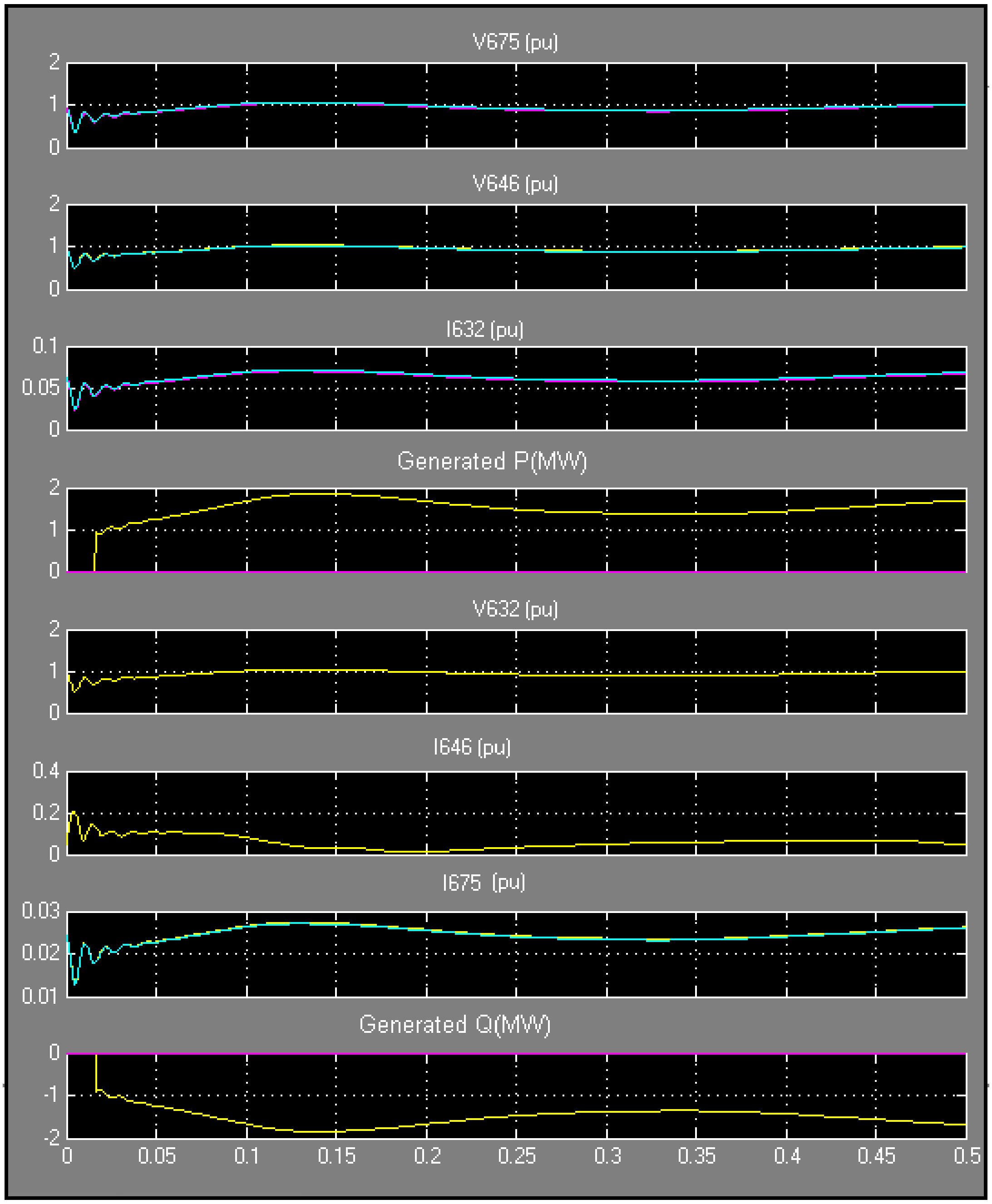


Figure 7.6: Grid voltage, current, active and reactive power under steady state condition

7.4 Impact of WEC during transient condition

To investigate the dynamic behaviours and the impact of WEC on the grid voltage, current, active and reactive power with network disturbance, a severe fault (i.e., three phase to ground fault) occurred at bus 634 at t = 5 s and it clears at t = 10 seconds. The behaviours and the impact of WEC are shown in Figure 7.7 below. It can be seen that the voltage dips that the fault caused to the network is very low compared to Figure 7.3 when there is no WEC integration into the network. It means that the integration of WEC into a distribution network can reduce the voltage dip caused by network disturbance or large load switching this is because the WEC is being added to an existing generation.

In the same vein, the impact of WEC causes the network voltage, current, active and the reactive power to be unstable as shown in Figures 7.7 and 7.8 (fast moving voltage variation) compared to the Figure 7.3, stability in this context is the maintainability of the voltage magnitude while active and reactive powers are being transported by the WEC. There is fast changing in the magnitude of the generator voltage, grid voltages, currents, active and the reactive power which can be regarded as fast moving voltage fluctuations [**160**]. The main concern is that it may result into the phenomenon called light flicker with the frequency change between about 1 to 10 Hz, changes more than 2 % will result into the noticeable changes in the light intensity as mentioned in section 5.3.8 above. The disturbance caused a great instability in the generated active and reactive power, the generator still supplies voltage that is closed to 1.0 pu into the network, this is because the bus where the fault occurred (bus 634) is far from the bus where WEC is connected (bus 652) into the network.

The network voltages, currents, active and reactive power are unstable even after the fault is cleared, which is sometimes dependent on the types of equipment connected to the network, e.g, some equipment may have tripped during the fault, and take a longer time to be connected, other equipment connected during the fault may take higher reactive power after the fault is cleared, which can also cause a reduction in the network power transfer and voltage instability, since the WEC generated voltage, current, active and the reactive power are not recovered for a short period of time, the network experiences less or shortage of generation in the local consumption. To reduce these challenges, there is need to strength the network by installing a FACTS device into the network. It can be concluded based on the simulation results that the presence of WEC in a distribution network can contribute to network instability during severe fault condition which can result into long term instability as mentioned in section 5.3

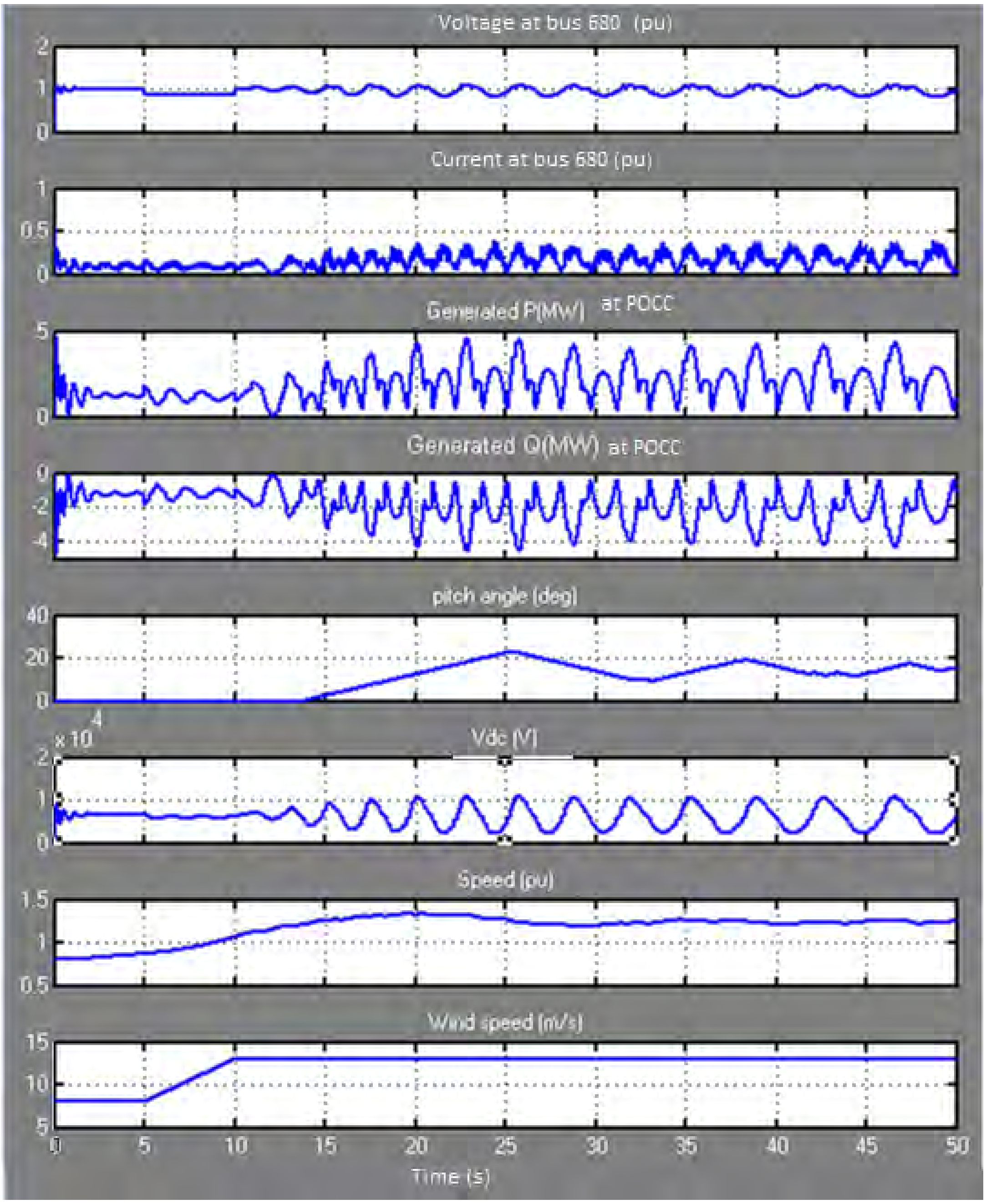


Figure 7.7: Active and the reactive power, voltage and current at the point of common coupling.

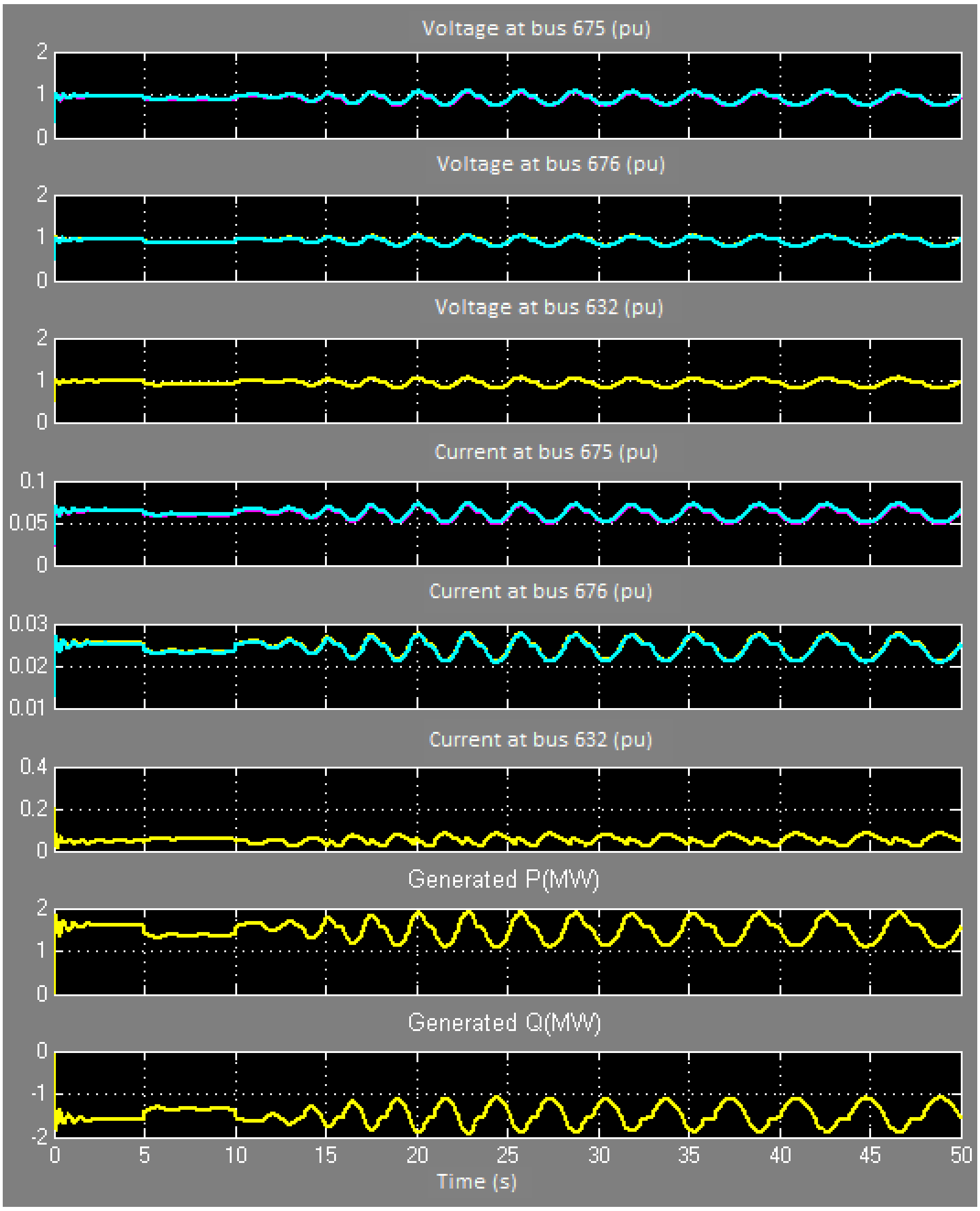


Figure 7.8: Grid voltage and current, active and the reactive power at different buses with WEC connection

7.4.1 Voltage instability improvement

As it is known that the injection of reactive power is advantageous for raising the network voltage, it not only improves the power quality in the distribution system, but it also can improve the transient stability. A reactive power compensation device where the reactive power is linearly proportional to the voltage such as STATCOM is required which can mitigate most power quality problems such as voltage instability, dips, flicker etc. WEC operates at a constant voltage and will produce a different impact on the improvement of voltage stability, which means the FACTS devices will help the WEC to generate more reactive power in the steady state after the disturbance to bring the WEC terminal voltage back to its pre-disturbance value. Flexible AC transmission system (FACTS) device e.g STATCOM is installed at the point of common coupling the parameter is in Appendix A, Table 10. The network simulation is repeated again for the same time duration with the same fault, it is found that power transfer capacity improved, the compensation of active and reactive power injected is controlled by the device and maintained its stability at t = 20 s as shown in Figure 7.9. The installation of STATCOM at PCC introduced damping into the network, which kept the voltage constant within an acceptable range, but the generator oscillates for 15 s seconds during the pre-fault and post fault respectively which quickly maintained the stability state with the help of the STATCOM. The risk of fast fluctuations, oscillations, over voltage and under voltage was mitigated. Figures 7.9 and 7.10 showed an improved network simulation graph of the WEC and grid voltage, current, active and the reactive power. The installed STATCOM has good voltage control, it generates both capacitive and inductive power, it is very fast in compensating for transient state instability condition and a stable operating point is attained.

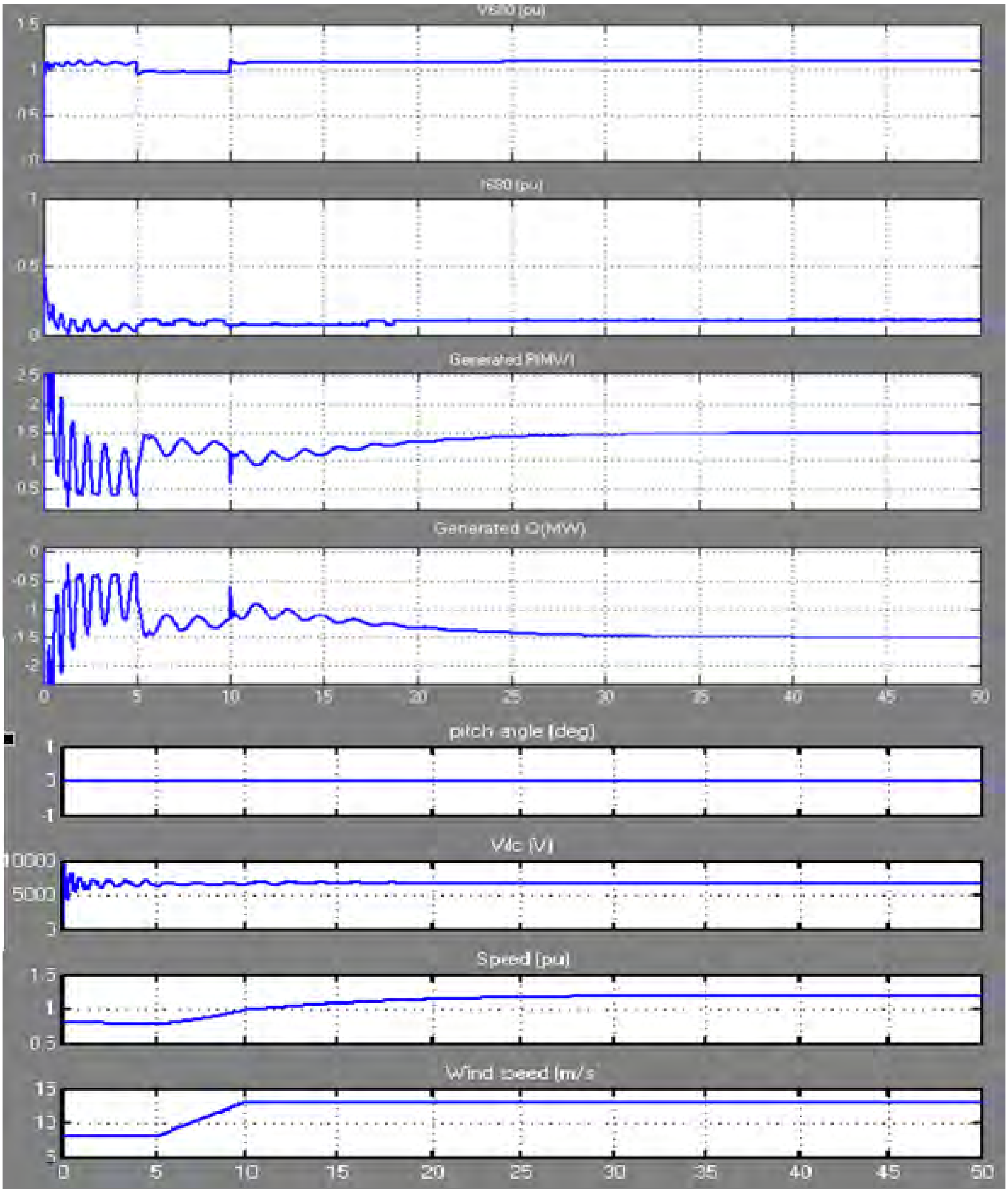


Figure 7.9: Improved WEC voltage and current, active and the reactive power

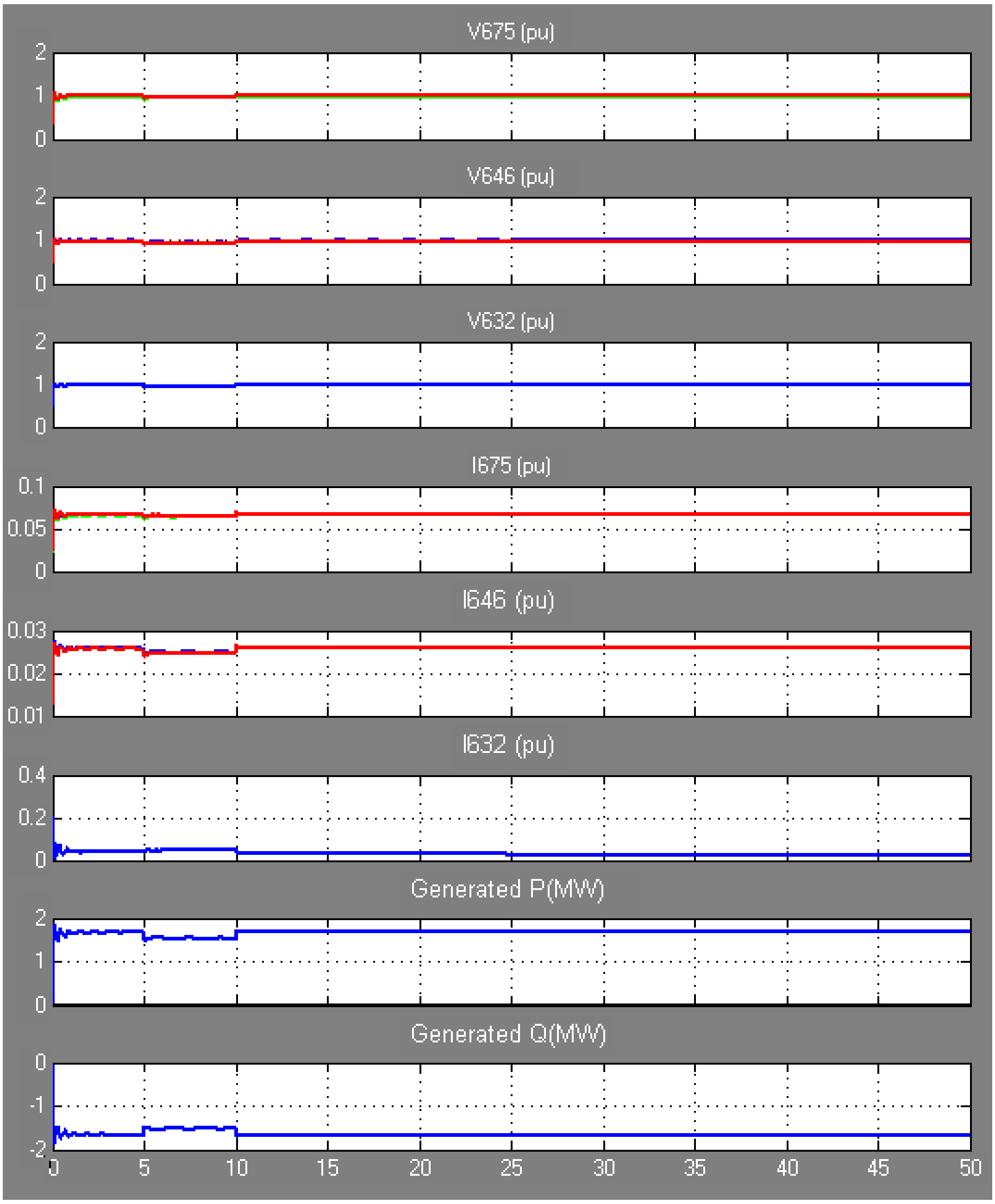


Figure 7.10: Improved Grid voltage and current, active and the reactive power

7.5 Summary

The voltage dip created (0.81 per unit) by a disturbance without WEC integration in the distribution network is severe and not acceptable in relation to the grid code act. The integration of WEC to a distribution network improved its voltage profile and therefore, decrease voltage drop across the loads, voltage dips are minimized. The integration of WEC to a distribution network during fault conditions creates instability on the generator terminal voltage, current, active and reactive power as well as the grid voltage, current, active and the reactive power. But, the network is strengthened when a compensation device is installed into the network, the dips are drastically reduced. It could be seen in the above simulations that the presence of WEC in the distribution network has a negative impact on certain disturbance levels. The presence of an appropriate compensatory FACTS device makes the system stronger and introduces damping into the network

7.6 The impact of WEC on a distribution network during fault conditions using PSCAD/EMTDS

Introduction

To compare the results of the impacts of the WEC on the voltage profile of a distribution network, most of the simulations performed in MATLAB/SIMULINK are repeated in PSCAD with varying WEC power. It is observed that the impact of WECs integration into a distribution network can improve the voltage profile. This section investigates the behaviour of the network during fault condition as well as the impact of WECs on the network voltage, current, active and reactive power and the network behaviour during fault conditions.

7.6.1 Behaviour of a distribution network under a fault condition without WEC integration

Figures 7.11, 7.12 and 7.13 depict the network instantaneous voltage, RMS voltage and current without disturbance in the network and without integration of WECs, the voltage is within the acceptable range but not up to the nominal voltage of the network. The network nominal voltage is 4.160 kV, while the grid voltages obtained without WEC integration into the network is 3.800 kV (about 0.91 pu). Figures 7.14, 7.15 and 7.16 illustrate the network voltage and current when there is grid disturbance between 5 s to 10 s in the network without WECs integration into the network. The occurrence of a three-phase to earth fault at bus 645 reduces the network voltage to zero within the duration of the fault before the voltage regains its steady state.

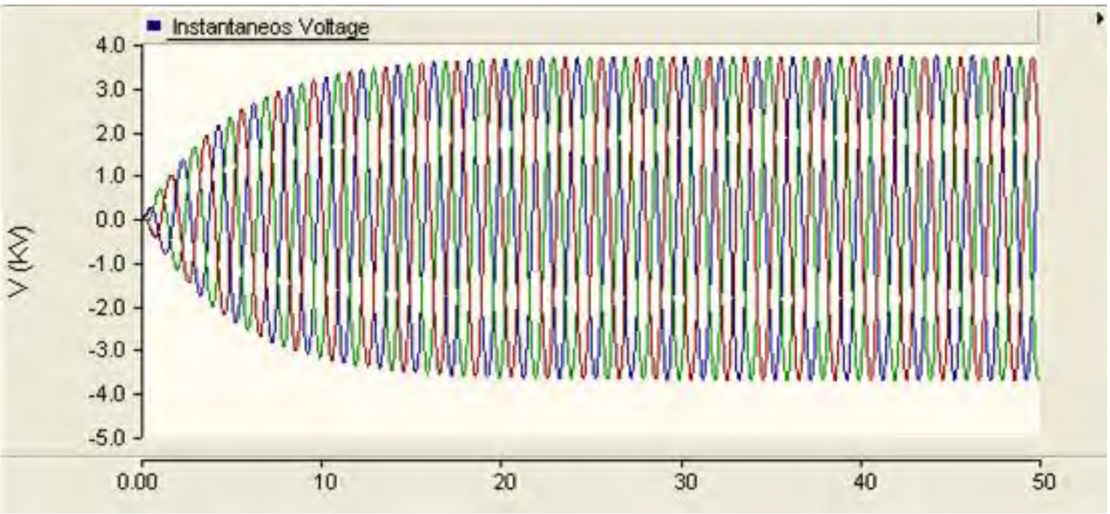


Figure 7.11: Grid voltages without WECs integration and fault

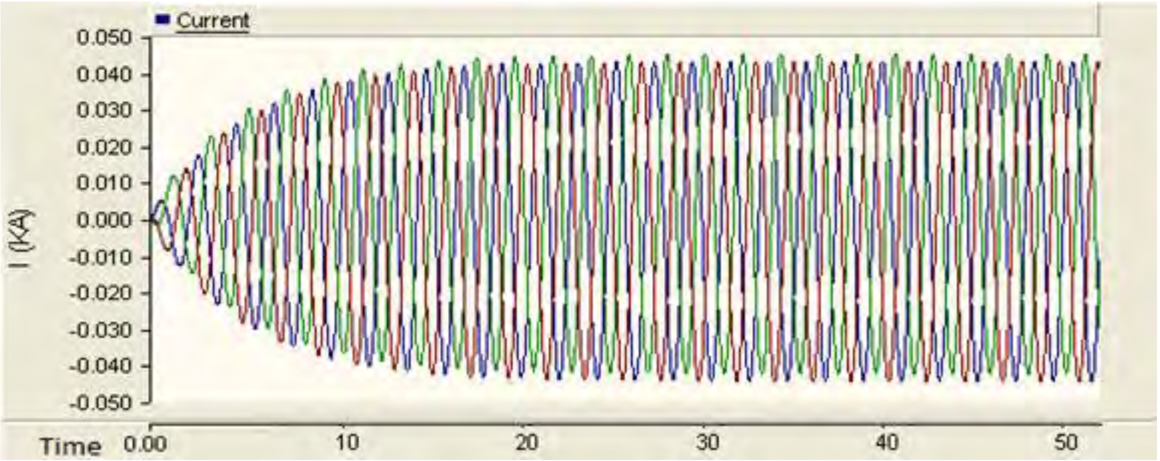


Figure 7.12: Grid currents without WECs integration and fault

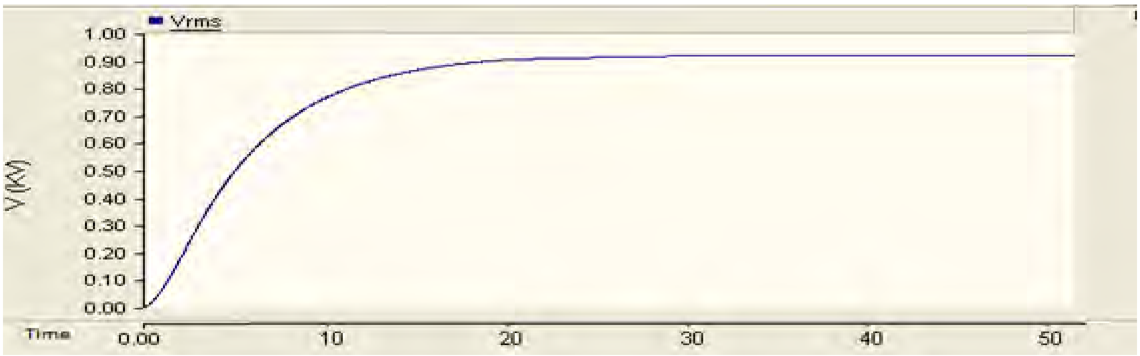


Figure 7.13: RMS voltages without WECs integration and fault

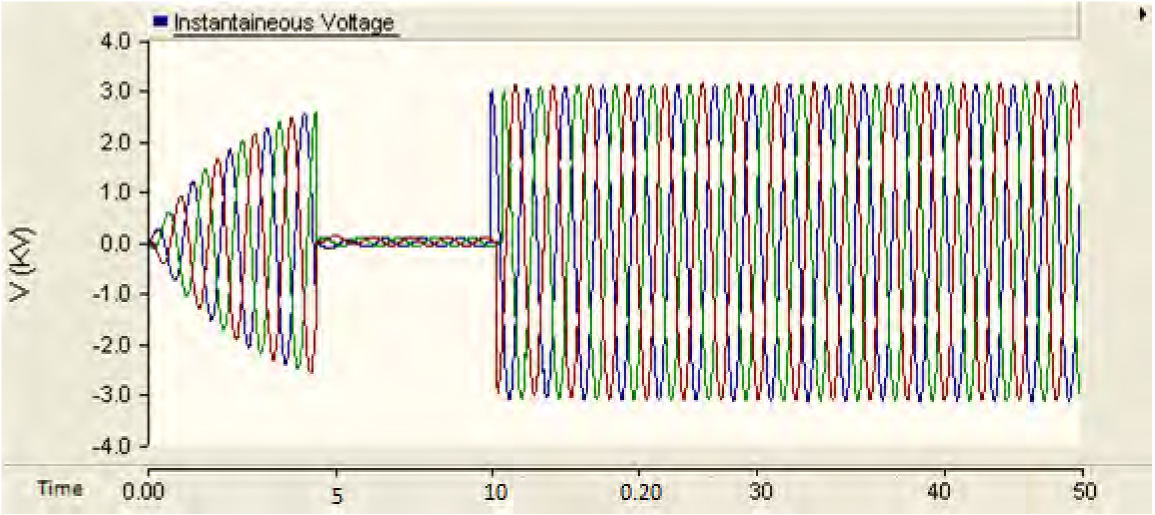


Figure 7.14: Grid voltages with fault without WECs integration at bus 634

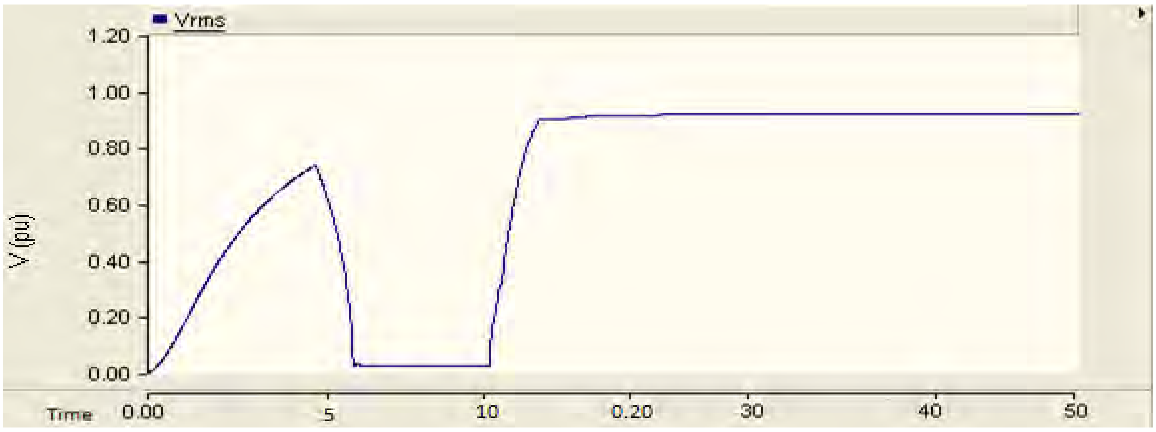


Figure 7.15: Grid RMS voltages with fault without WECs integration

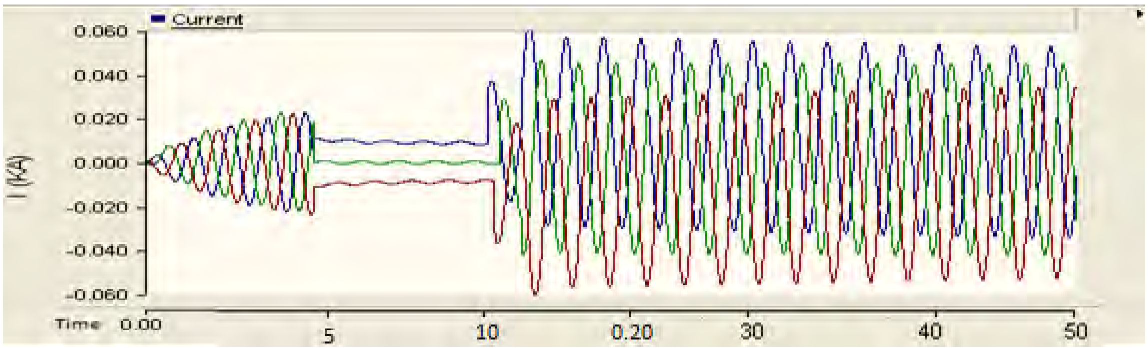


Figure 7.16: Grid current with fault without WECs integration

7.6.2 Behaviour of a distribution network under a fault condition with WEC integration

The simulation results of the impacts of WEC on a distribution network are shown in Figures 7.17 and 7.18 below when WEC is connected to bus 652 without grid disturbance. It is found that the voltage profile of the network is improved from 0.91 pu to the rated nominal value of the network and maintained 0.96 pu as shown in Figure 7.19. The generated active and reactive power increased smoothly to their rated value as shown in Figures 7.20 and 7.21 respectively.

Figures 7.22 and 7.23 show the simulation results when there is a disturbance in the network with WECs integration, the dips occurred as a result of the disturbance, the network voltage reduced to about 2 kV due to the fault, the voltage does not go to zero in Figure 7.24 as compared to Figures 7.14 to 7.16, where WECs is not connected to the network. This is due to the location of the fault that is very close to the substation but far to the point where the WEC is connected to the network, the supply from the WEC raised the voltage up and the WEC (DFIG have slight var and voltage control capability) can control the reactive power to a certain level, but after the clearing of the fault at 0.18s, the post fault voltage could not regain its stability until 0.28s (Figures 6.48 to 6.84). The effect of the disturbance on the generated active and reactive power is obvious (Figures 7.25 and 7.26), since the grid fault has reduced the voltage, the reduction in the voltage decreases the capability of the generator to deliver enough power, the active and reactive power is reduced to zero and to a negative value which means current leads the voltage i.e leading Power factor. It happens when load behave like capacitive load, negative sign means that Load generates/supplies reactive power or Vars in relation to IEEE four quadrant power flow direction in [**226**] , which means during the fault, the WEC is humming, it could not generate power i.e., It behaves like a motor, immediately after the fault is cleared, the WEC full voltage and power are restored, the post fault speed of the generator is therefore higher than its speed during fault which causes slightly higher voltage immediately the fault is cleared but, it finally maintain its stability at 0.28 s, generated active and reactive power are affected by the disturbance, it cannot maintain its stability even after the fault is cleared until 0.40 s.

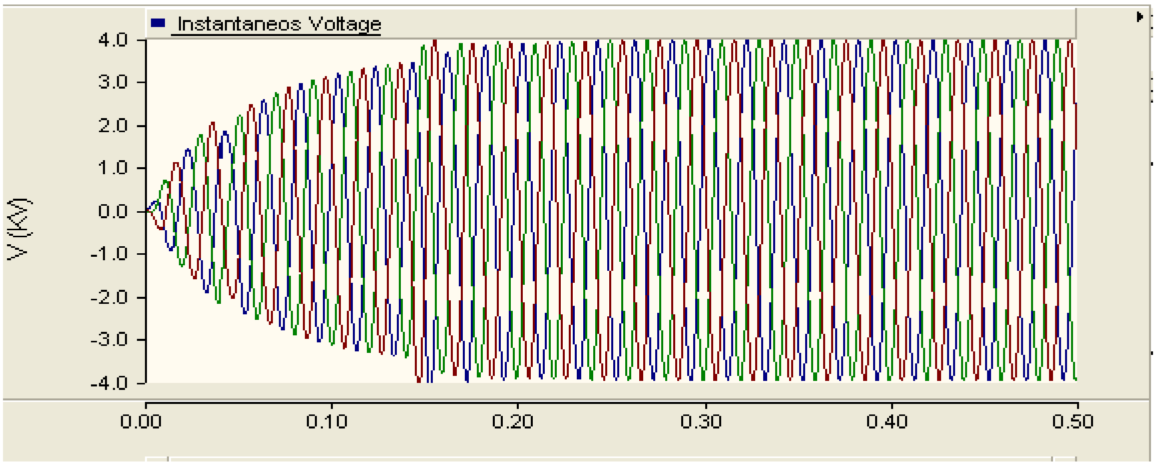


Figure 7.17: Grid instantaneous voltages with WEC integration without fault

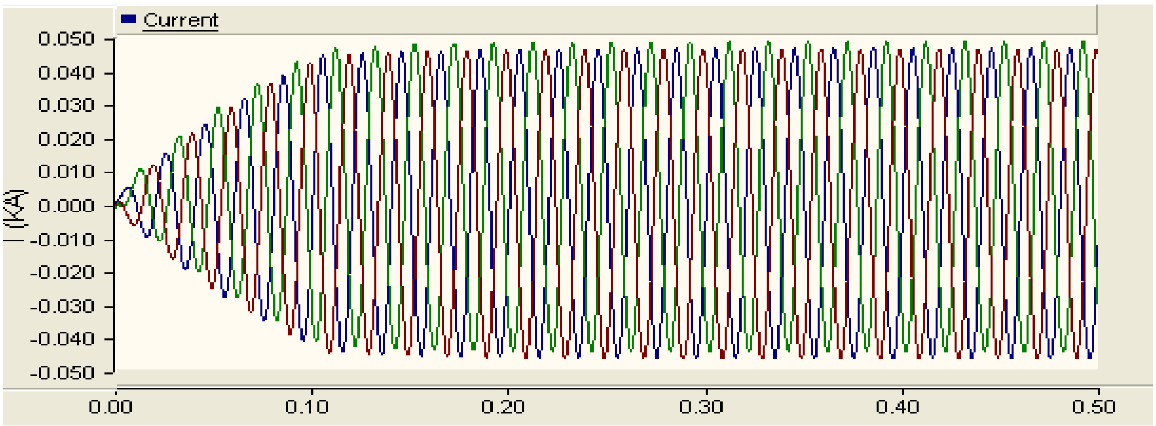


Figure 7.18: Grid instantaneous current with WEC integration without fault

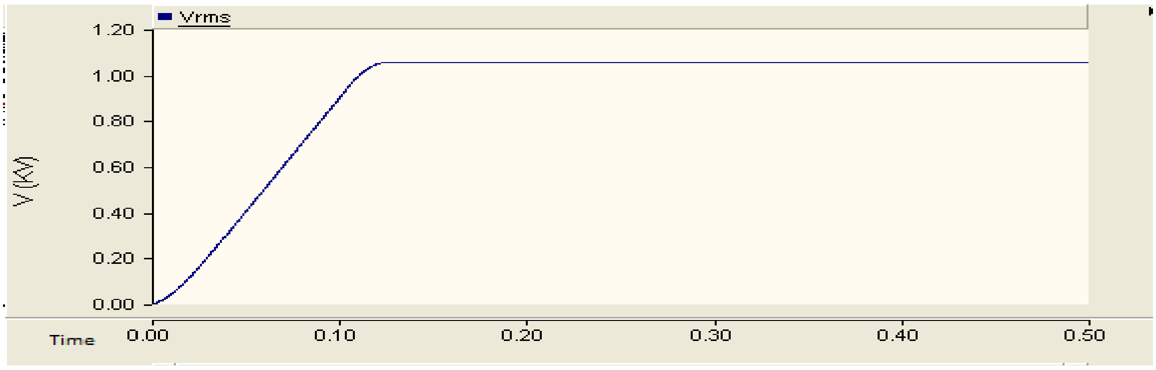


Figure 7.19: RMS voltage with WEC integration without fault

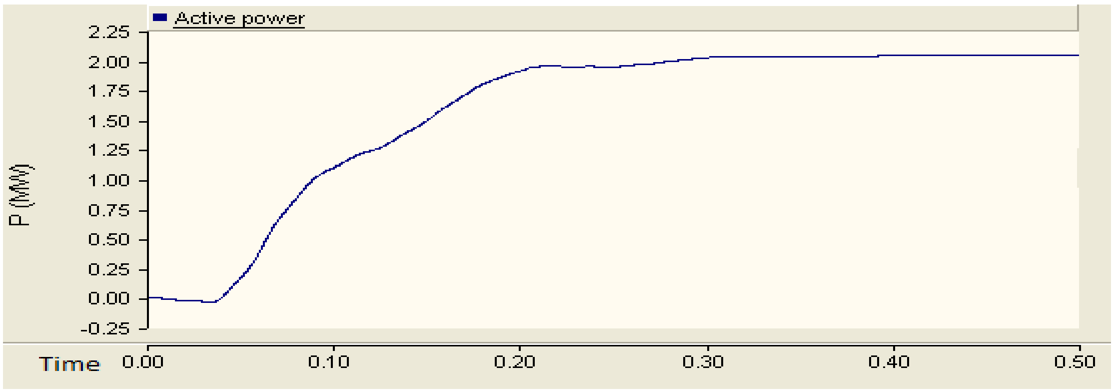


Figure 7.20: Generated active power

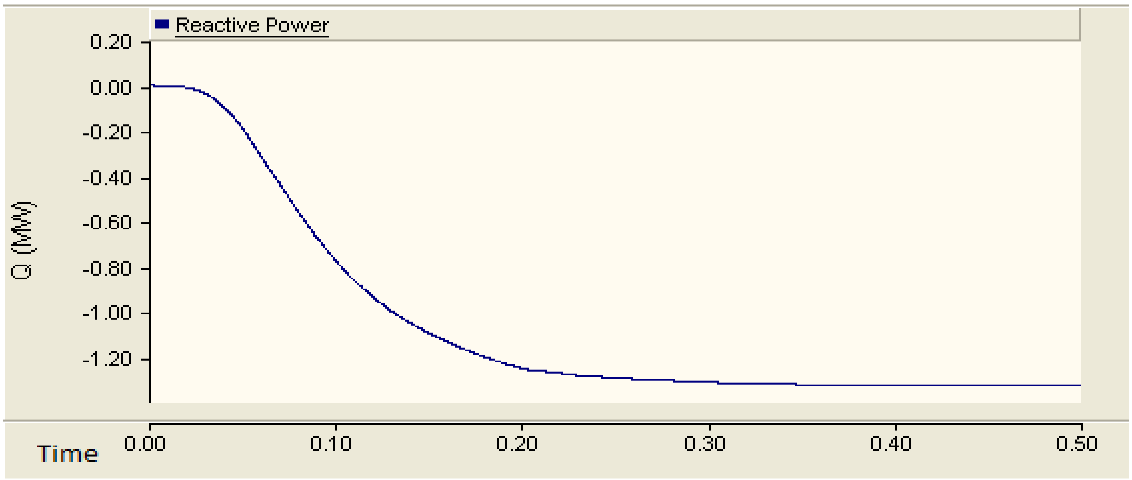


Figure 7.21: Generated reactive power

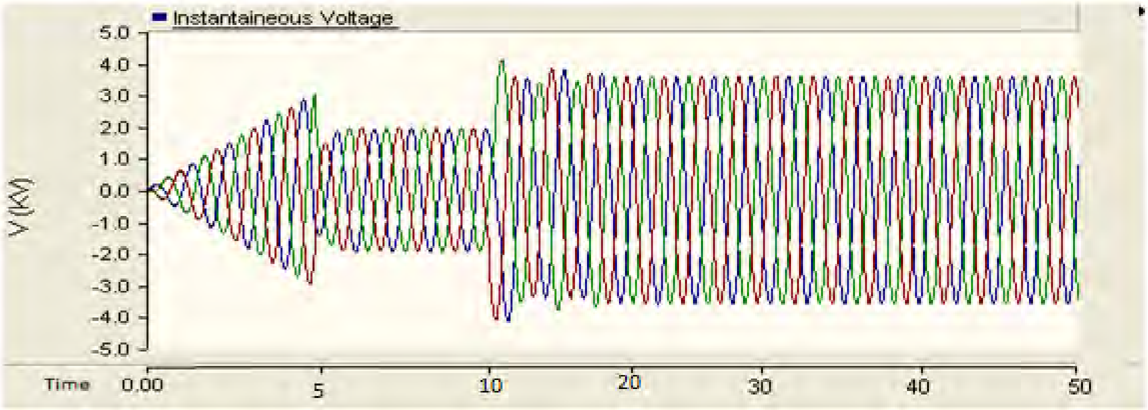


Figure 7.22: Grid instantaneous voltages with WEC integration and fault

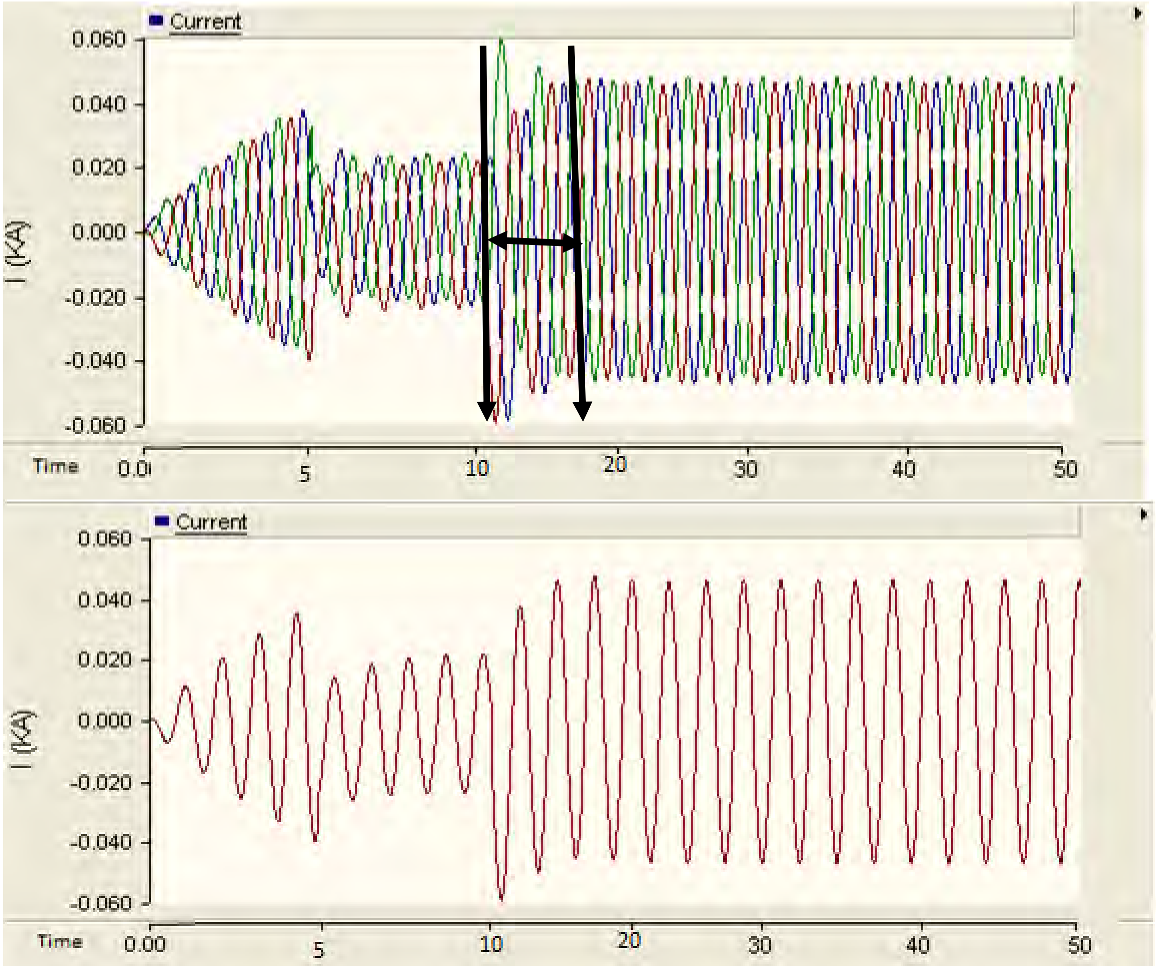


Figure 7.23: Grid instantaneous current with WEC integration and fault

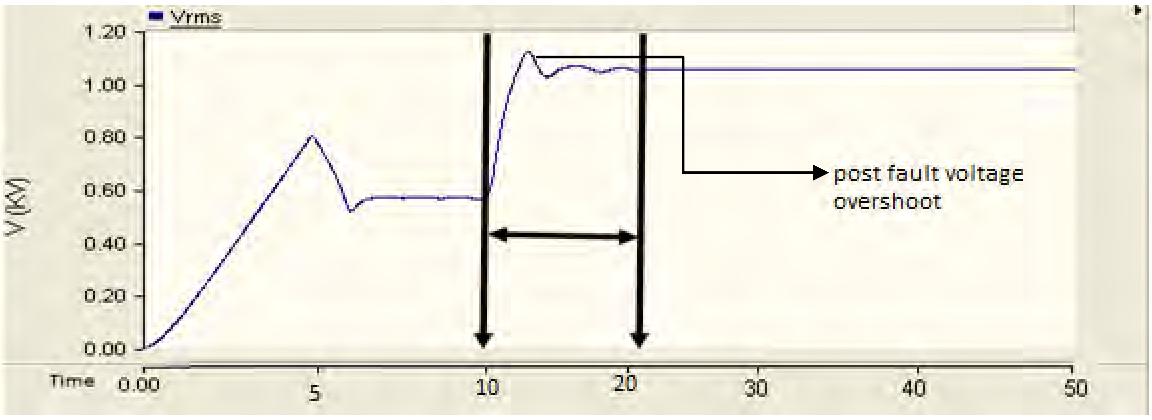


Figure 7.24: Grid RMS voltage with WEC integration and fault

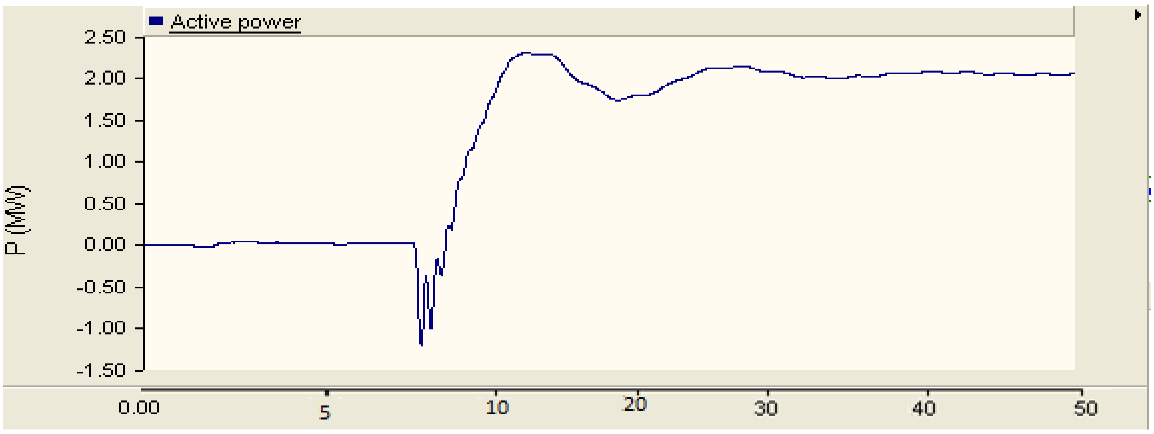


Figure 7.25: Generated active power with disturbance

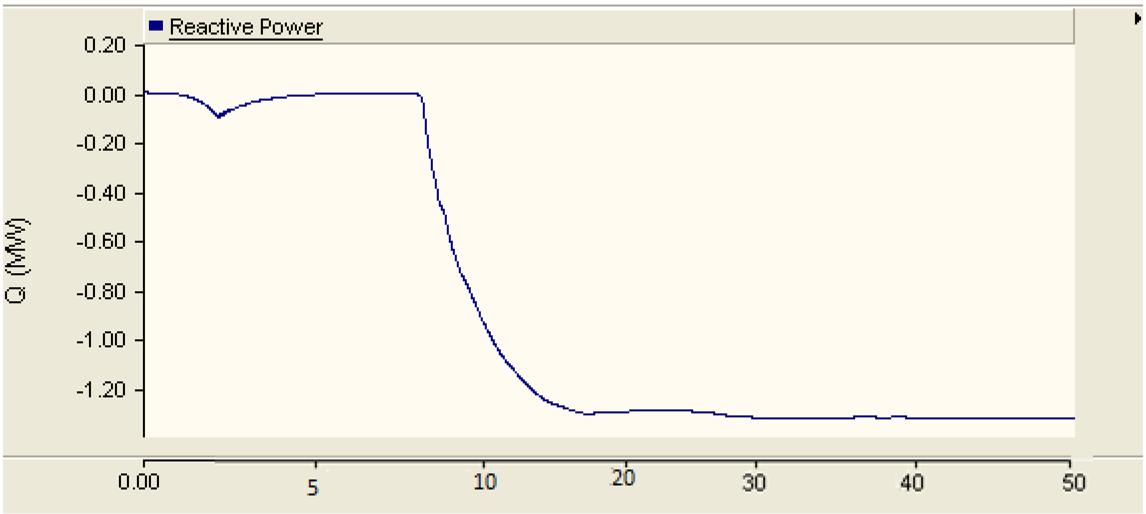


Figure 7.26: Generated reactive power with disturbance

7.6.3 Network plus WEC and STATCOM under a fault condition

The impact of WEC on a distribution network has been shown above, in order to provide a power quality measure into the network, a device like STATCOM that can generate and absorb reactive power can be installed into the network. A STATCOM is installed into the network, the parameters is in Appendix A at Table 10 and the simulation result for voltage, current, active and reactive power is depicted in Figures 7.27 to 7.34 below. The DC offset voltage and current produced in Figure7.27 and 7.29 is due to the use of a STATCOM that has an external programming input. A signal applied to this input gets amplified and produces a proportional voltage on the output terminals. The risk of severe dips and over voltage during fault and post fault is significantly mitigated by the STATCOM, and is able to keep the voltage close to 1 p.u as seen in Figure 7.28 below, the active power regains its rated capacity and becomes stable at exactly 0.12 s as compared to Figure 7.25, the compensation is effective due to the fact that STATCOM has a relative power output which is linearly proportional to the voltage. Steady state maintainability of voltages at all buses in the network after being subjected to a disturbance is achieved with the installation of STATCOM into the network. The improved active and reactive power is depicted in Figures 7.33 and 7.34, the STATCOM reference voltage is depicted the Figure 7.30, it maintained and kept the voltage to 1.0 pu, the wind speed is maintained at 14 m/s, the generator speed at 1.02 pu, and the pitch angle at 11.5 degrees (Figure 7.31 to 7.32)

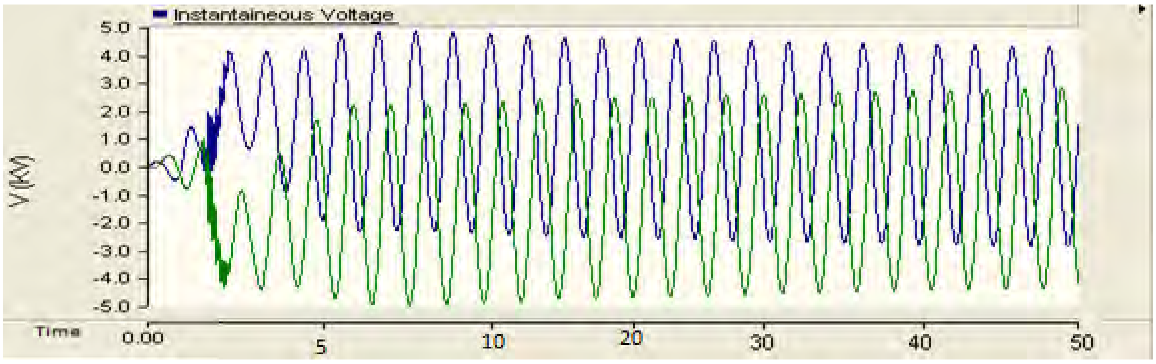


Figure 7.27: Grid voltage during fault with WEC and STATCOM

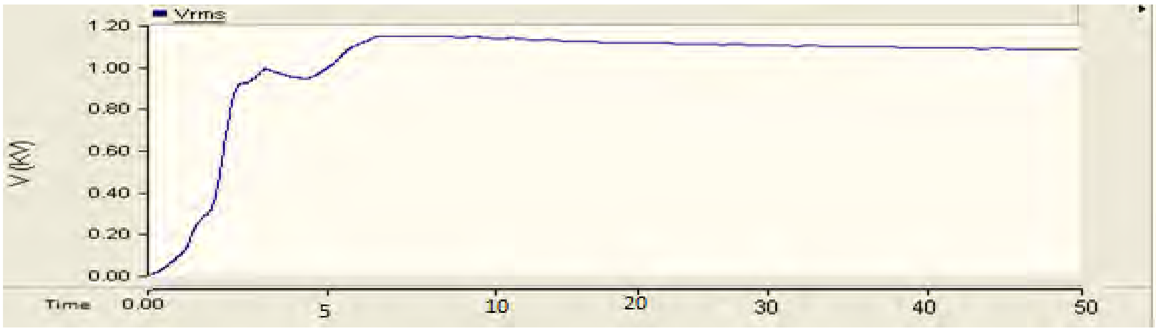


Figure 2.28: Grid RMS voltages during fault with WEC and STATCOM

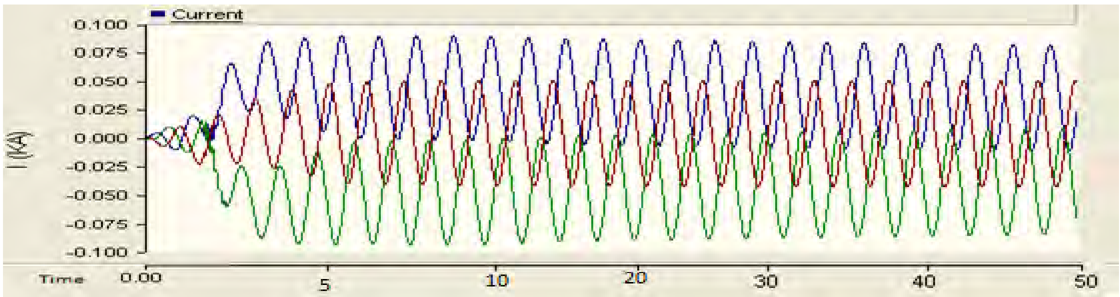


Figure 7.29: Grid current during fault with WEC and STATCOM

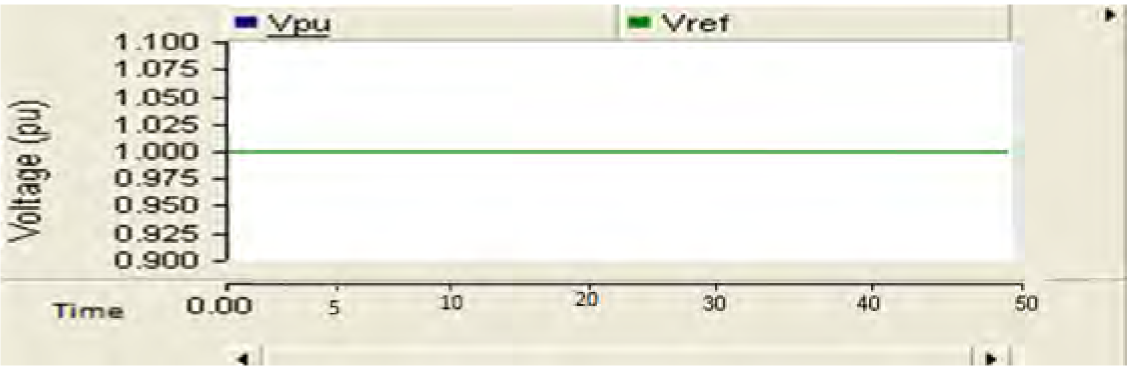


Figure 7.30: STATCOM reference voltage during fault

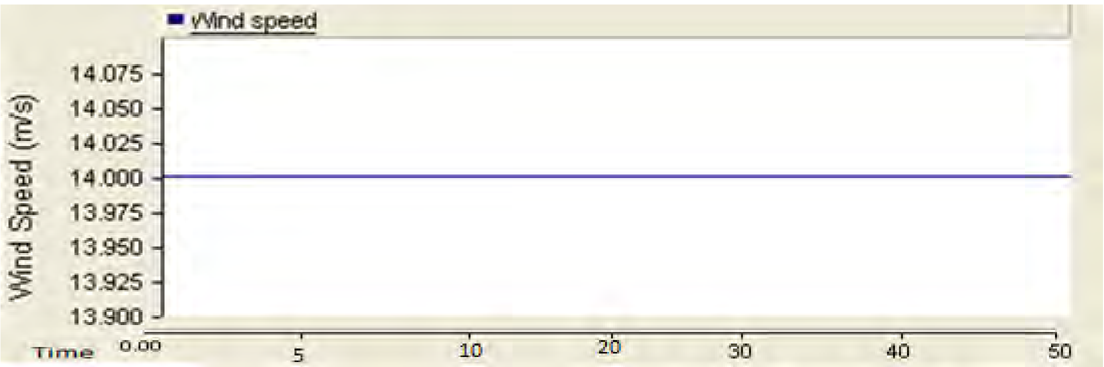


Figure 7.31: Wind speed

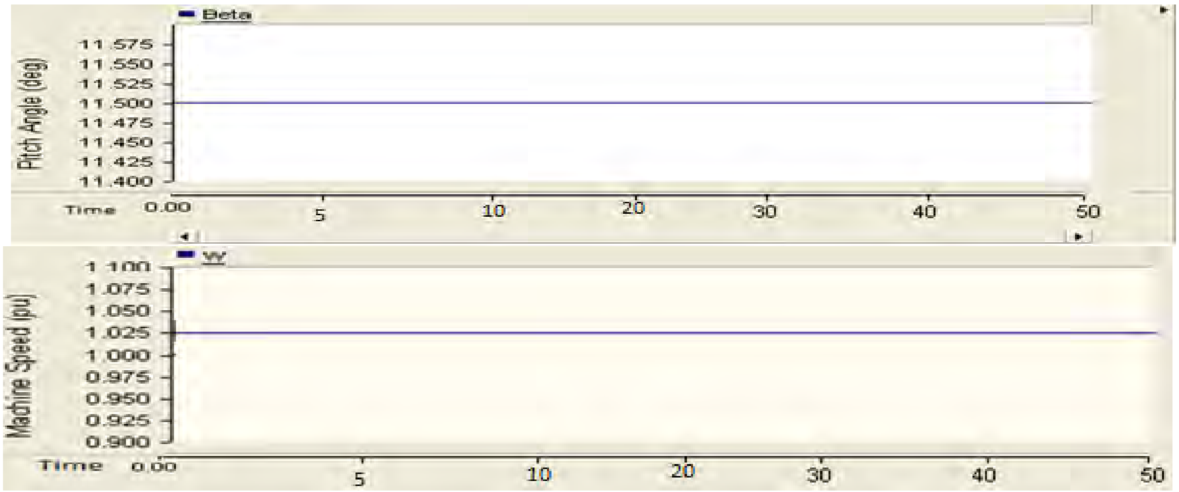


Figure 7.32: Pitch angle and Machine speed

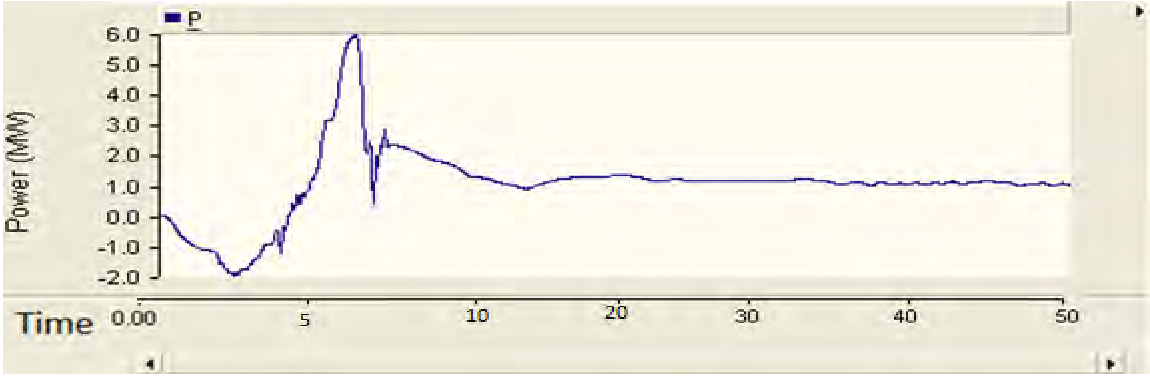


Figure 7.33: Generated active power during fault and with STATCOM

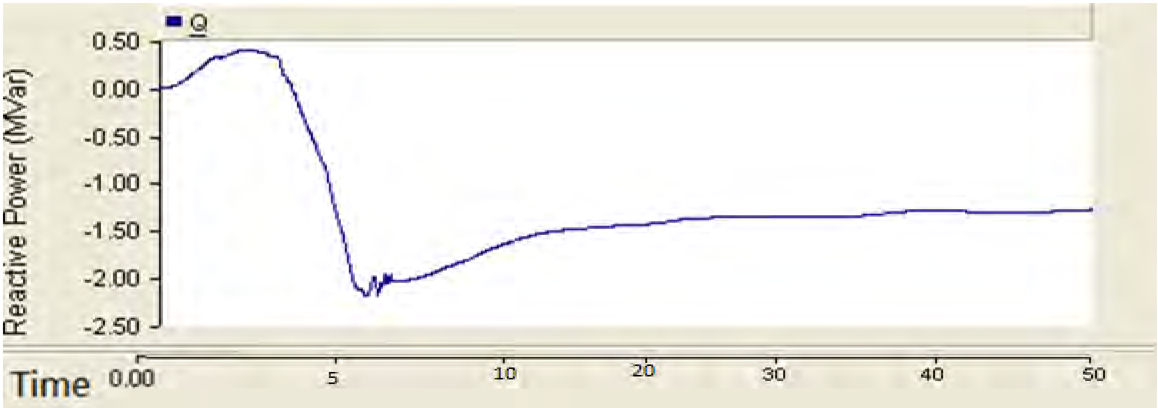


Figure 7.34: Generated reactive power during fault and with STATCOM

Summary

The presences of distributed generation have both positive and negative impacts on a distribution network which has been shown, among are the reduction in the voltage dips, voltage profile improvement, , instability in grid voltage during a disturbance and reduction in generator terminal voltage. The voltage at the generator terminal, generated power and the grid voltage are being controlled successfully by controlling the reactive power through the FACTS device installed into the network.

7.7 Simulation results comparison between MATLAB/SIMULINK and PSCAD/EMTDC

Introduction

WEC modelling and simulation results using MATLAB/SIMULINK and PSCAD/EMTDC have been investigated in above sections, different scenario cases were examined to investigate the impacts of WEC integration into the distribution network. In this section, comparison between the results of the software used shall be discussed.

7.7.1 Comparison of the simulation results obtained using MATLAB/SIMULINK and PSCAD/EMTDC

The similarities and differences in simulation results obtained in MATLAB/SIMULINK and PSCAD/EMTDC are analysed in Tables 7.1 and 7.2 below. It can be observed in Table 7.1 that the connection of WEC to a distribution network can improve the voltage profiles which are confirmed by both packages. It shows that connection of WEC to a distribution network can reduce voltage dip compared to a network that has no DG integration. It also shows that installing compensation device to a network that contains DG integration can further improve voltage dip and network stability than when it is only DG in the system. It can be observed in Table 7.2 that both packages show some differences which may be due to the initialization methods in both packages which are not exactly the same, PSCAD model needs more simulation time than the MATLAB i.e., MATLAB faster than PSCAD. The voltage stability is quickly achieved in PSCAD packages, the details are shown in Table 7.2

Table 7.1: Similarities

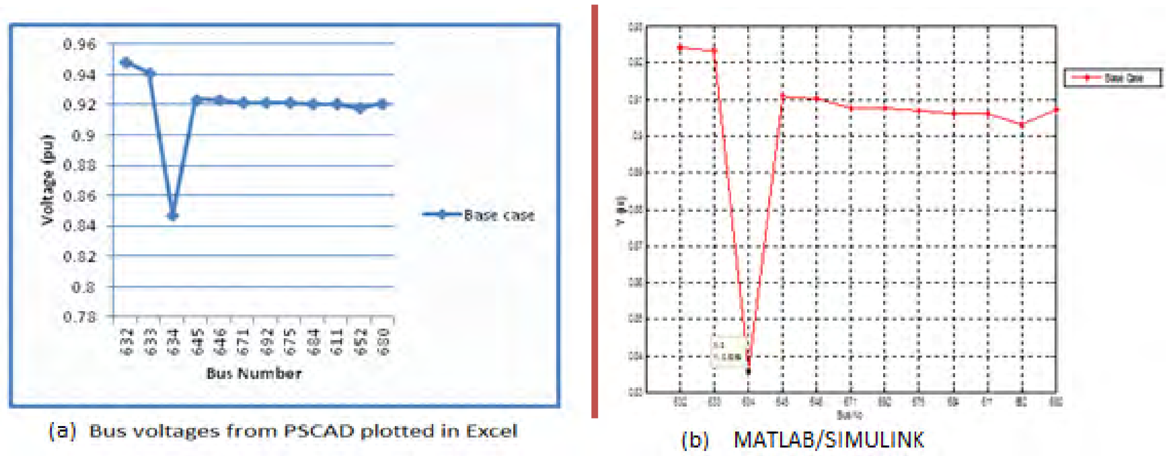
		MATLAB/SIMULINK	PSCAD/EMTDC
1.	Voltage profile Figure 7.36	improve	improve
2.	Voltage rise at bus 634 and in Figure 7.37	Occurs when WEC penetration level greater than 7 %	Occurs when WEC penetration level greater than 7 %
3.	Steady state power in Figure 7.38	Smooth increase	Smooth increase
4.	Zero voltage during the duration of fault without WEC in Figure 7.41	Zero voltage during fault conditions	Zero voltage during fault conditions
5.	Voltage dip at farthest bus in Figure 7.42	Voltage did not reduced to zero at the farthest bus	Voltage did not reduced to zero at the farthest bus
6.	Voltage dip reduction with fault and WEC in Figure 7.43	There is reduction in voltage dip	There is reduction in voltage dip
7.	Stability with STATCOM	Voltage stability improved	improved

Table 7.2: Differences

		MATLAB/SIMULINK	PSCAD/EMTDC
1.	Voltage drop in Figure 7.35 and Table 7.3	There is more voltage drops as reflected in MATLAB. The weakest bus is16.41 % drop, but converge faster than PSCAD with WEC integration	There is less voltage drops. The weakest bus is 15.28 %. but converge slower with WEC integration
2.	Voltage rise Figure 7.37	With 7 % WEC penetration level, voltage rise occurred at bus 634	With 14 % WEC penetration level, voltage rise occurred at bus 634
3.	Point of common coupling in Table 7.3	There is significance voltage increase more than PSCAD package with difference WEC penetration levels	There is significance voltage increase less than MATLAB/SIMULINK package with difference WEC penetration levels
4.	Active and reactive power in Figures 7.38 and 7.39	At 0.05s in MATLAB/SIMULINK simulation, the active power has reached its rated value	In PSCAD simulation, the active power did not reach its rated value until 0.2s
5.	swing or oscillation in Figure 7.40	There is indication of swing or oscillation with WEC integration in 0.02s in the MATLAB/SIMULINK package and the generated voltage could not maintain its stability until 0.45s	the traces of voltage swing or oscillation is not noticed with PSACD and the voltage reached stability at 0.12s
6.	Transient analysis in Figure 7.41	The dips created as a result of a grid fault is not as severe as that of PSCAD and after the fault is cleared, the voltage swings or oscillates (fast fluctuation), it cannot maintain its stability throughout	Grid disturbance create more voltage dips in the PSCAD than in MATLAB, after the fault is cleared, little over voltage occurred for like 0.03s, then network stability is quickly achieved in the PSCAD package after some seconds
7.	Voltage stability in Figure 7.43 and 7.44	Voltage stability is less achieved in MATLAB/SIMULINK	Voltage stability is quickly established in PSCAD package than MATLAB/SIMULINK
8	Pitch angle in Figure 7.44	The pitch angle could not stable until 0.45 s at 20^0	The pitch angle is maintained at 11.5^0 from the start of the simulation.

Table 7.3: WEC penetration analysis in MATLAB and PSCAD

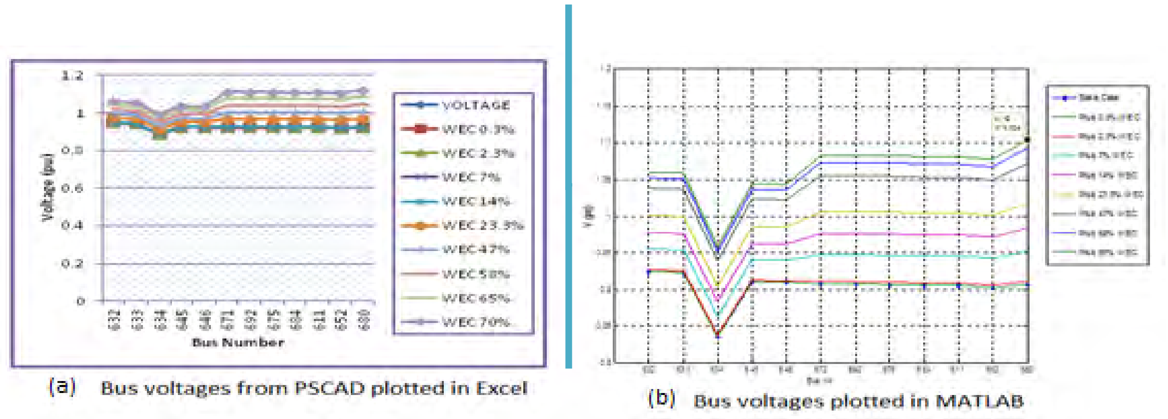
Bus No	Base Voltage	WEC 0.3 %	WEC 2.3 %	WEC 7 %	WEC 14 %	WEC 23.3 %	WEC 47 %	WEC 58 %	WEC 65 %	WEC 70 %
MATLAB BUS 652	0.9030	0.9030	0.9067	0.9482	0.9806	1.0144	1.0689	1.0889	1.101	1.1078
PSCAD 652	0.918	0.918	0.9188	0.9197	0.9199	0.9647	0.9936	1.0321	1.0503	1.0611
MATLAB 680	0.9071	0.9072	0.9111	0.9517	0.9844	1.0177	1.0721	1.0929	1.1041	-
PSCAD 680	0.9211	0.9213	0.9226	0.9242	0.9253	0.9698	1.0062	1.0454	1.0876	1.1214



(a) Bus voltages from PSCAD plotted in Excel

(b) MATLAB/SIMULINK

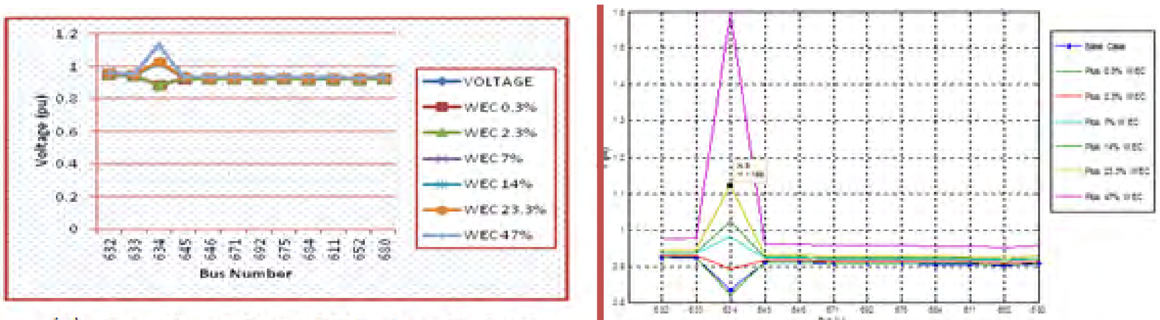
Figure 7.35: Base case voltage profiles



(a) Bus voltages from PSCAD plotted in Excel

(b) Bus voltages plotted in MATLAB

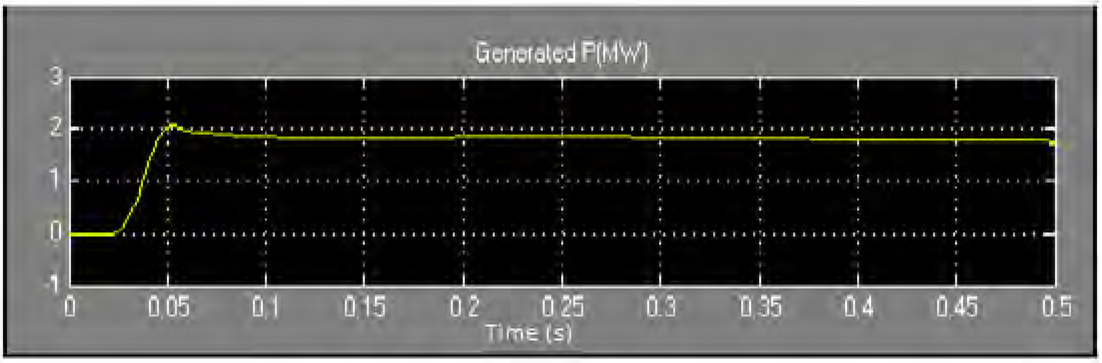
Figure 7.36: Voltage profiles improvement with WEC integration in MATLAB/SIMULINK and PSCAD



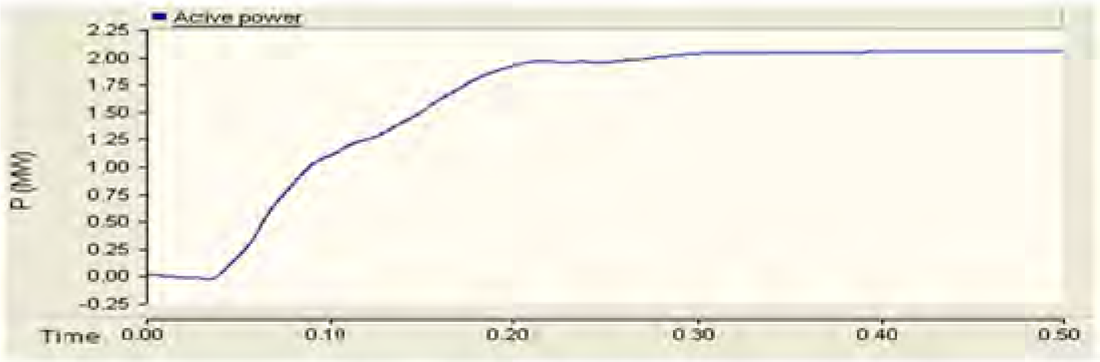
(a) Bus voltages from PSCAD plotted in Excel

(b) Bus voltages plotted in MATLAB

Figure 7.37: Voltage profiles of bus 634 in PSCAD and MATLAB

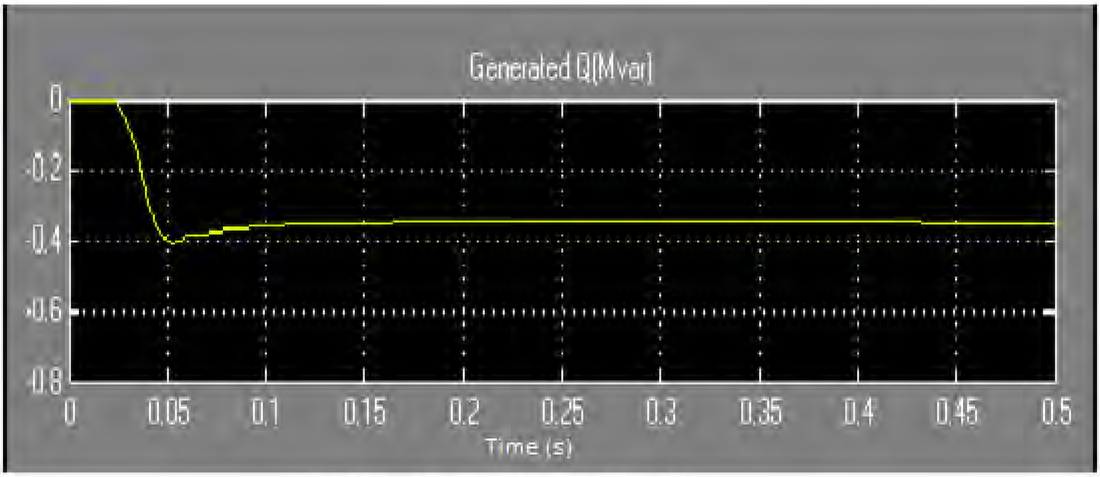


(a) Bus voltages plotted in MATLAB

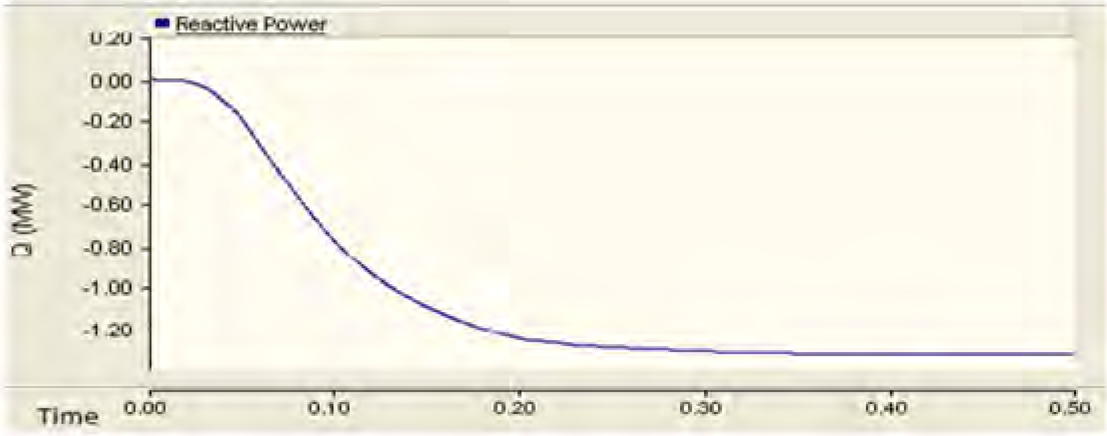


(b) Bus voltages from PSCAD

Figure 7.38: Active powers in PSCAD and MATLAB/SIMULINK

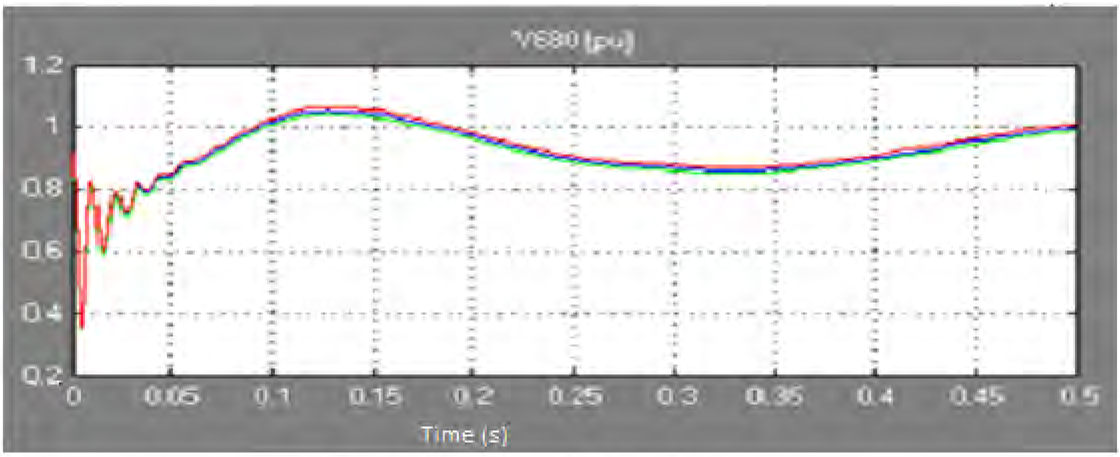


(a) Bus voltages plotted in MATLAB

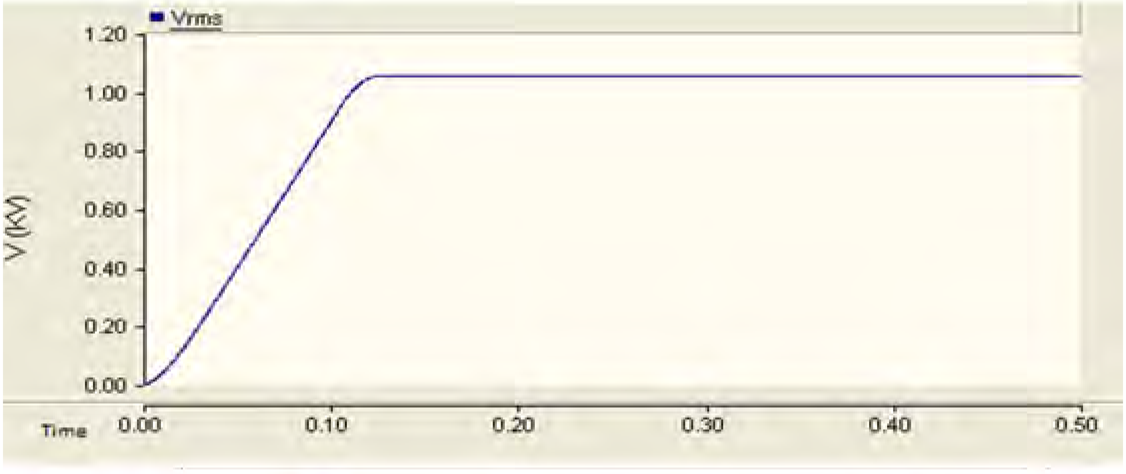


(b) Bus voltages from PSCAD

Figure 7.39: Reactive powers in MATLAB/SIMULINK and PSCAD

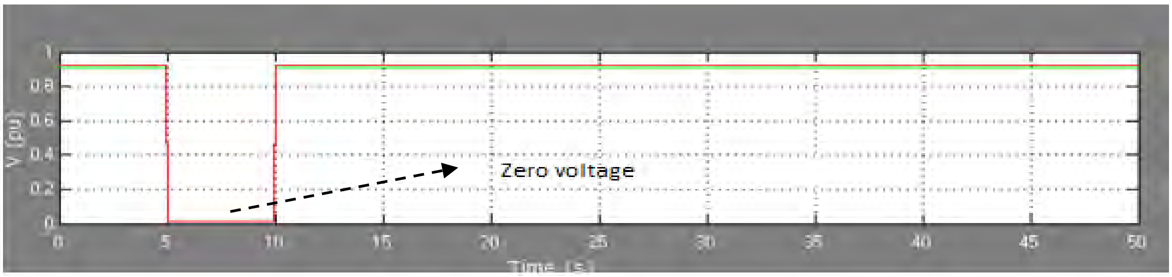


(a) Bus voltages plotted in MATLAB

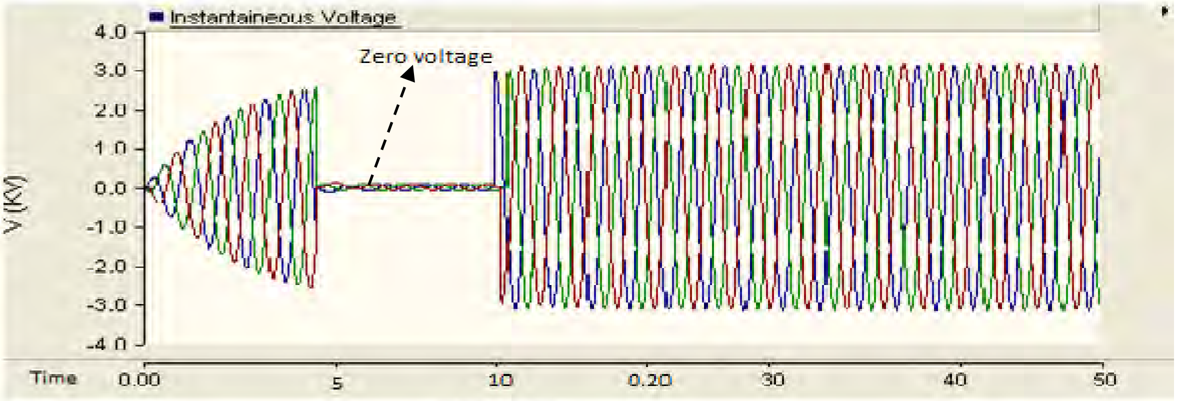


(b) Bus voltages from PSCAD

Figure 7.40: Voltages with WEC integration in MATLAB/SIMULINK and PSCAD

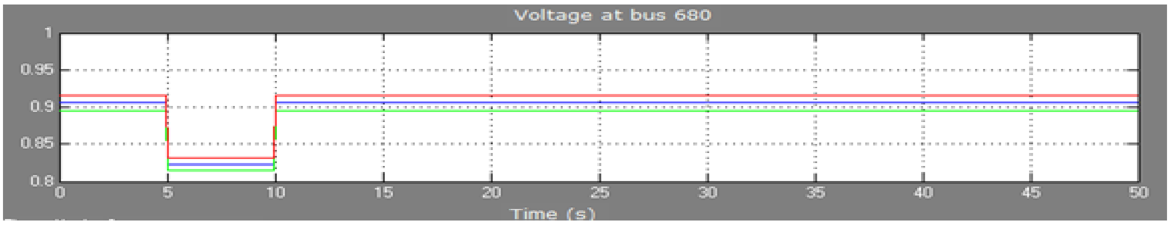


(a) MATLAB/SIMULINK

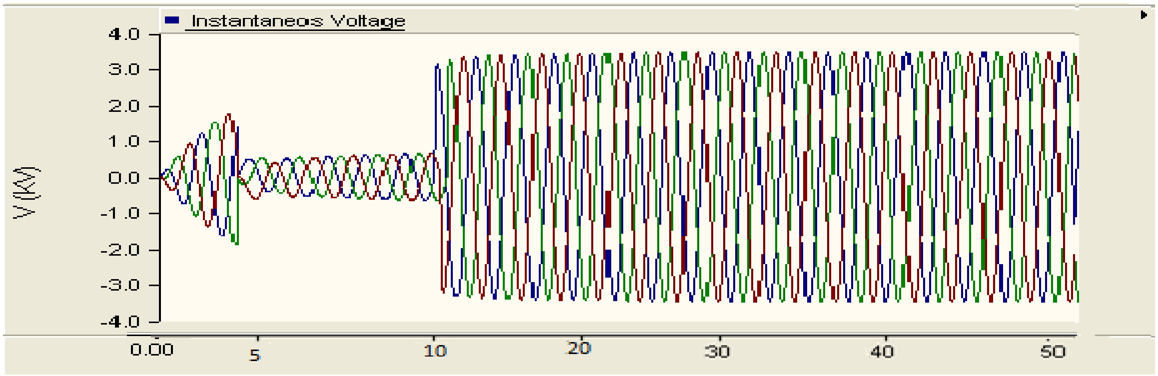


(b) PSCAD

Figure 7.41: Zero voltage at bus 634 where the three-phase fault to earth without WEC integration

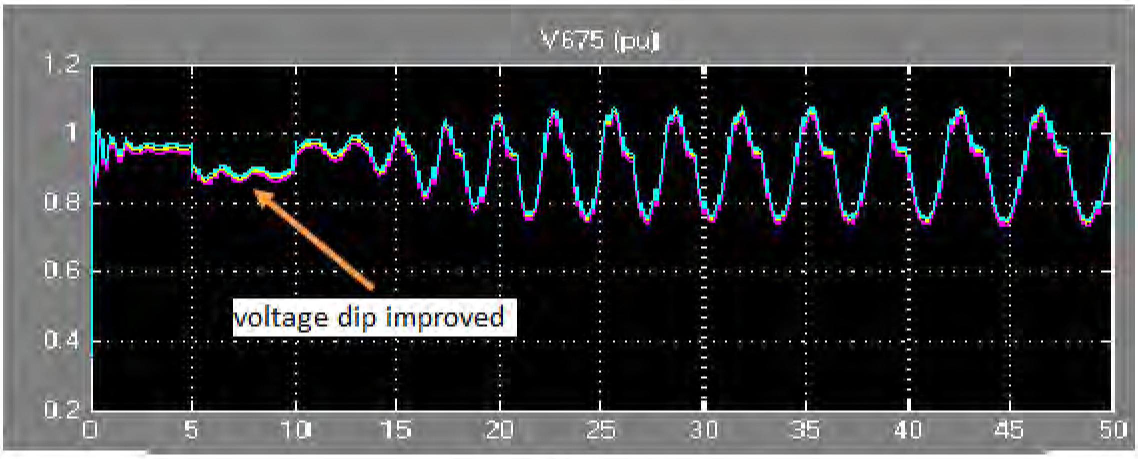


(a) MATLAB/SIMULINK

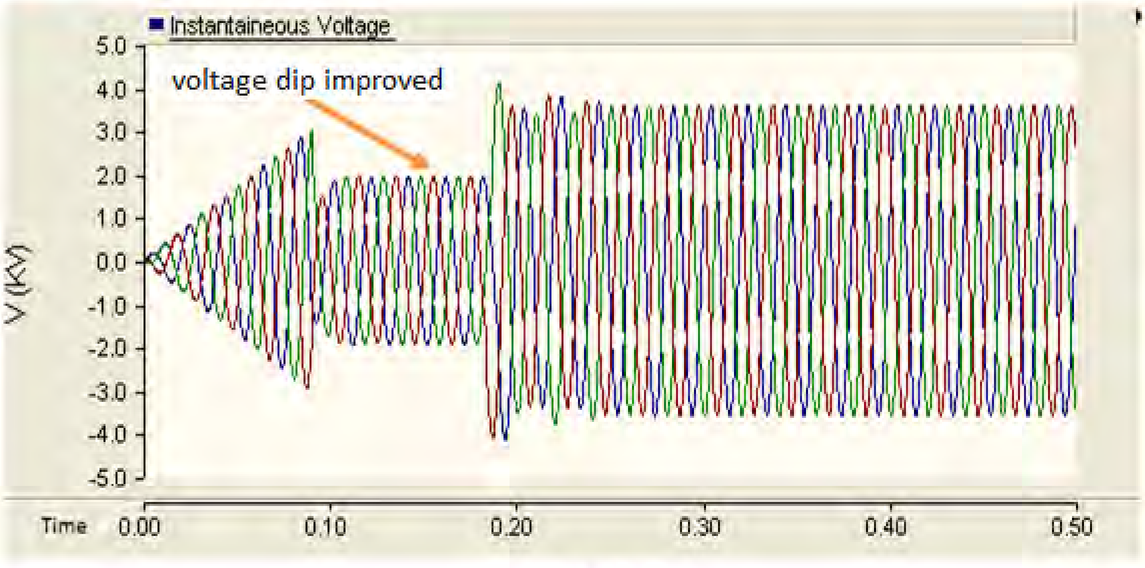


(b) PSCAD

Figure 7.42: Voltage dip at the farthest bus (bus 680) where the three-phase fault to earth without WEC integration

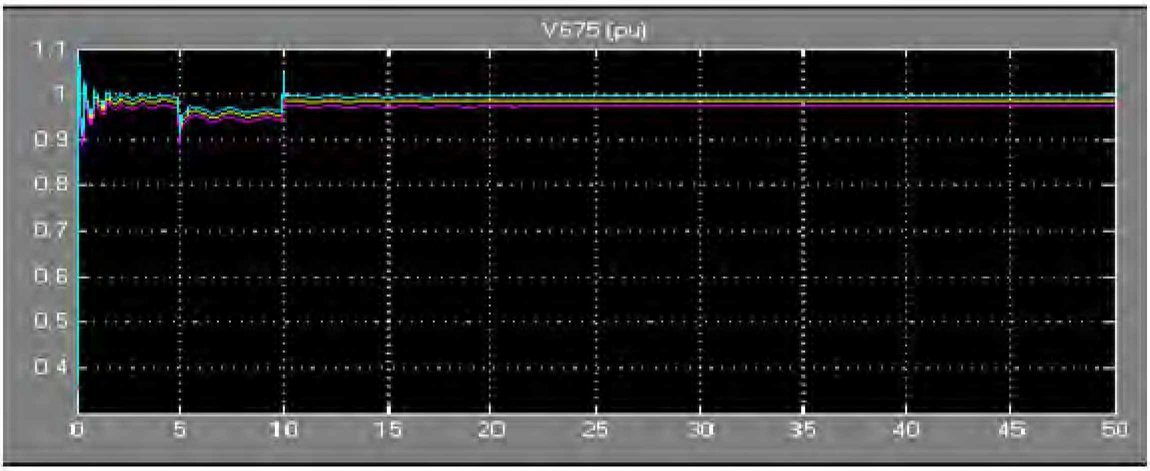


(a) MATLAB/SIMULINK

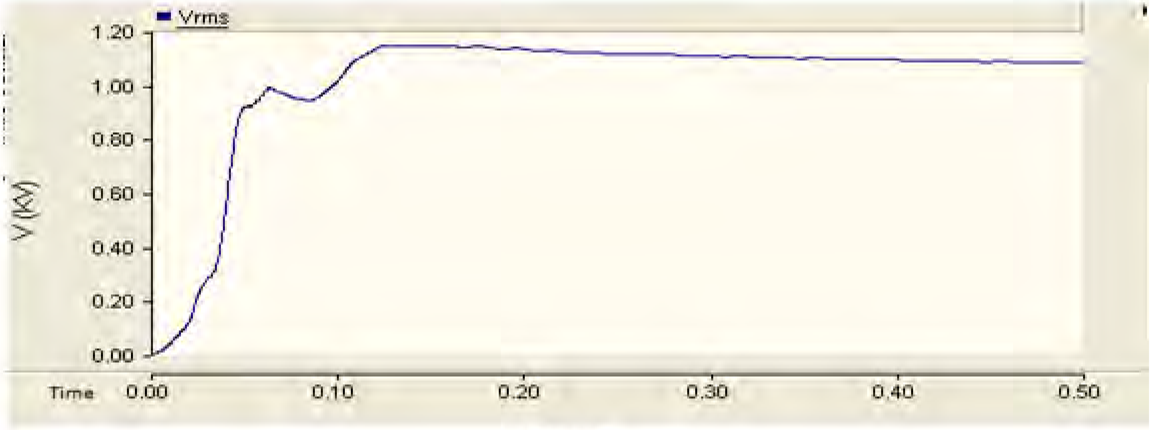


(b) PSCAD

Figure 7.43: Voltage dips improvement during fault conditions in MATLAB and PSCAD with WEC integration

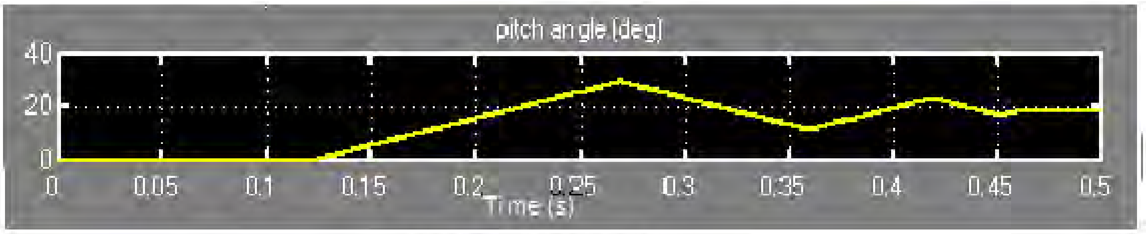


(a) MATLAB/SIMULINK

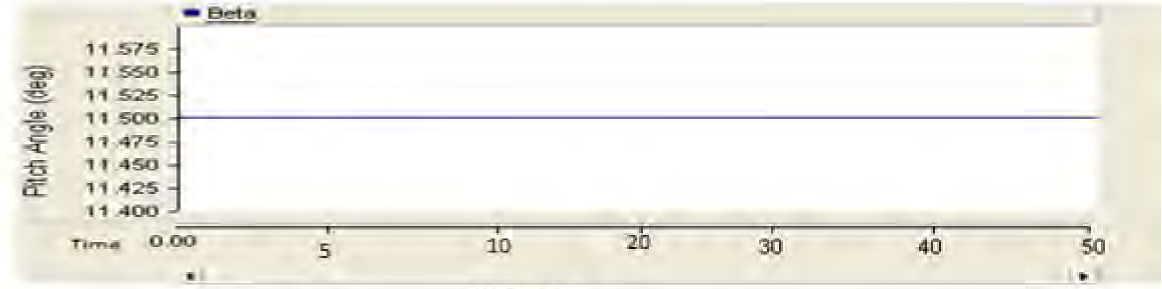


(b) PSCAD

Figure 7.44: Voltage profiles with compensation



(a) MATLAB/SIMULINK



(b) PSCAD

Figure 7.44: Pitch angle

Table 7.4: Comparison of a distribution network with and without WEC integration impacts

S/N	Distribution network without WEC integration	Distribution network with WEC integration
1	Low voltage profiles	Improved voltage profiles
2	No fear of over voltage/voltage rise	There is the fear of over voltage/voltage rise
3	Possible increase in the risk of overloading	Decrease in the risk of overloading
4	Increase in the dips due to grid disturbances	Decrease in the dips due to a fault
5	Weak network	Active network
6	Voltage flow in one direction	Voltage in either direction depends on the location
7	Non-linear load generates harmonics	Load and WEC e.g., Power electronic converter generates harmonics
8	Increase in losses, i.e., longer transmission of power to remote locations	Reduction in losses, i.e., close to the load

Summary

Simulation cases of WEC with the DFIG models implemented in MATLAB and PSCAD have been presented, the impacts of the implementing WEC models are very similar under the voltage profile and the differences between the transient state responses are smalls, the impacts of the WEC implemented DFIG models are very similar under the voltage dip and the differences between the transient state responses are not very significant.
WEC models are very similar both in PSCAD and MATLAB during the steady state, but they present little differences in the start-up period, since the MATLAB presents more oscillations than the PSCAD one. This is due to the

initialization methods in both package models are not exactly the same, the models and solvers in both packages are quite differ to each other.

The WEC models are quite similar both in steady and in transient states. The PSCAD model needs more simulation time than the MATLAB one, since in these WEC integrations, simulation cases, MATLAB model take around ten times less than the PSCAD model e.g., MATLAB is faster than PSCAD. Also there is a difference in the pitch angle i.e., that of PSCAD is stable at 11.5^0 while MATLAB/SIMULINK is not stable until 0.45 s at 20^0.

Chapter 8

Impacts of WEC on harmonic injection, voltage flicker and dip

Introduction

Voltage waveform magnitude distortion caused by the sinusoidal current demand of the nonlinear loads is a function of the source impedance. Source impedance is not an easily defined value in the case of a DG set because generator reactance varies with time, following sudden load changes. Generator subtransient reactance (X_d'') and subtransient short circuit time constant (T_d'') are primary parameters influencing distortion during the short SCR commutation periods. A standby generator is characteristically of higher impedance than transformers. A substantial difference in kVA rating of the two sources often leads to greater impedance differences. Utility transformers are often rated to take the total plant load while most of the time, DGs are often used to carry emergency or critical loads. Thus, DG may have 5 to 100 times greater subtransient reactance than normal source transformers. Consequently, non-linear loads may work fine on utility, but may react entirely different when powered by a DG. Using an oversized generator to reduce reactance may be of some benefit. Nevertheless, to get a significant reduction in reactance is not economically viable. There are many forms of voltage harmonics created in the systems with non-linear loads - harmonic currents demanded by the non-linear loads flowing through various system impedances thereby distorting the bus voltages upstream, voltage clamping, voltage notching and ringing type of voltage-source distortions at the converter input terminals [227]. The closer a particular bus is to a converter bus, the greater the effect of voltage clamping and notching, the net effect of non-linear loads is harmonic current and voltage that flow all the time.

8.1 Impact of WEC on harmonic generation with connection of non-linear load

8.1.1 Harmonic generation without WEC

When a 12 pulse converter and non-linear loads were connected to the network, the converter and load parameters are depicted in Table A3 at the Appendix A, the system is simulated without WEC integration and the results are depicted in Figures below, Figure 8.1 shows the network no-load voltage when a converter has not been connected into the system, there is zero current because no-loads are connected into the network. When the converter is connected with non linear loads in the network, Figure 8.2 shows the simulation results, it can be observed that the harmonic voltage and current wave forms are generated from the non-linear loads, and the converter side; thus, the grid voltage is affected. When the fast fourier transform (FFT) is selected from the FFT tool of the powergui from the MATLAB/SIMULINK to plot the harmonic analysis of the system, it is found that the total harmonic generated in the network is 7.66 % for the three phases as depicted in the figures 8.3 to 8.5 below which is very high and cannot be acceptable for a distribution network, it is against the IEEE standard and requirements for harmonic generation for distribution network which is stated in Table 8.1 below [**228**].

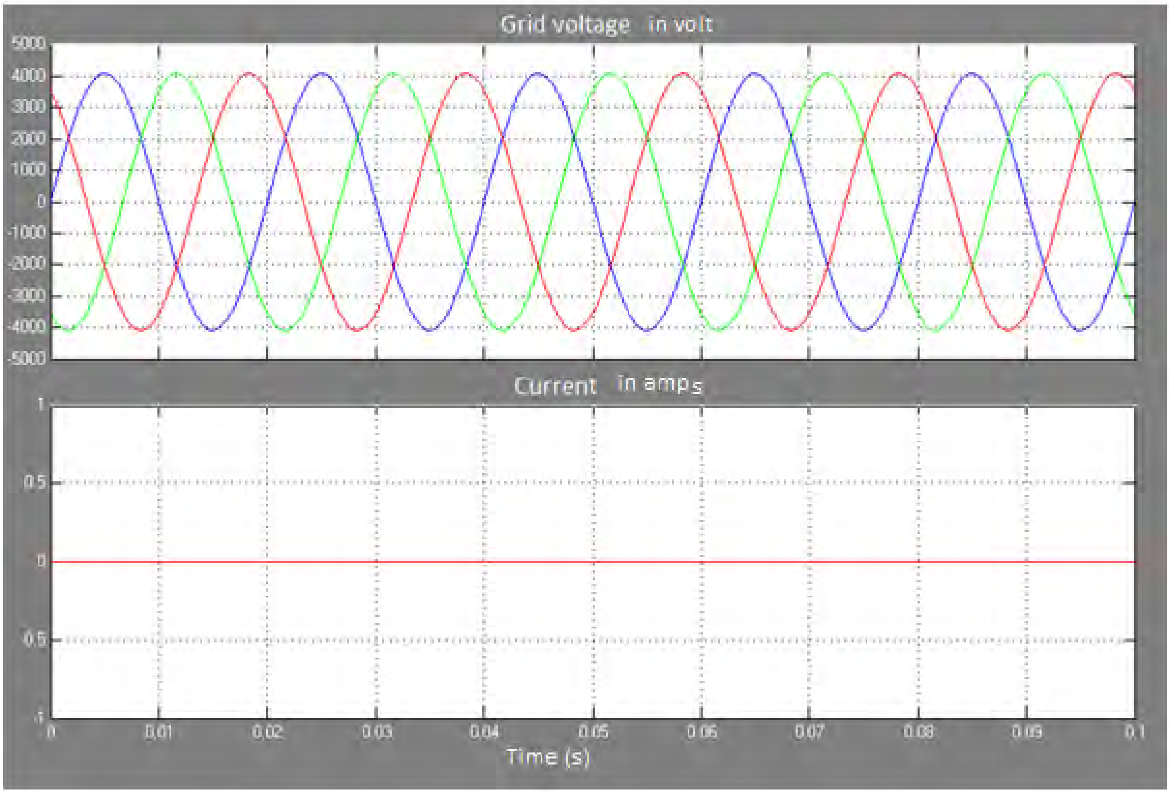


Figure 8.1: Network no-load voltage without converter

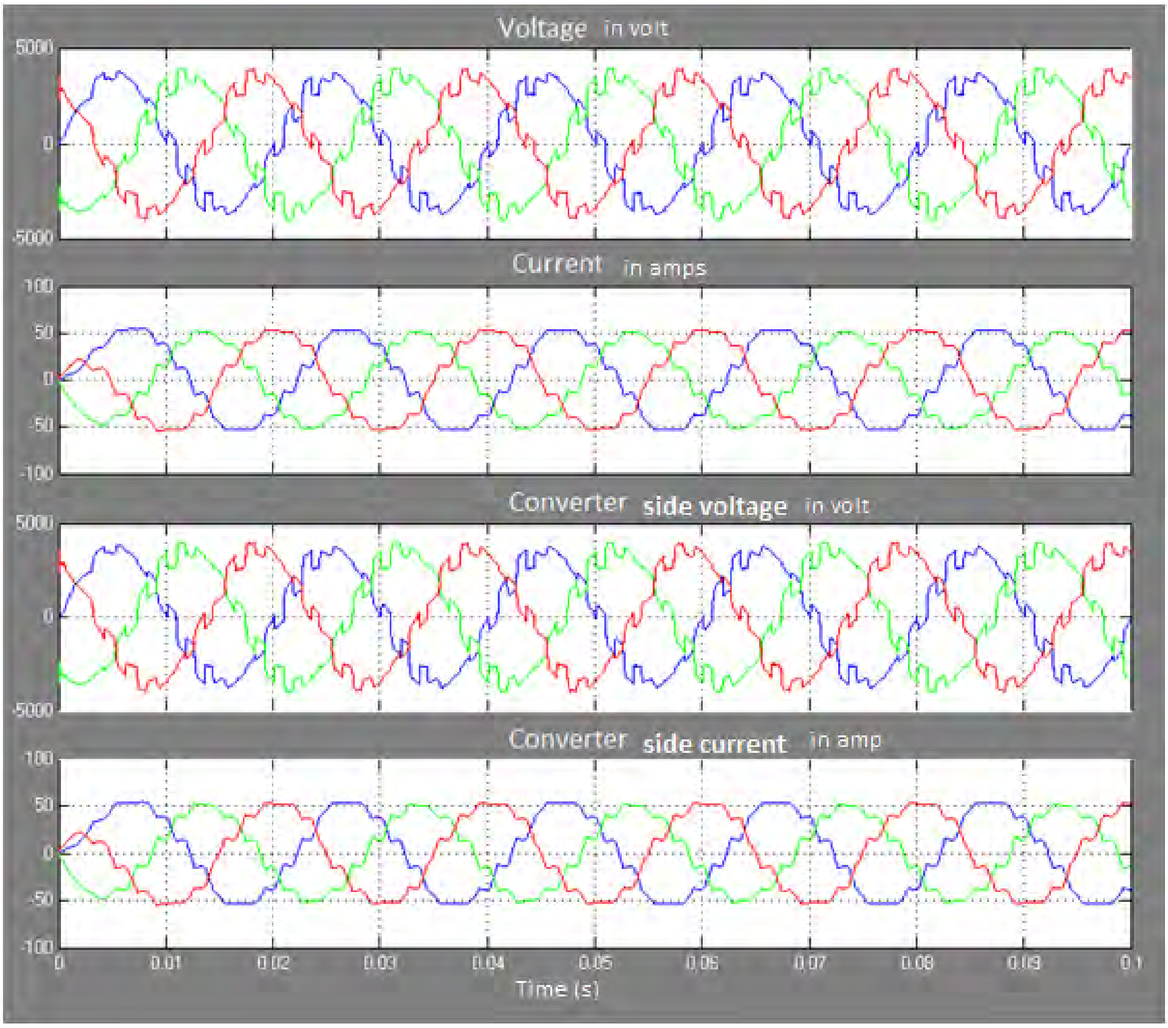


Figure 8.2: Network voltages, currents, with converter and nonlinear loads

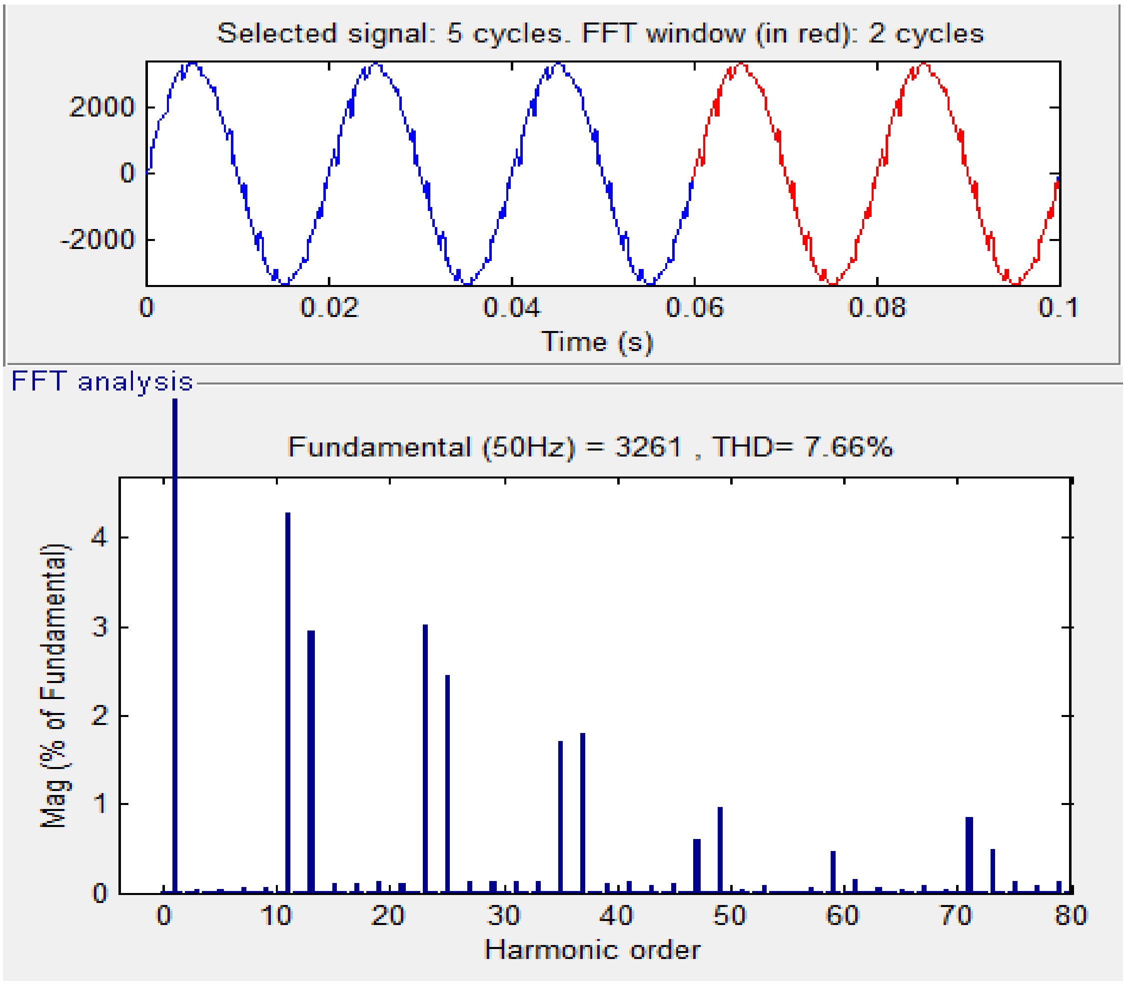


Figure 8.3: Harmonic wave and total harmonic distortion for first phase

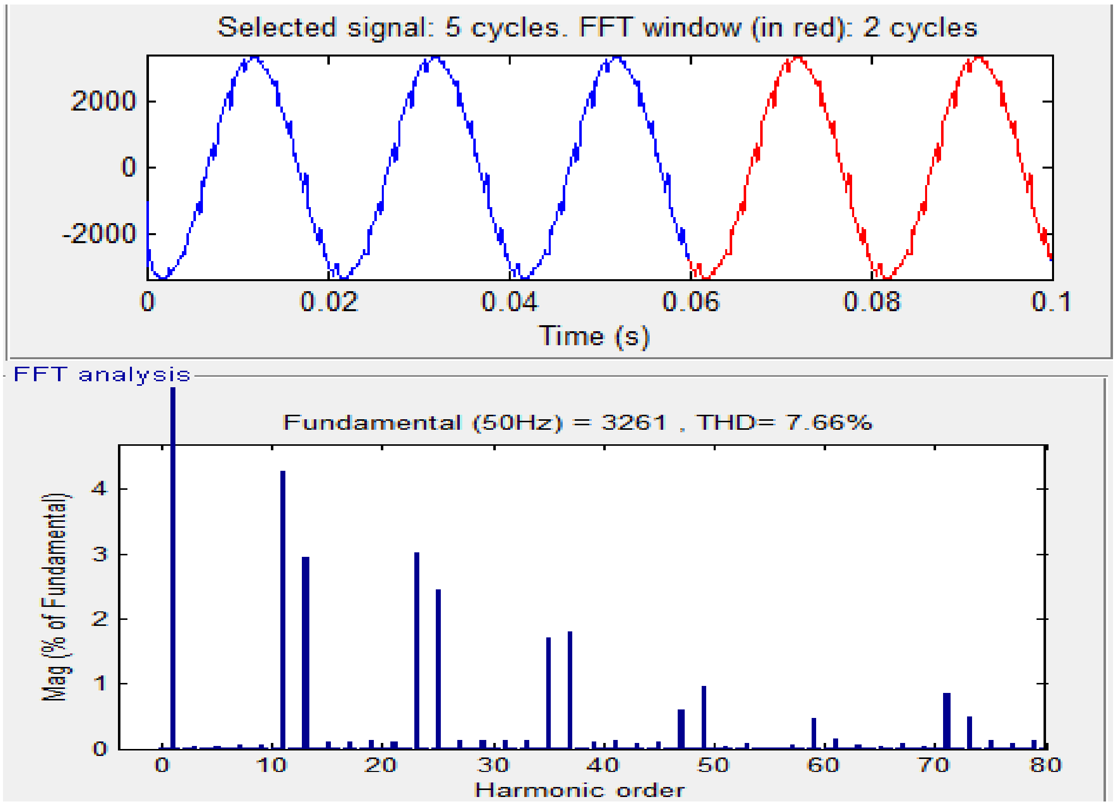


Figure 8.4: Harmonic wave and total harmonic distortion for second Phase

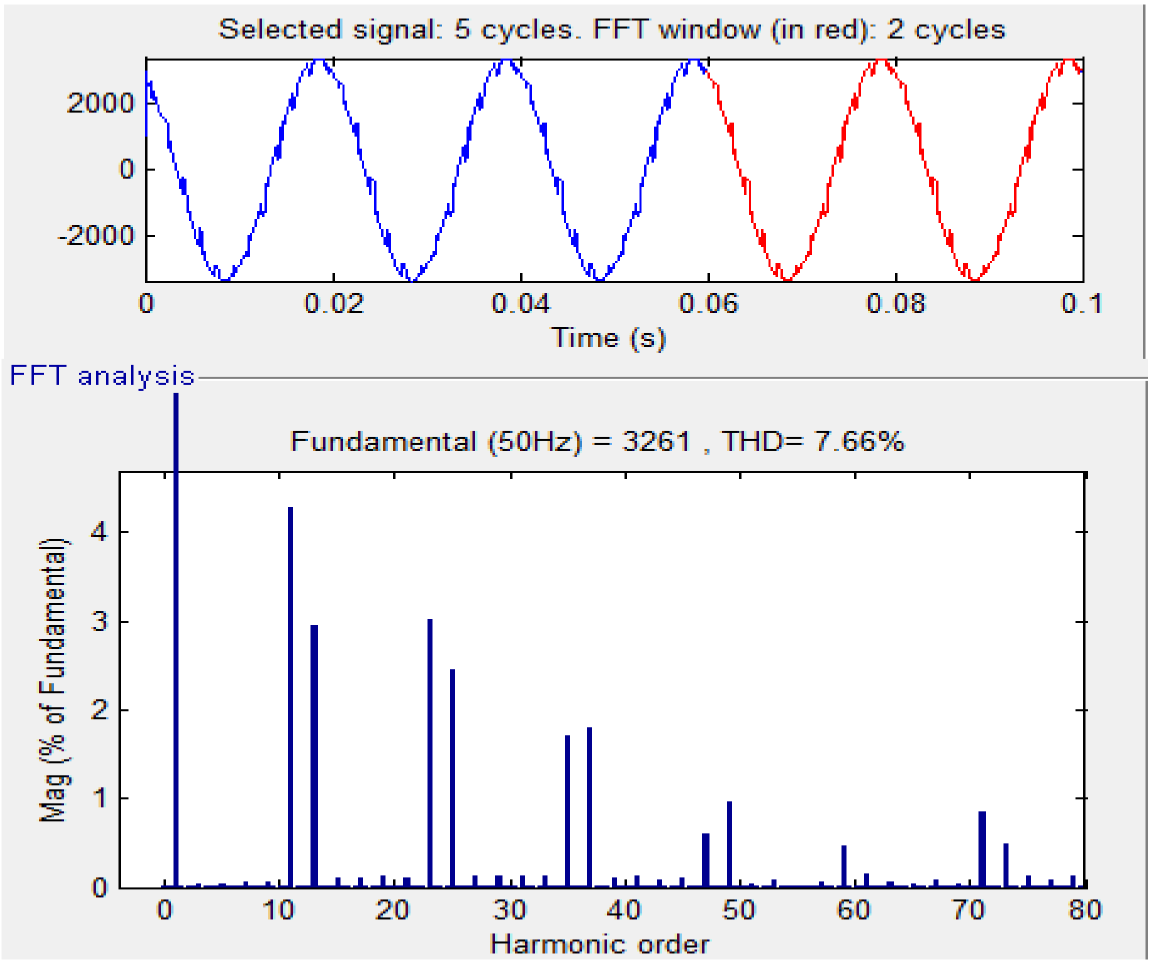


Figure 8.5: Harmonic wave and total harmonic distortion for third phase

Table 8.1: voltage distortion limits from IEEE 519

Bus voltage at POCC	Individual voltage distortion (%)	Total voltage distortion THD (%)
Below 69KV	3	5
69KV to 137.9KV	1.5	2.5
138KV and above	1	1.5
High voltage systems can have up to 2 % THD where the cause is a high voltage DC terminal which will attenuate by the time it is tapped for a user		

8.1.2 Impact of WEC on harmonic

Having shown successfully in the section above that power electronic converter and nonlinear loads can generate harmonic voltage and current when they are connected to a distribution network. In this section, the impact of WEC (DFIG) on harmonic generation shall be investigated. When a DFIG is connected into the network at the point of common coupling, the network parameters can be found in Table A3 in the Appendix A. The simulation process is repeated and the results are shown in the figures below. It can be observed that harmonic voltage, current and wave form increased with the connection of WEC in the network, which means that WEC contributes to the harmonic generation in the network with power electronic converter at the point of common coupling and nonlinear loads are connected as shown in Figure 8.6, figure 8.7 depicted the bus at which the DFIG is connected, while figures 8.8 to 8.10 show the total harmonics generation in the network when WEC is connected to the network, the harmonic increased from 7.66% to 9.97% for the first and second phases and 7.66% to 9.93% for the third phase as analysed by the FFT tool in the Powergui. This is because DFIG consists of converters as already discussed in the section 3.12 of this dissertation, which give rise to the increase in the harmonic generation in the system. The introduction of full power electronic converters (power electronic based DG) into a distribution network can create or increase harmonic generation in the system which is not suitable, it can cause such effects as increased transformer, capacitor, motor or generator heating, mis-operation of electronic equipment which relies on voltage zero crossing detection or is sensitive to wave shape, incorrect readings on meters, mis-operation of protective relays, interference with telephone circuits, etc. The likelihood of such ill effects occurring is greatly increased if a resonant condition occurs. Resonance occurs when a harmonic frequency produced by a non-linear load closely coincides with a power system natural frequency [**229**]**,** [**230**]. There is a need to mitigate these harmonic current and voltage in the distribution network. The next section gives details of the mitigation.

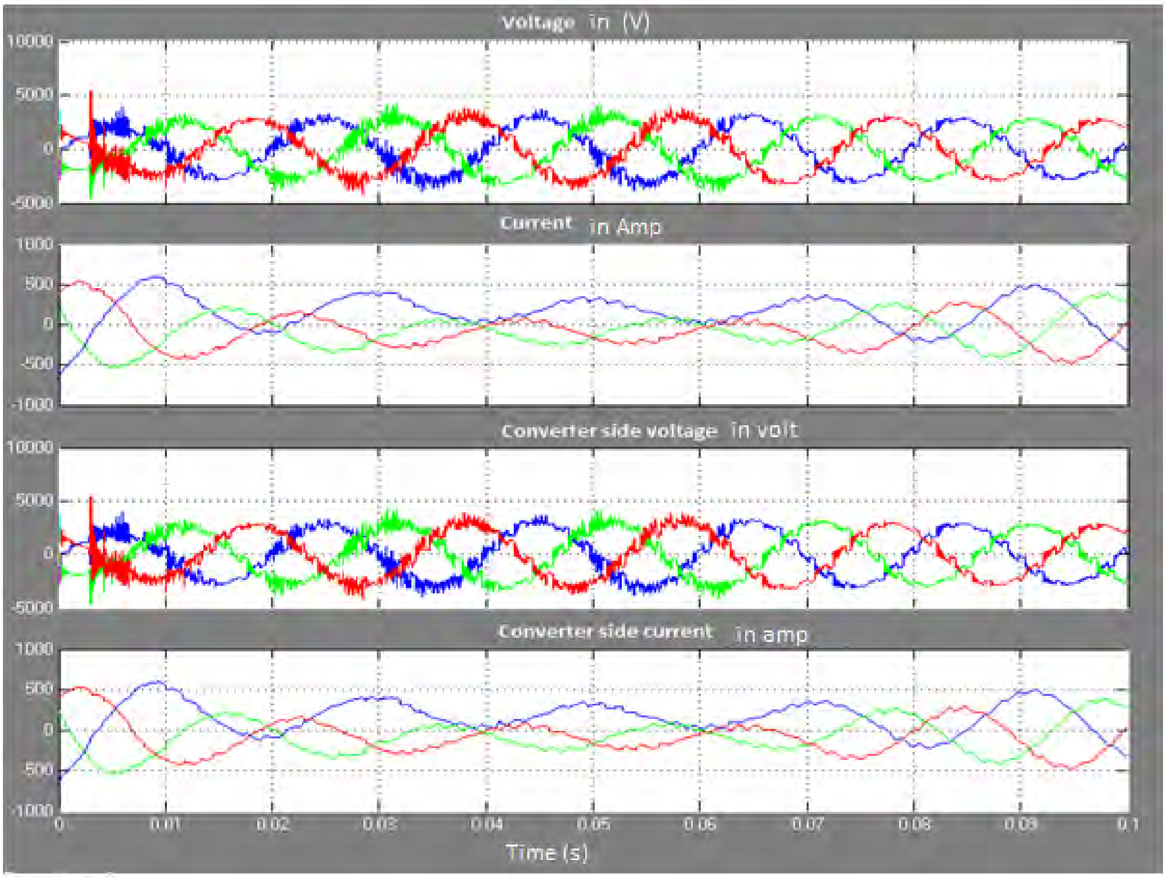


Figure 8.6: Grid voltage and current with WEC integration

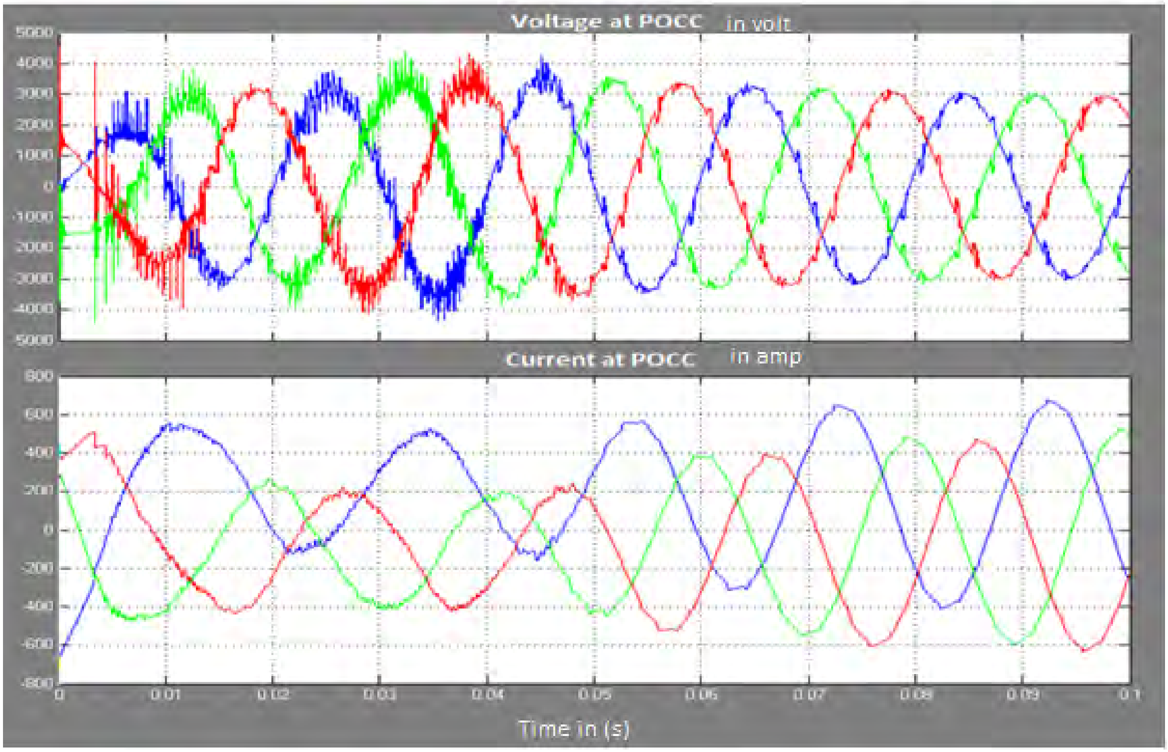


Figure 8.7: Voltage and current at the POCC

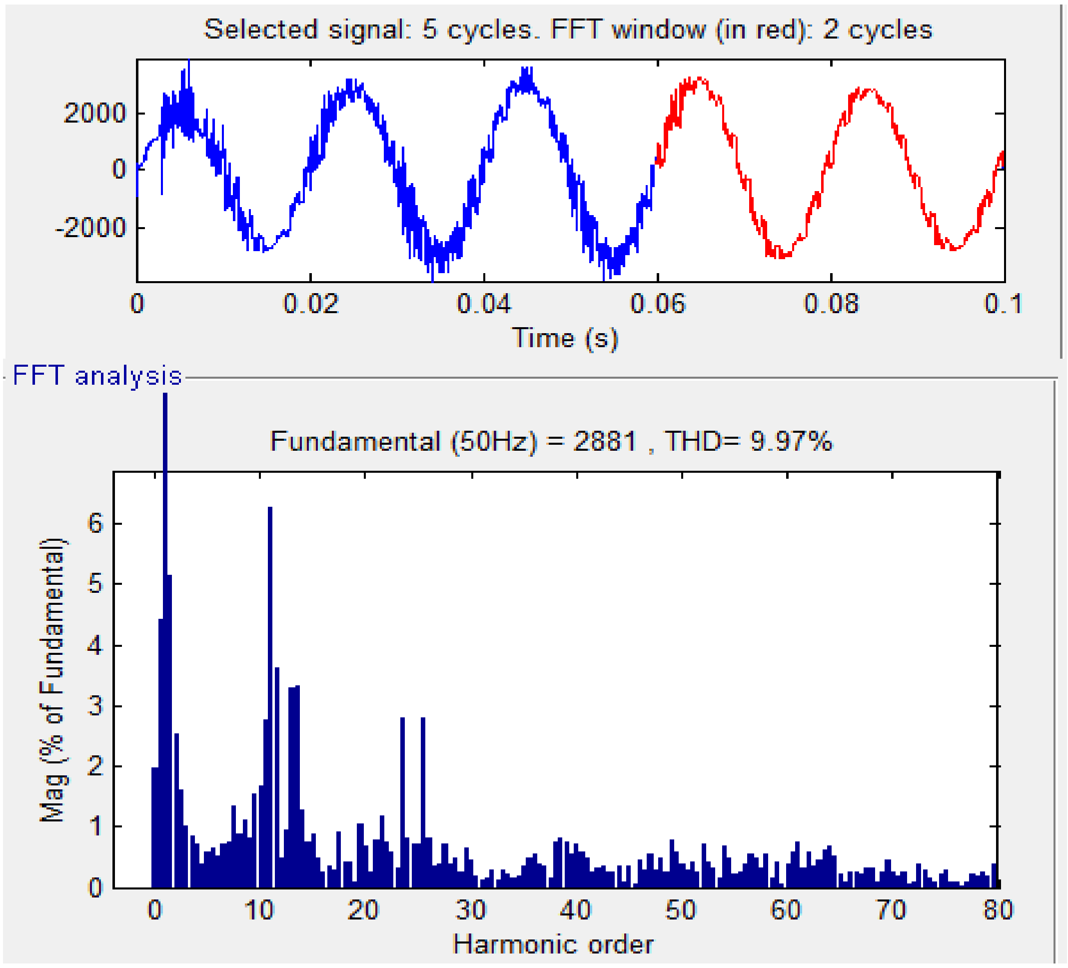


Figure 8.8: Harmonic wave and total harmonic distortion for first phase

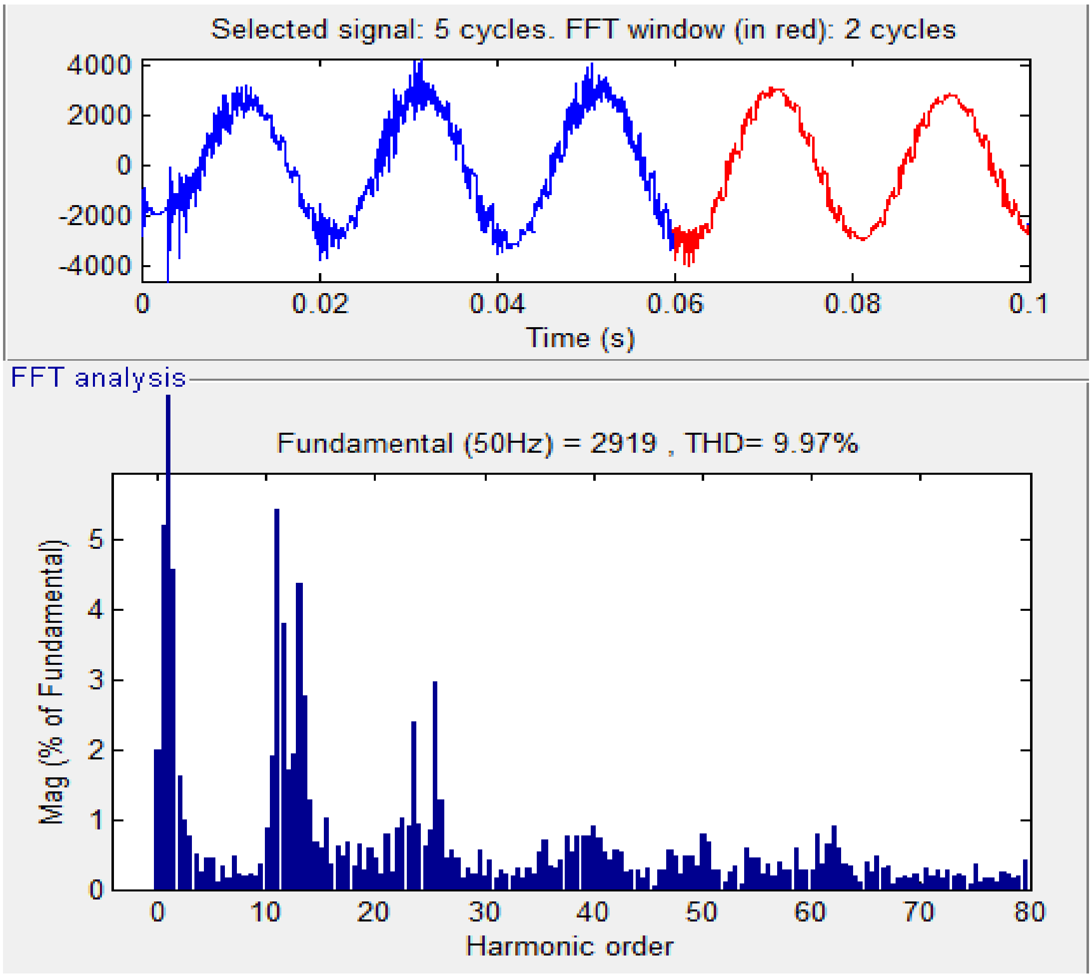


Figure 8.9: Harmonic wave and total harmonic distortion for second phase

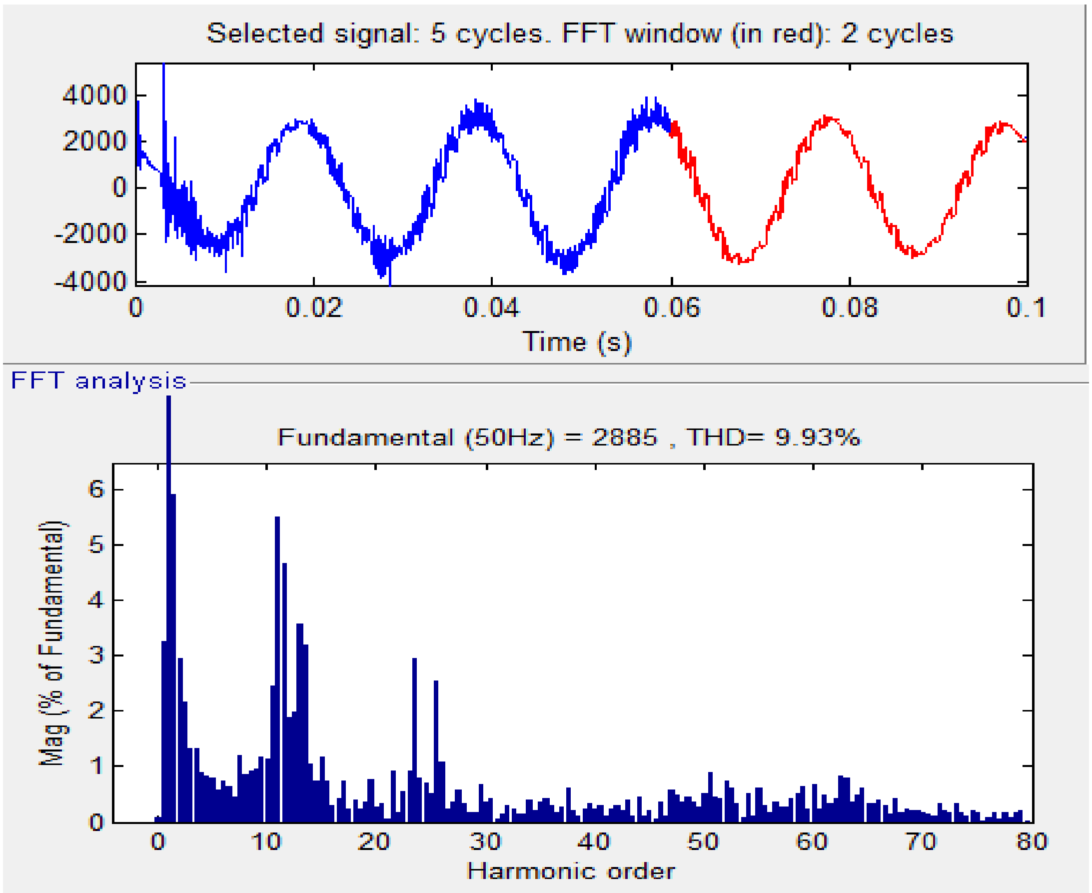


Figure 8.10: Harmonic wave and total harmonic distortion for third phase

8.1.3 Harmonic mitigation in a distribution network

The previous section investigates the contribution of WEC to harmonic generation in a distribution network. It is very glaring through the simulation results obtained that the current and voltage harmonics are generated into the system from the converter side and non-linear loads. In this section, a necessary compensatory device is provided in the network to reduce the effects of the harmonic voltage and current in the system. A 3-phase 1.6 Mvar harmonic filter is installed at the POCC of the network, the network is simulated again, and the result of the simulation is shown in Figure 8.11 below. It can be observed that the harmonic filters eliminate the harmonics generated by the converter and the nonlinear loads, which means that as long as the harmonic filter is installed into the network containing converter based DG and nonlinear loads; the harmonic generated in the system can be minimised. When fast fourier transform (FFT) is selected from the FFT tool of the powergui from the MATLAB/SIMULINK to plot the harmonic analysis of the system as done in the previous section, it is found that the total harmonic distortion of the network has reduced to the normal value in compliance with IEEE standard and requirement, the first phase reduce from 9.97 % to 1.43 %, the second phase from 9.97 % to 1.0 % and the third phase from 9.93 % to 1.92 % as shown in Figures 8.12 to 8.14

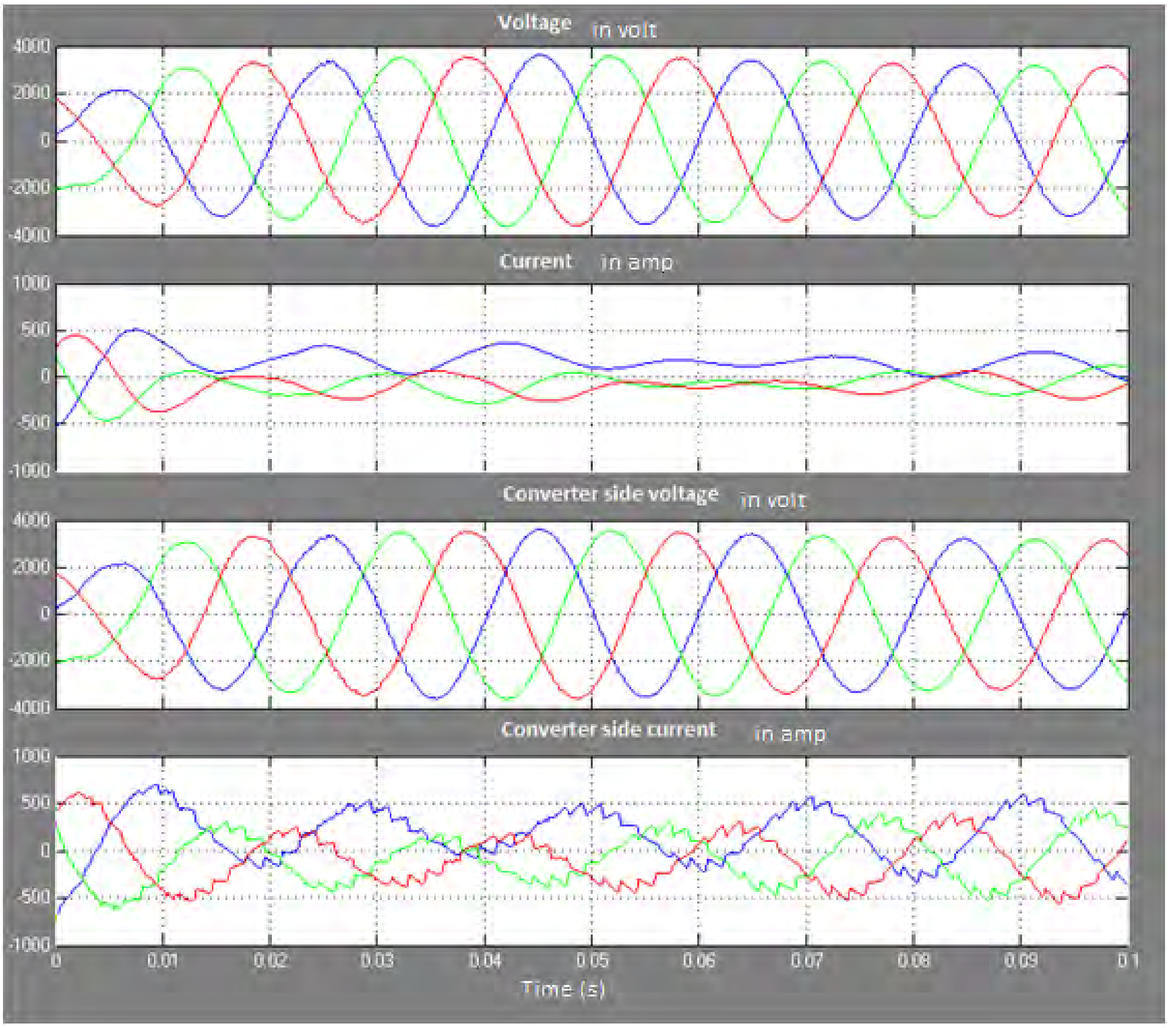


Figure 8.11: Harmonic current and voltage mitigation

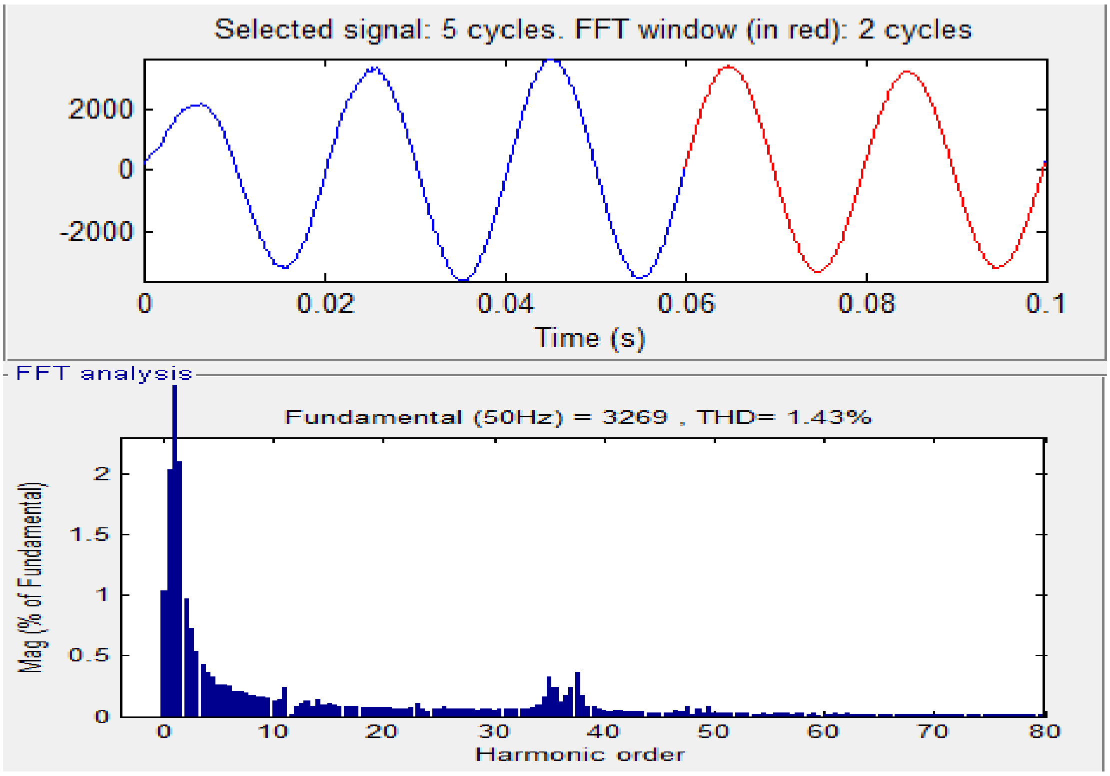


Figure 8.12: Harmonic wave and total harmonic distortion for first phase with filters

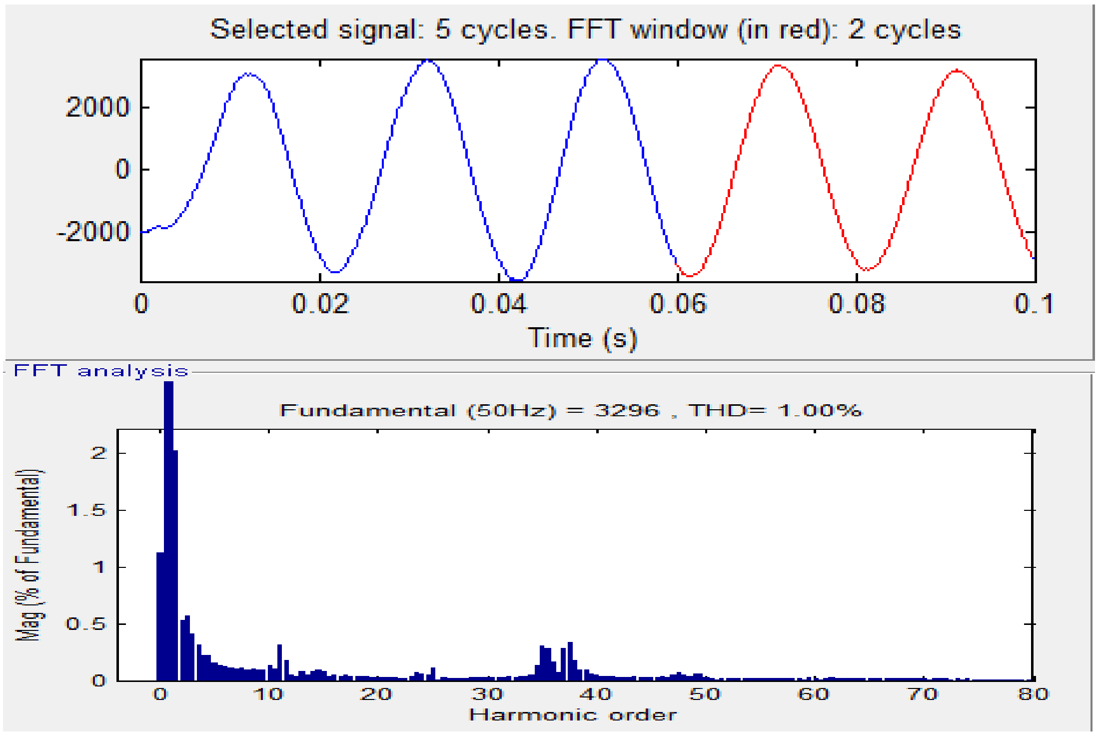


Figure 8.13: Harmonic wave and total harmonic distortion for second phase with filters

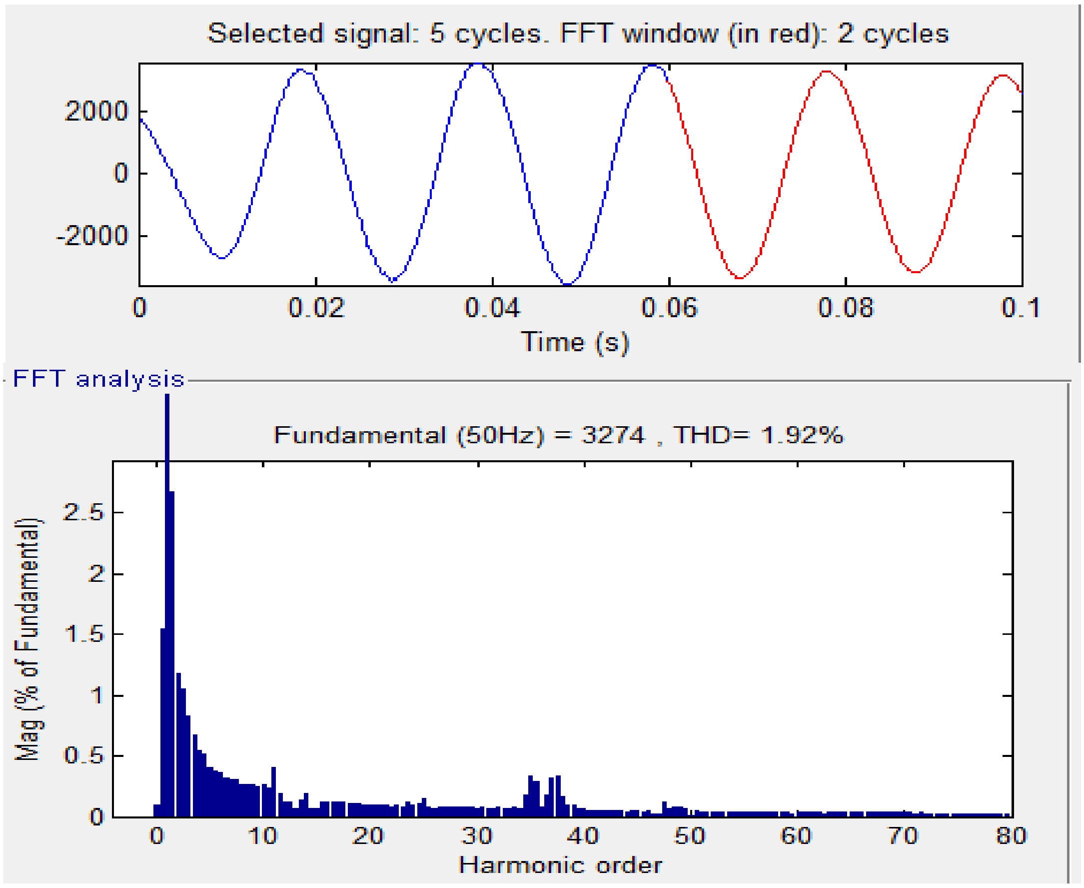


Figure 8.14: Harmonic wave and total harmonic distortion for third phase with filters

8.1.4 Frequency domain response

The impacts of WEC on harmonic generation in a distribution network have been investigated in the previous sections, it is obvious that the WEC contributed to the harmonic generation in the system, but when harmonic filters are installed at the point of POCC, the effects are mitigated. This section discusses and shows the impedance and frequency of the harmonic filters as computed by the MATLAB/SIMULINK. From the simulation window (Powergui), impedance versus frequency measurement and phase angle versus frequency are selected which compute and display the filter's frequency response as shown in Figure 8.15 below. The impedance of the filter can be found to be 11 ohms at the phase angle of 90^0 and frequency of 50 Hz. To compare the value of the filter obtained from simulated result with the chosen value (1.6 MVar filter), the following formula can be used

$$Q_C = \frac{V^2}{X_C} \quad \text{.........} \quad (8.1)$$

Q_C= Negative reactive power
V = Supply voltage (line to line)
X_C = Impedance of filter

$$Q_C = \frac{4160^2}{11} \quad (8.2)$$

Q_C = 1.57 Mvar (Obtained from simulated result)
Q_C= 1.6 MVar (chosen filter value)
The chosen filter value is the same as the calculated value which is obtained from the simulation graph. 1.57 MVar confirms that the total reactive power of the filter at 50 Hz is 1.6 Mvar.

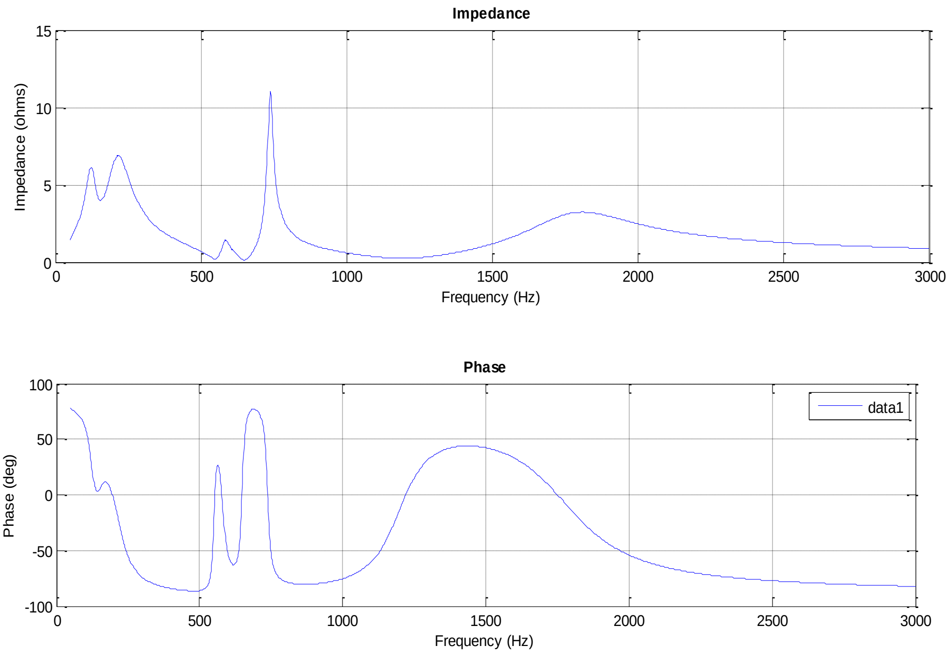


Figure 8.15: Filter impedance and frequency

8.2 Impact of WEC on voltage flicker

Introduction

Voltage flicker is one of the power quality issues in a distribution network, which is caused as a result of the fluctuations in the consumer loads connected to the network. Variations in the wind speed may also result into the fluctuations in active power output at the generator terminal; hence, it may lead to voltage fluctuations. Consequently, voltage fluctuation will lead to flicker emission in distribution feeders. In this section, the impact of WEC on voltage flicker when dynamic loads are connected to the network is investigated.

8.2.1 Flicker generation in a distribution network

When dynamic load such as electrical arc furnace is connected to the bus 675, the parameters are shown in Table A6 in Appendix A. The network is simulated for 0.5 s without WEC integration and the reference voltage is maintained at 1.05 pu and is connected into the IEEE modified network shown in Figure A2 in Appendix A. Figure 8.16 shows the reference voltage when dynamic loads have not been connected to the network, while Figure 8.17 shows the variations in active, and reactive power at bus 675 (1st trace) as well as grid voltages (trace 2) are more than 2 %. The grid voltages vary between 0.96 pu and 1.04 pu (+/- 4 % variation), this is as a result of switching of large dynamic load (electric arc furnace) connected to the bus 675 which affects the reference voltage and the quality of power delivered to the system.

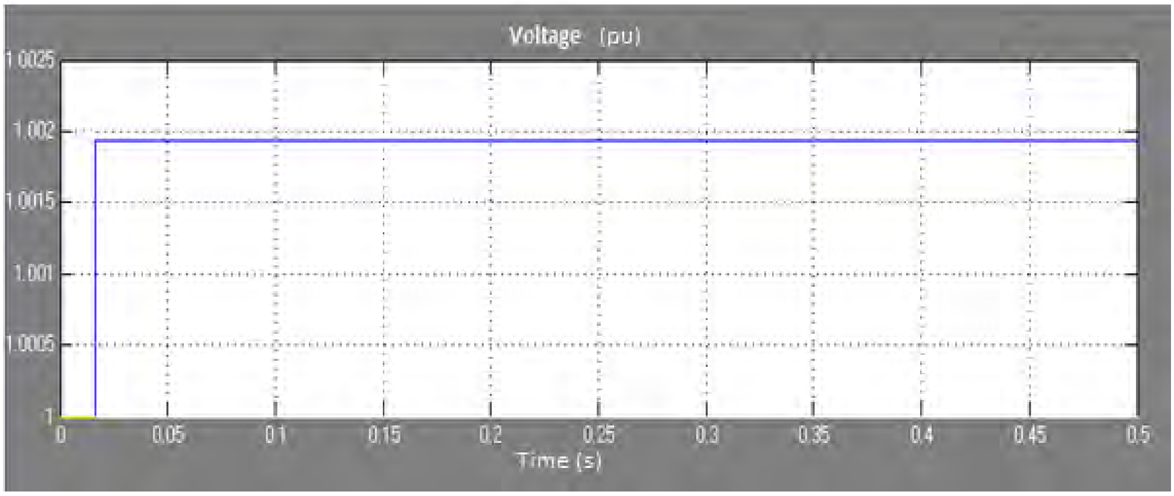


Figure 8.16: Grid voltages without dynamic load

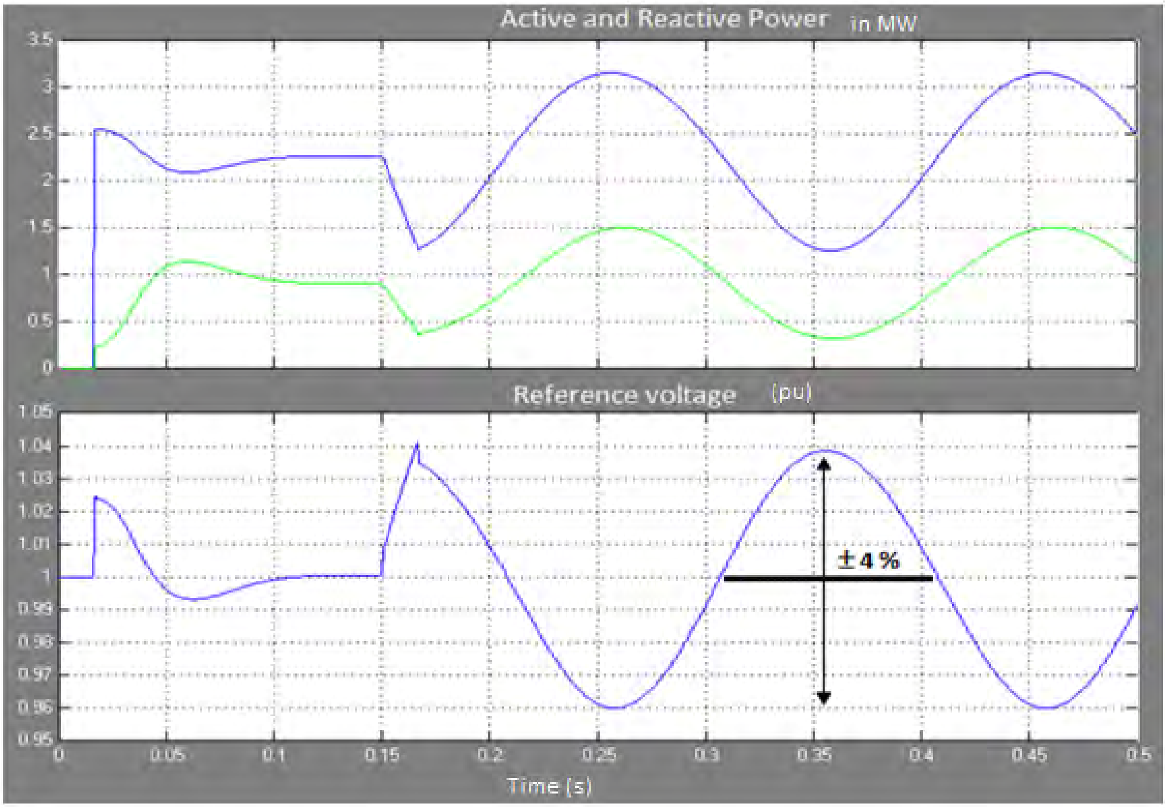


Figure 8.17: Active, reactive power and reference voltage with dynamic load

8.2.2 Impact of WEC on voltage flicker

Generation of voltage flicker due to the connection of dynamic loads is discussed in the section above, in this section; the impact of the WEC on voltage flicker shall be investigated. WEC is connected at the point of common coupling in the network and set to the voltage control mode, simulation process is repeated for 5 second, the results are depicted in Figure 8.18 below. It is observed that the reference voltage improved from 1.01 to 1.05 pu with WEC integration as shown in the second trace first line, and voltage flicker has reduced from ± 4 % to ± 0.01 %. The connection of WEC (DFIG) to a distribution network reduces voltage flicker which is in agreement with the research work done in **[231],** by strengthening the grid and increasing the voltage level integration of WEC (DFIG) can minimise the flicker emission.

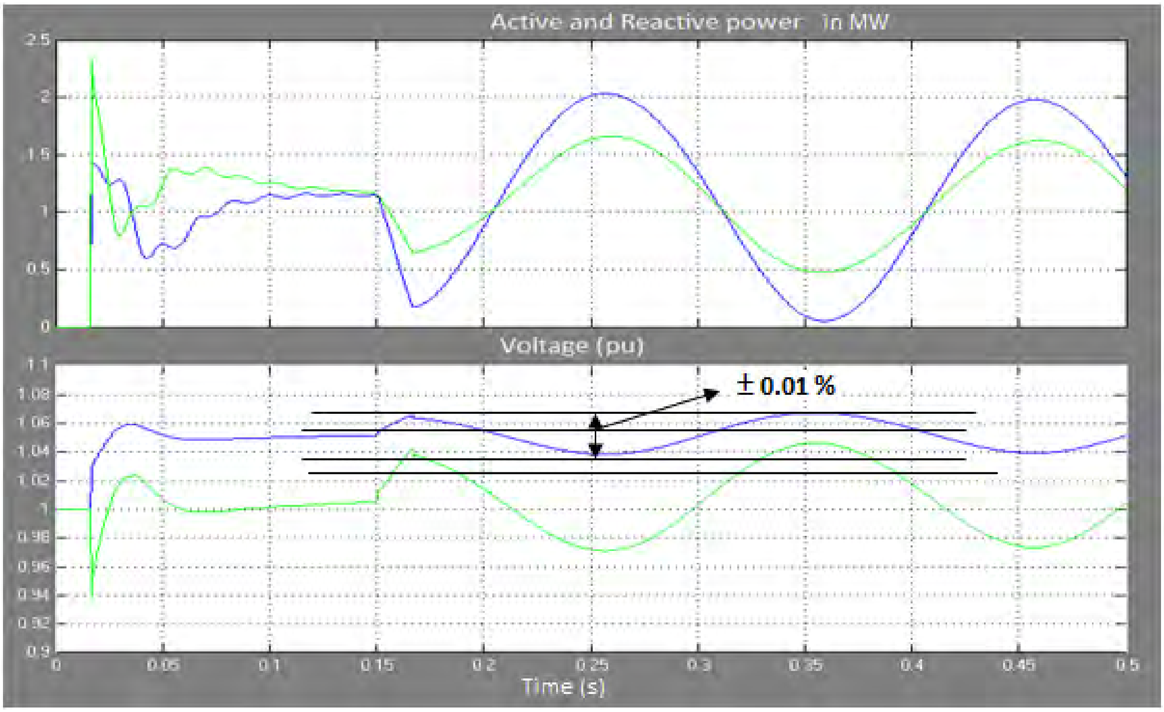


Figure 8.18: Active, reactive power and reference voltages with dynamic loads and WEC integration

8.2.3 Connection of DFIG and STATCOM

When a STATCOM is installed into the network with the connection of DFIG at the POCC, there is an improvement in the voltage than when only WEC is connected to the system. STATCOM regulates the grid voltages by absorbing or generating reactive power while maintaining 1.05 pu as shown in the Figure 8.19, the voltage flicker is almost eliminated, the STATCOM compensates for the voltage by injecting reactive currents modulated as shown in the Figures 8.19 third trace and Figure 8.20. It varies between 0.6 pu capacitive when voltage is low and 0.6 pu inductive when the voltage is high as depicted in Figure 8.21 (second trace).

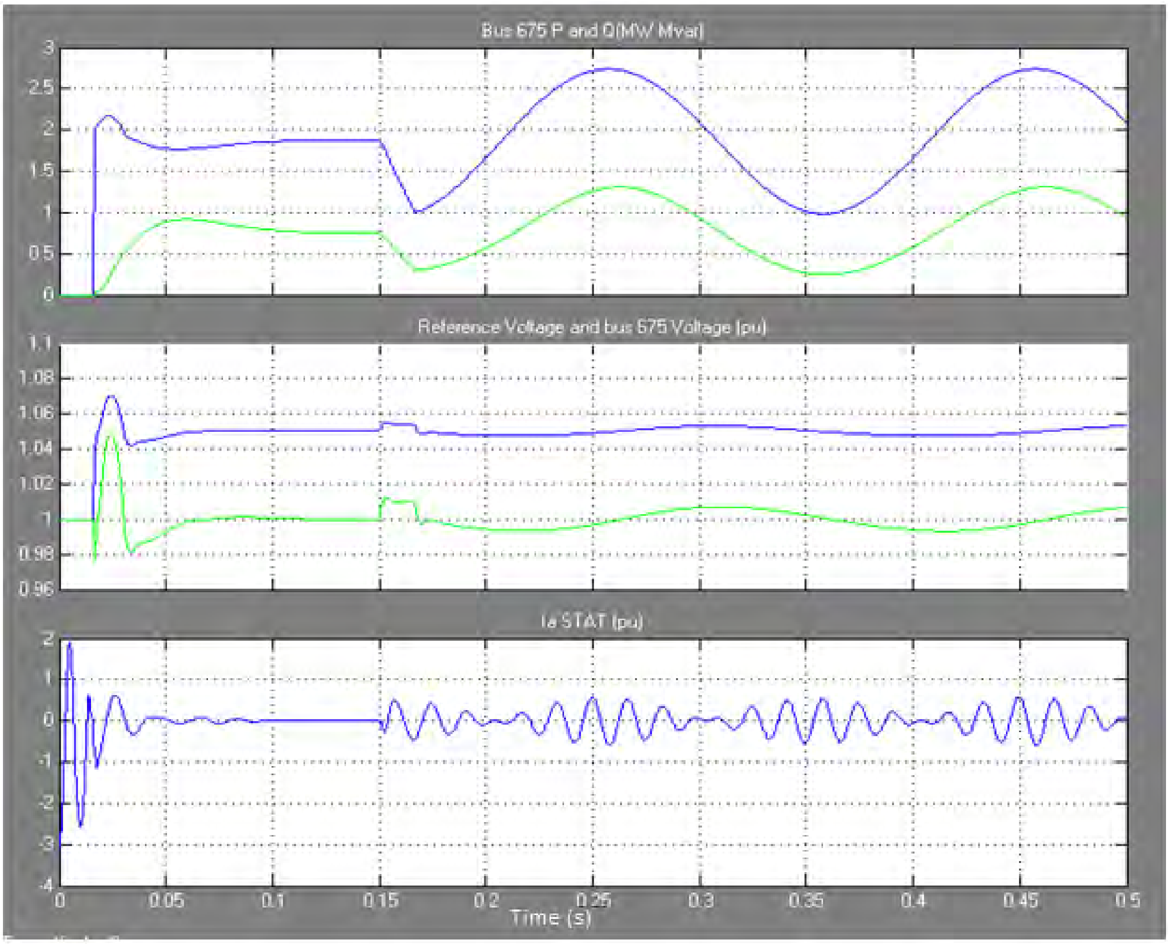


Figure 8.19: Active, reactive, reference voltage and STATCOM modulated current

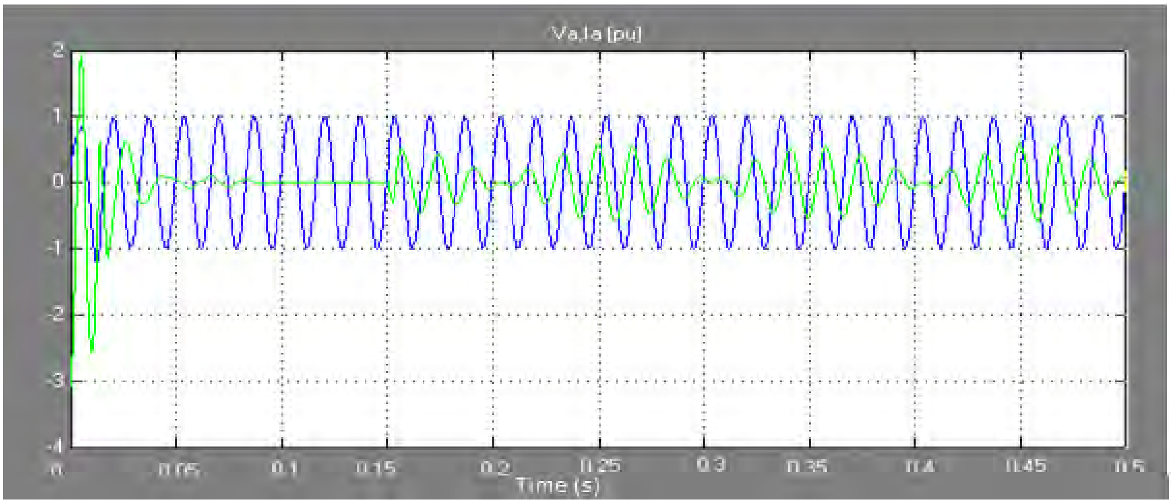


Figure 8.20: STATCOM modulated voltage and current

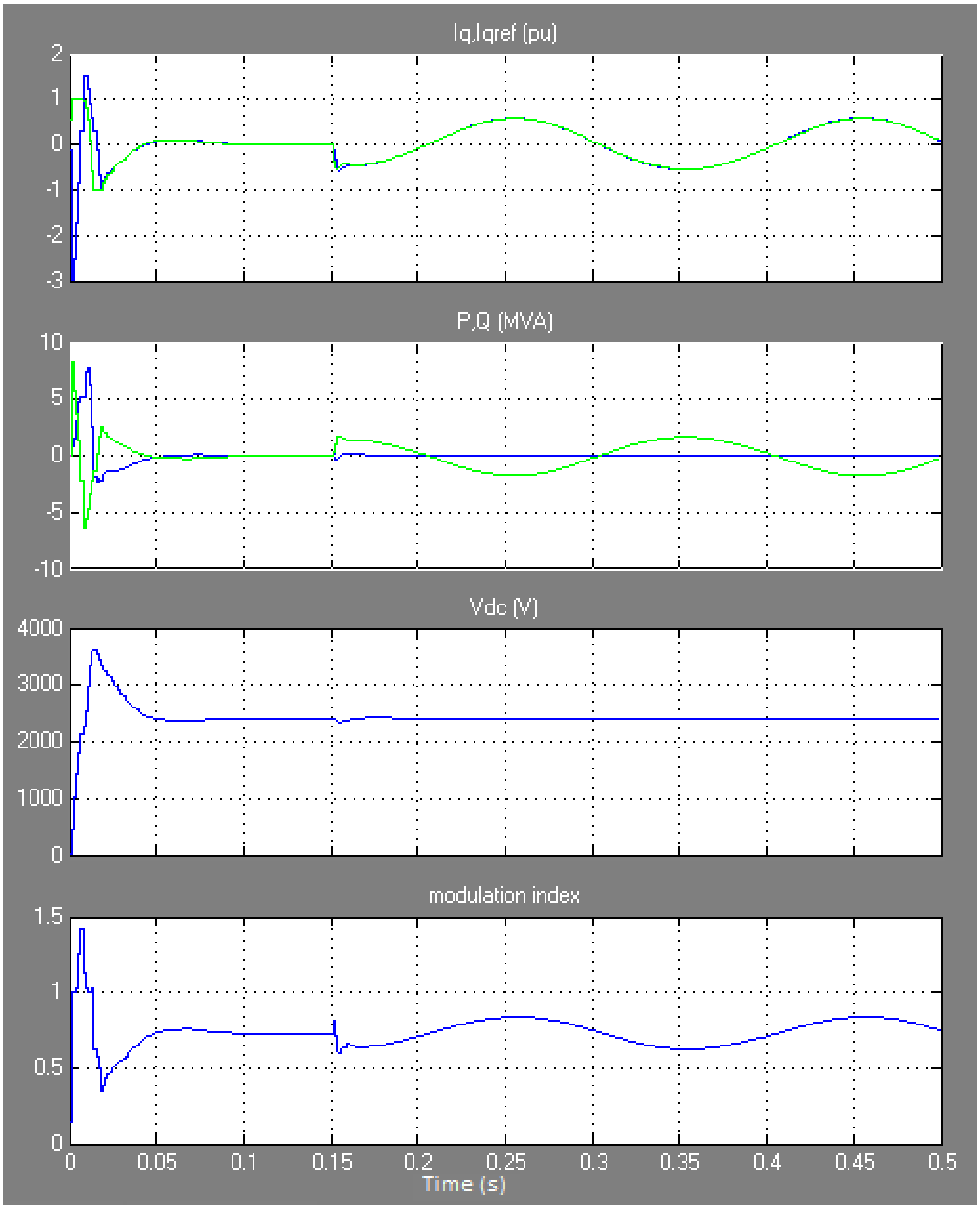


Figure 8.21: STATCOM controller wave forms

8.3 Impacts of WEC on voltage dip

Introduction

The impact of WEC on the electric grid is no longer negligible since the proportion of wind energy in the electric production is increasing on daily basis. The network voltage decreased when there is a disturbance in the network, WEC may be automatically disconnected, but with high wind energy penetration, WEC must withstand certain voltage dips or remain connected after the dips is cleared. The impacts of WEC on voltage dip are investigated in this section.

8.3.1 Distribution network without WEC integration

The IEEE modified network in Figure A15 in the appendix B is simulated without disturbance and the result is shown in the figure 8.22 below, the voltage is within an accepted range. The occurrence of grid disturbance at the centre of the system between 0.2 s to 0.3 s creates severe dips in the network without WEC integration, the network voltage reduced from 0.96 to 0.83 pu during the disturbance, which is not acceptable in compliance with the grid code act, Figure 8.21 shows the grid voltage with disturbance.

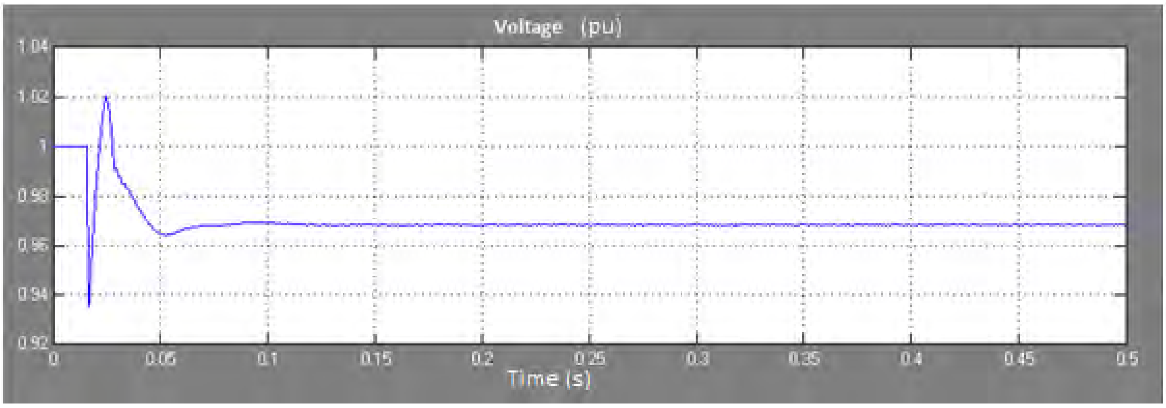


Figure 8.22: Grid voltage without disturbance

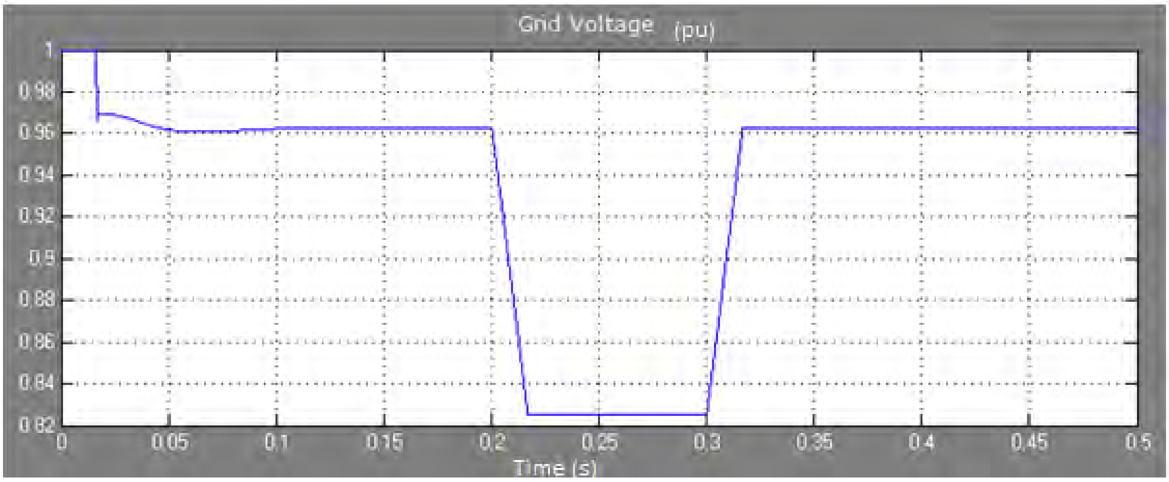


Figure 8.21: Grid voltage with disturbance

8.3.2 Impact of WEC on voltage dip

To investigate the impact of WEC on voltage dip, WEC is integrated into the network and the simulation process is repeated, it is observed that the integration of WEC improved the network voltage profile as depicted in Figure 8.22 while the power is delivered in the network. The occurrences of grid disturbance (three phase fault) at bus B as shown in Figure A15 at the Appendix C, between 0.2 s to 0.3 s create severe voltage dips in the network, when the network is simulated for 0.5 s, voltage dips to about 0.82 pu for the reference voltage and 0.85 pu at the bus where wind power is connected to the network (point of common coupling) as shown in Figure 8.23. The voltage obtained by the presence of WEC in the network is acceptable in relation to the grid code act (0.85 to 1.1 per unit). Therefore, WEC must remain connected to the network. The integration of WEC to distribution network based on this simulation does not contribute to the voltage dip during fault conditions rather; it reduces the voltage dip and increases voltage profile of the network.

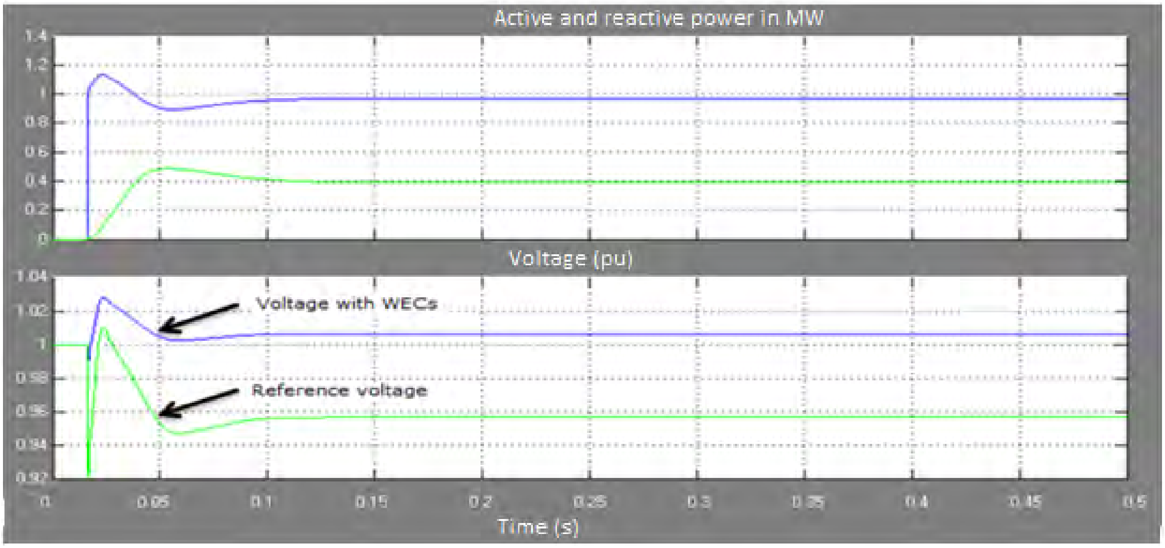


Figure 8.22: Grid voltage profiles, active and reactive power

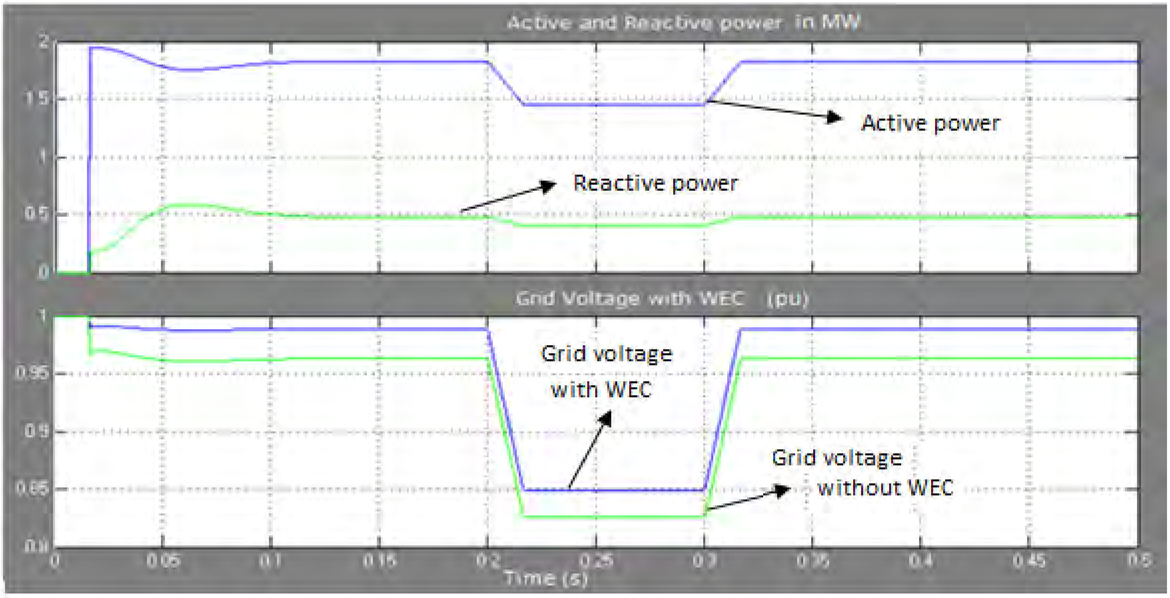


Figure 8.23: Voltage dips with WEC and grid disturbance

8.3.3 Connection of WEC with STATCOM

When a STATCOM (the parameters can be found in Appendix A, Table A10) is connected at the point of common coupling with WEC and the simulation is repeated, within the duration of the fault 0.2s to 0.3 s, STATCOM produced reactive current and modulated current and voltage as shown in Figures 8.24 third trace and 8.25, therefore, it generates reactive power within the duration of the fault to compensate for the voltage dips Q = - 3.8 MVar in Figure 8.26 and improve the voltage to 0.87 pu and maintained 1.0 pu after the fault is cleared as shown in Figure 8.34

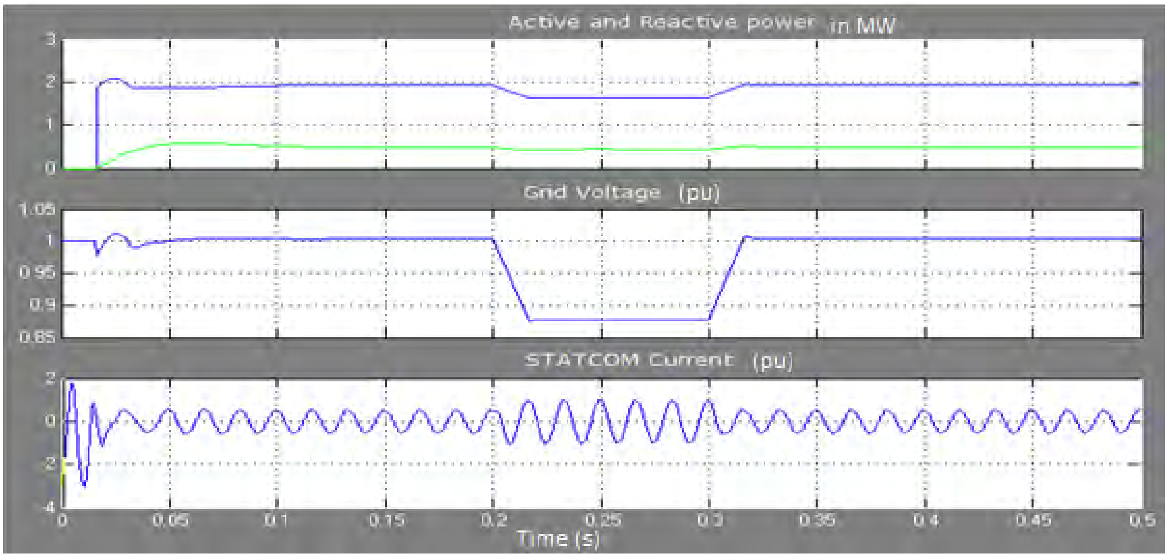


Figure 8.24: Voltage dips with WEC plus STATCOM and grid disturbance

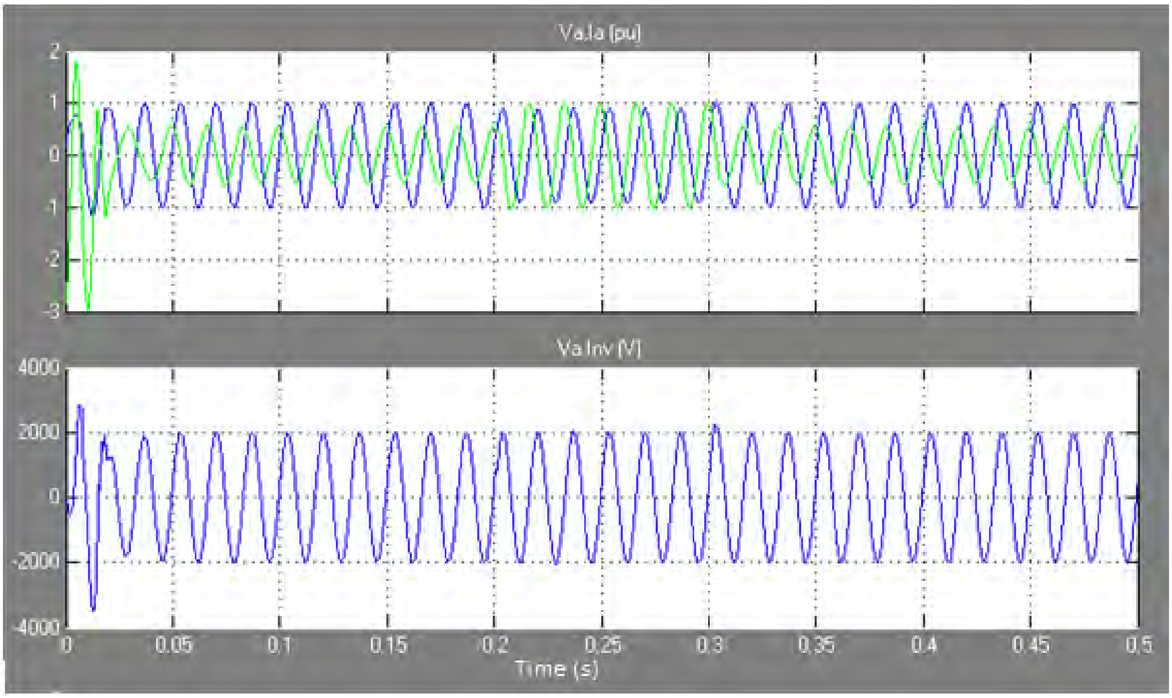


Figure 8.25: STATCOM modulated current and voltage

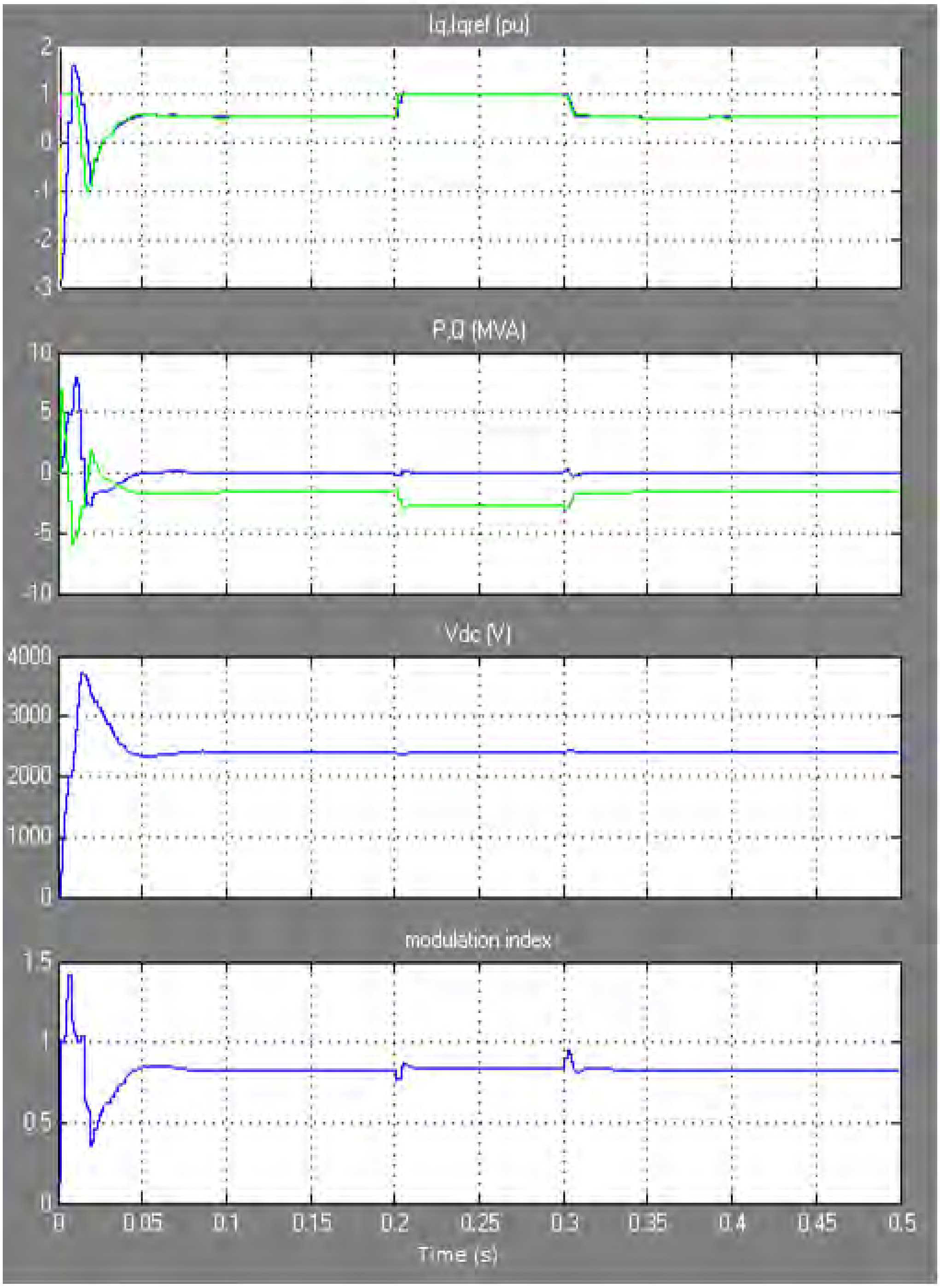


Figure 8.26: STATCOM active and reactive power controllers

8.4 Dynamic STATCOM response

STATCOM is chosen over the SVC in this dissertation to mitigate power quality problems because it has better active and reactive control capability. It is necessary to investigate its dynamic response and compare the performances to that of SVC. In this section, the dynamic response of a STATCOM is verified; the circuit is modelled in MATLAB/SIMULINK and depicted in Figure A14 in Appendix B. The voltage regulation is selected in the STATCOM dialogue box, droop (regulating slope) parameter is set to 0.03, for a given maximum capacitive/inductive range, this droop is used to extend the linear operating range of the STATCOM and also to ensure automatic load sharing with other voltage compensators. The Var Regulator Gains are set to 5 (proportional gain KP) and 1000 (integral gain Ki). The step Vref block is programmed to modify the STATCOM reference voltage Vref as follows: Initially Vref is set to 1 pu; at t=0.2 s, Vref is decreased to 0.97 pu; then at t=0.4 s, Vref is increased to 1.03; and finally at 0.6 s, Vref is set back to 1 pu, during this process, the fault breaker is not allowed to operate. The network is simulated, Figure 8.27 displays the results of Vref signal along with the measured STATCOM voltage Vm and the reactive power Qm absorbed (positive value) or generated (negative value) by the STATCOM at droop equal to 0.03 to control the voltage to the required value while the Figure 8.28 shows the STATCOM controller wave form. The faster response of the STATCOM depends on the value of the regulation gain, i.e., the larger the regulation gain, the faster the STATCOM response as shown in Figure 8.29, while the smaller the droop, the larger the sloop and vice versa as shown in Figure 8.30. The regulation gain and the droop must be correctly chosen so that the slope will not be too large and the STATCOM response will not be too slow.

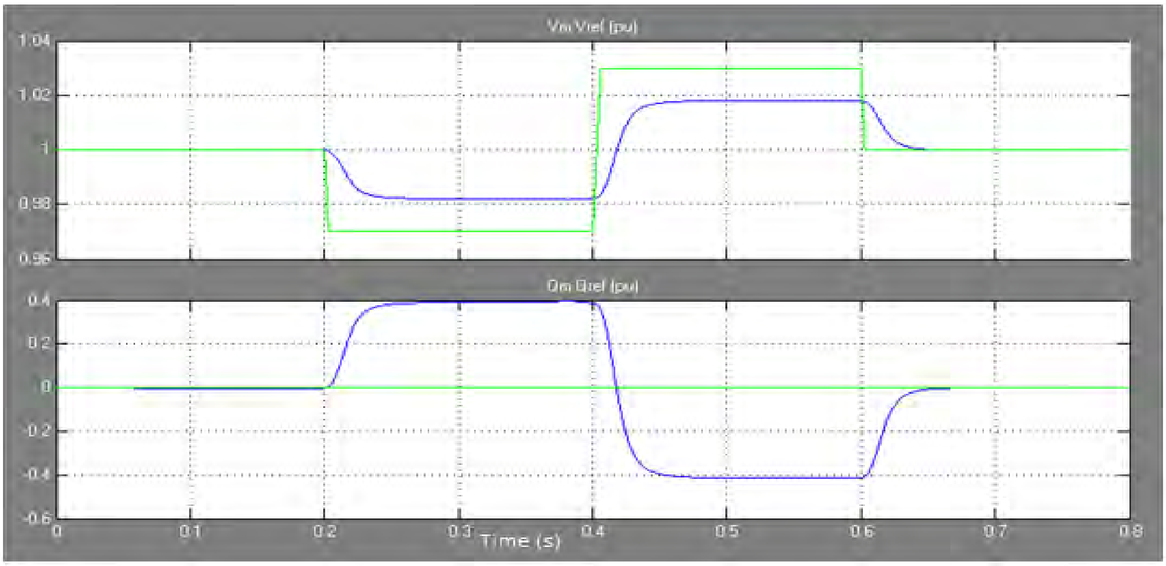


Figure 8.27: Reference voltage, STATCOM voltage and reactive power

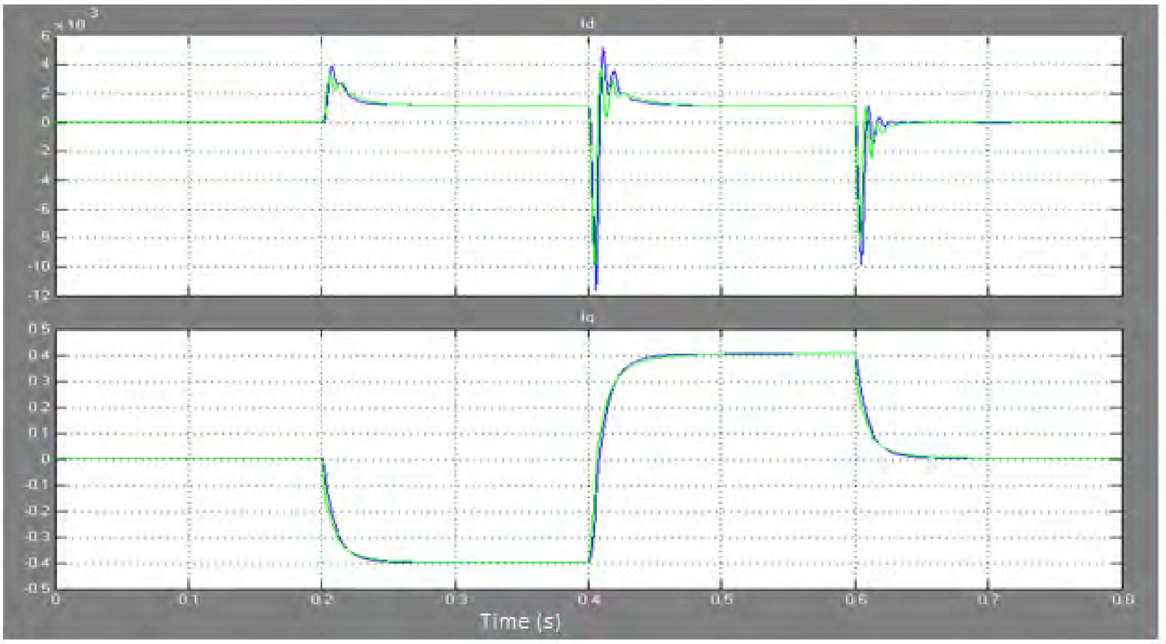


Figure 8.28: STATCOM controller wave form

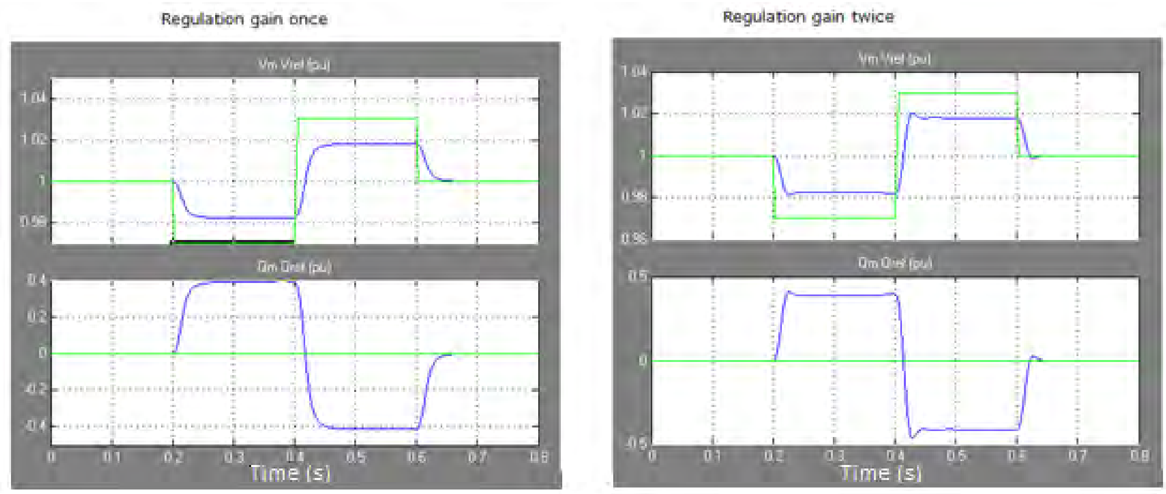


Figure 8.29: Effect of STATCOM regulation gain

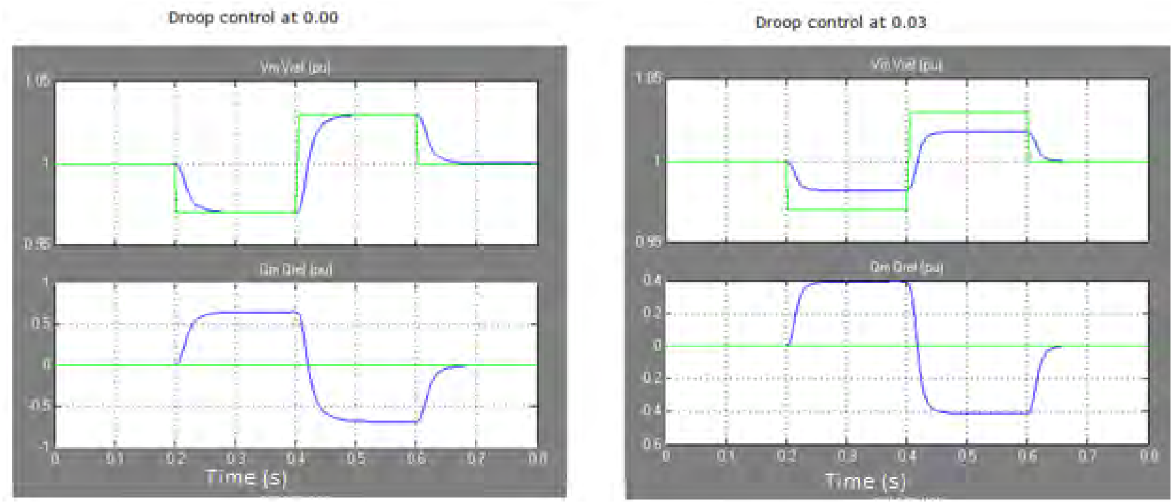


Figure 8.30: The effects of STATCOM droop

8.4.1 Comparison of STATCOM and SVC performances under fault conditions in a distribution network

The Static Synchronous Compensator (STATCOM) is one of the key FACTS devices, based on voltage-sourced converter, the STATCOM regulates system voltage by absorbing or generating reactive power. Contrary to a thyristor-based Static Var Compensator (SVC), STATCOM output current (inductive or capacitive) can be controlled independently of the AC system voltage. This comparison is made based on the results obtained from the simulation of a modified IEEE 13 bus test system used in this dissertation. The parameters of the STATCOM and SVC can be found in Table A10 at Appendix A. When the network is simulated without disturbance, the STATCOM and SVC voltage are shown in Figure 8.31, the power flow on the grid is 3.5 MW and the grid voltage level is maintained at 0.9 pu as shown in Figures 8.32 and 8.33 below. When there is a disturbance in the system i.e. the value of the fault impedance is programmed to produce 30 % voltage sag on the grid, to investigate the comparison in performance of STATCOM and SVC, SVC is connected to a power grid similar to the power grid on which STATCOM is connected, the circuit layout is modelled in MATLAB/SIMULINK and it can be found in Figure A14 in Appendix B, the STATCOM and SVC are phasor models and of the same power rating, installed at the midpoint of the network, before running the simulation, the fault breaker is programmed to operate at t=0. 2 s for the duration of 10 cycles and the STATCOM droop is set to 0.03. The simulation results in Figure 8.34 shows the measured voltage Vm of both STATCOM and SVC (blue colour for STATCOM), which means that the STATCOM can mitigate voltage dips than SVC, the reactive power (capacitive) Qm generated by the STATCOM (blue trace) is more than that of the SVC (green trace) during the

10-cycle fault which cause the voltage to improve during fault conditions than SVC, therefore, a key difference between the SVC and the STATCOM can be observed. The reactive power generated by the SVC is -0.48 pu and the reactive power generated by the STATCOM is -0.71 pu. It can be seen that the maximum capacitive power generated by an SVC is proportional to the square of the system voltage (constant susceptance) while the maximum capacitive power generated by a STATCOM decreases linearly with voltage decrease (constant current). This ability to provide more capacitive power during a fault is one important advantage of the STATCOM over the SVC. In addition, the STATCOM exhibits a faster response than the SVC because with the voltage-sourced converter, the STATCOM has no delay associated with the thyristor firing (in the order of 4 ms for an SVC).

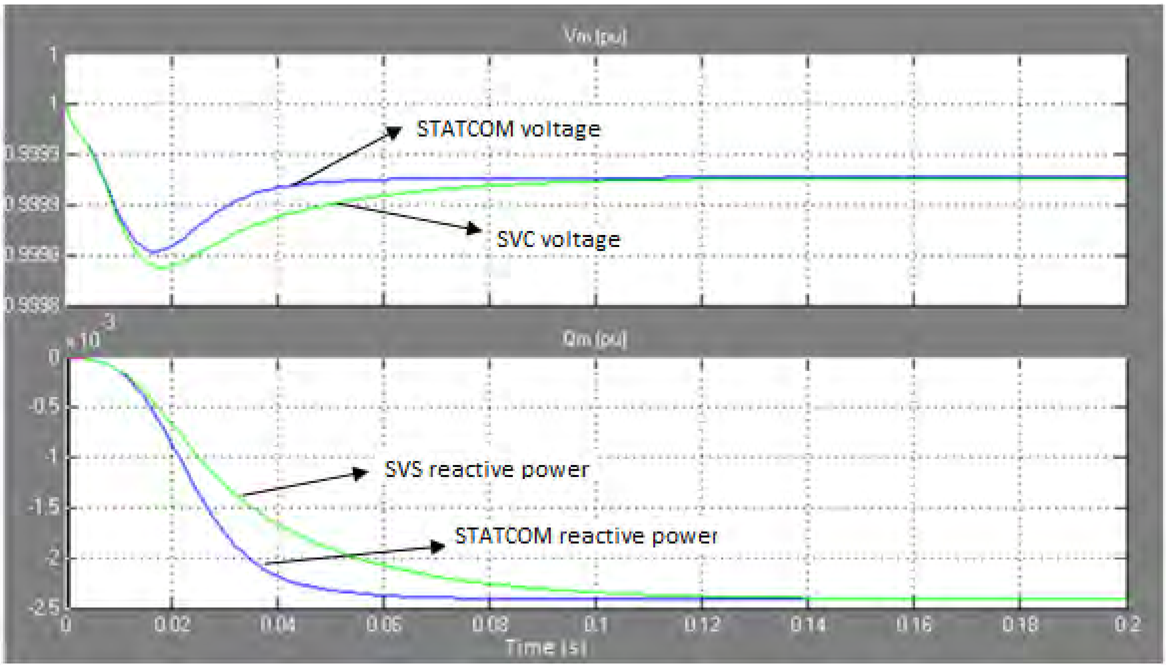


Figure 8.31: STATCOM and SVC voltage and reactive power without fault

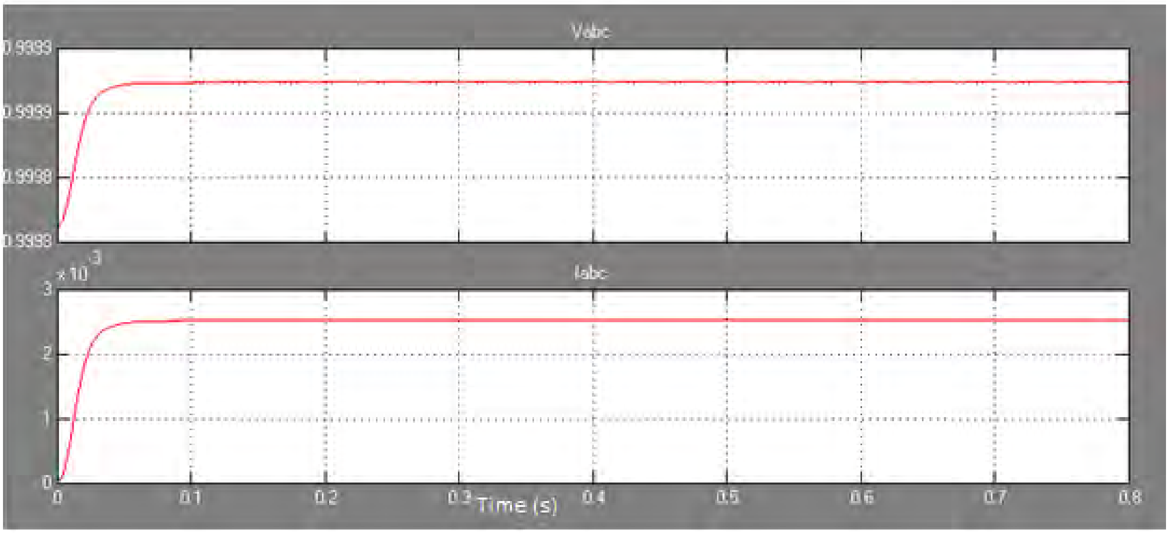


Figure 8.32: Grid voltage and current without fault and compensation

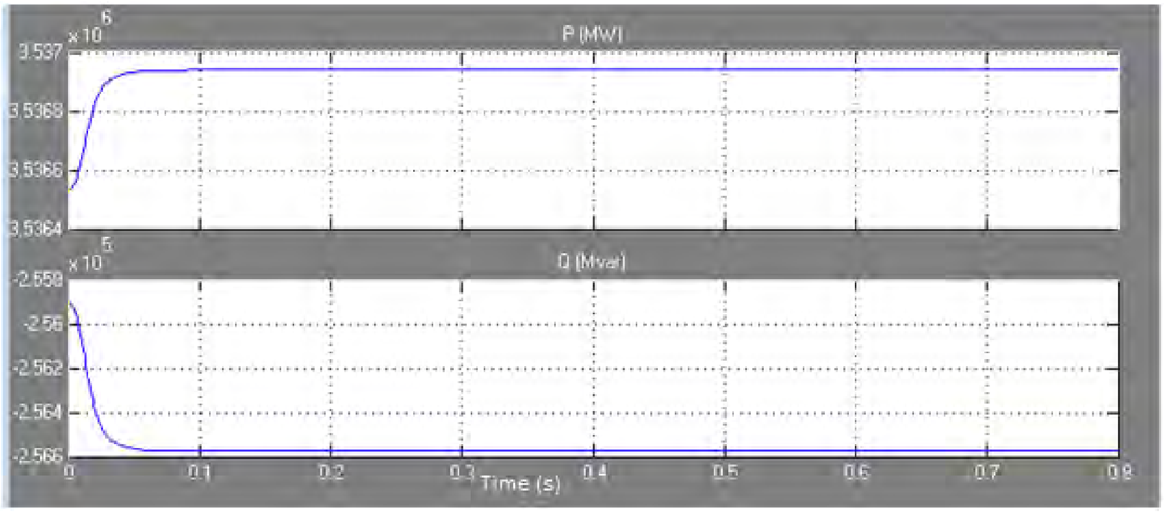


Figure 8.33: Grid active and reactive power without fault and compensation

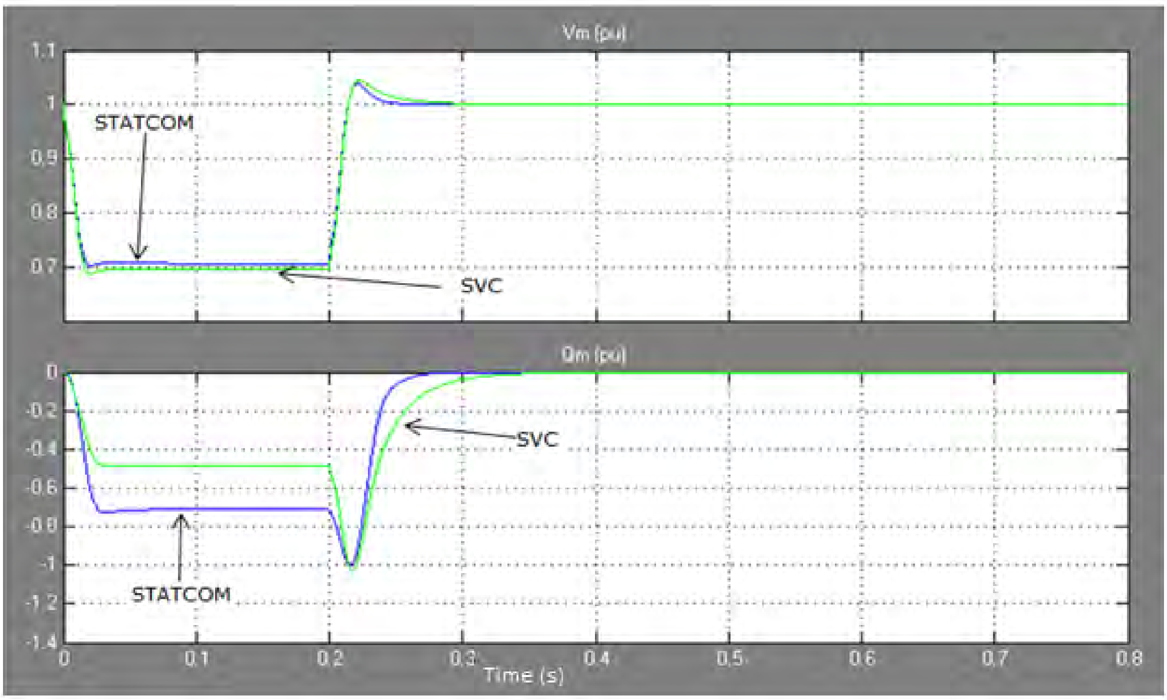


Figure 8.34: Voltage and reactive power of STATCOM and SVC

Reactive power compensation devices like capacitors, STATCOM and SVC are used to provide voltage regulation in a distribution network as mentioned in the section 3.16; meanwhile, STATCOM has the advantages of better voltage control capability, fast response time and generate more reactive power (capacitive) than SVC during fault condition based on the research work done in this dissertation.

8.5 Summary

It has been shown in the research work done in this dissertation that the impacts of WEC with power electronic interface, such as DFIG and connection of nonlinear loads to a distribution network contributed to the voltage distortion and harmonic injection into the network, but this harmonic effect can be minimized by the installation of filtering device at the point of common coupling. Connection of WEC to the network did not contribute to the voltage flicker, rather, it reduces voltage flicker. Voltage dips are minimised with the connection of WEC, while the network voltage profile is improved. Therefore the impacts of WEC on a distribution network have positive as well as negative effects.

Chapter 9

Conclusions and Recommendations for Future Works

9.1 Conclusion

Electric power systems are made up of units that produce and the devices that utilize electricity, which are connected by a power grid. The transmission of electrical energy from the point of generation to the distribution level are the main functions of the power grid in which, steady and constant voltage of high power quality is supplied to the consumers; whereas, any changes in the generation and consumption side can pose problems in the system. Several recent blackouts that occurred across the countries of the world, demand and price peaks of electricity, dependent only on conventional methods of power generation, production and emission of carbon dioxide etc, have given rise to the introduction of new types of electricity generation into the power system. The large conventional electricity production units are replaced by small units and renewable energy sources. Changing from conventional method of electricity generation, electricity production from fossil fuel, coal, gas, nuclear and oil to the renewable energy source, energy from the sun, solar, wind, tide and wave, geothermal and biomass etc can reduce the emission and improve sustainable environment.

The terminology mostly used for the production of the new types of electrical energy differs, such as renewable energy sources, distributed resources, distributed generation, embedded generation, small scale generation etc; these new methods pose new challenges into the power system planning, management, and operation. Research is going on across all countries in the world on how to assess and know the prospect of the new method renewable energy source in each country, how to harness it, and probably, the integration impacts on the power system grid or network. This dissertation is divided into two parts; First part describes in details the various renewable energy resources in the world, the prospect and the assessment of renewable energy in South Africa and Nigeria while the second aspect stressed on the integration issues and the impact of WEC on a medium and low voltage distribution network.

9.1.1 Assessment and prospect of renewable

A comprehensive literature review on different types of renewable energy sources, advantages and disadvantages, Assessment and prospect of renewable energy in South Africa/Nigeria

The following conclusions are drawn based on the literature review done

- Most of the countries of the world are investing in the alternative source of energy generation (renewable energy resource) that is naturally replenished (inexhaustible) on a human time scale, clean, pollution free, and environmental friendly
- Fossil fuels, coal, gas, nuclear, etc, are not present in all countries of the world, nearly every town has access to sunlight, wind, water, refuses, and the geothermal power from the Earth, harnessing these sources of renewable energy is what most countries need.
- Prices for fossil fuels are skyrocketing as existing stockpiles are consumed, which is leading companies to use more expensive and hazardous extraction processes to recover these limited resources.
- Additionally, conflicts around the world have constrained supply flows of oil and gas causing frequent price spikes. Renewable energy sources do not face these same problems. Limitless sources like solar power and wind will never suffer from spills, leaks, resource exhaustion, or contaminate land. Renewable energy can be deployed nearly everywhere and without the need for expensive power lines distributing the energy since they are capable of delivering power directly to the end consumer
- Renewable energy is also cheaper and more economically viable than other sources of generating energy. It is estimated that as a result of renewable energy manufacturing, hundreds of thousands of stable jobs will be created.
- South Africa is well endowed with renewable energy resources, especially solar energy, wind, biomass and small hydro. Tapping into this resource would help to reduce emissions from coal and nuclear power station. Although, renewable energy resources development has started in South Africa, such as wind farm development, rooftop solar, off grid solar and wind, all other renewable energy sources need to be developed.
- Nigeria has a prospect of renewable energy like wind, solar, hydro, and biomass; Only the major hydro is harnessed, small hydropower have not been developed, solar and wind have not be harnessed. The renewable energy resources in Nigeria need to be developed.

9.1.2 Impacts of DG (WEC) on a distribution network

The simulation results obtained based on the MATLAB/SIMULINK and PSCAD/EMTDC show that the impacts of WEC on a distribution network depend on:

- The penetration level of WEC on the network (DFIG)
- The location of WEC on the network
- The load condition of the network
- The transmission length
- The network fault conditions

The following conclusions are drawn based on the simulation performed on the impacts of WEC on a distribution network.

The integration of WEC on a distribution network can:

- Improve the voltage profiles
- Cause voltage fast moving instability during fault conditions
- Turn a weak network to an active network by injecting active power into the network
- Cause voltage rise/over voltage in a distribution network, especially, if the WEC power is greater than the load (excess generation) and at the point of common coupling
- Contribute to the harmonic injection thereby result to the poor power qualities to the end user unless a filtering device is installed into the network.
- Reduce voltage flicker if it is installed in a strategy location in the network.
- Minimise voltage dip created by grid disturbance, switching of large load and improve network voltage profile.

STATCOM operation and compensation capability are better than SVC in power quality mitigation

9.2 Recommendation based on the research

- Renewable energy resources should be more focussed upon in Africa to reduce the effects of gases produced from fossil fuels, which is harmful to human health, to increase the chances of job creation in Africa, to reduce the total dependence on fossil fuels, decrease the environmental hazards and increase sustainable development.
- Based on the research work done in this dissertation, it is highly advisable for the utility company to draw the voltage profile of any distribution network to know the weakest points, the connection of WEC should be made only at the weakest bus either for the utility or independently owned generating unit and the power of such WEC should not be more than the load connected to the same bus.
- The point of common coupling should be monitored e.g by installing a voltage control device, either to regulate the voltage at that point or to switch off the generator in case of over voltage or excess generation

- If power electronic based DG such as DFIG is to be integrated into a distribution network, it should be incorporated by an appropriate filtering device to avoid harmonic injection into the system which can cause power quality problems.

9.3 Future works

- The impacts of WEC on a distribution network using more than one wind energy generator should be considered (combination of DFIG, SCIG, PM etc); Their rotor angle behaviours, electrical and mechanical torque behaviours, and tripping action behaviours during a disturbance should be investigated
- Further research is necessary for modelling and control of DFIG in order to improve on the dynamic Var and voltage control behaviour during a fault. By achieving this, it will give a better result
- Replacement of large generating unit or conventional power station with WEC only should be investigated in relation to the transient stability, and voltage dips.
- The impacts and effects of other wind generators as well as other renewable distributed generation on a distribution network should be investigated and also the effects of wind variability should be considered.
- The comparison of STATCOM to voltage regulator and capacitor should be investigated.

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Conference Paper Published

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Appendix A

Network parameters

Table A1: Load data

Bus A	Bus B	Active power (KW)	Reactive power (KVAr)	Line length in KM
632	645	200	116	0.1524
632	633	170	100	0.1524
633	634	480	270	0.1524
645	646	170	110	0.0914
650	632	230	132	0.610
684	652	300	200	0.244
632	671	170	151	0.610
671	684	375	202	0.091
671	680	118	93	0.305
671	692	270	80	0.091
684	611	950	770	0.091
692	675	128	86	0.152

Table A2: Transformer data

Parameters	**Value**
Substation	5 MVA
HV	115 kV
LV	4.16 kV
Frequency	50 Hz
X	8
R	1 Ω
Inline transformer	0.5 MVA
HV	4.16 kV
LV	0.48 kV
X	2
R	1.1 Ω

Table A3: Converter parameter and DC load

12 pulse generator	50 HZ, 30^0
Pulse width (degree)	40
Power electronic device	2 Thyristors
	DC load
Resistive load	4.6 MW
Inductor	0.5e3 H
DFIG power	2 MVA at 0.9 p.f

rectifier	2 universal diode
Snubber resistance	2000 ohms
Snubber capacitance	0.1e-6 F
Ron	1 e-3ohms

Table A4: Harmonic Filter parameter

0.4Mvar	C type high pass filter	Tune to 3rd harmonic F1
0.4Mvar	Double tune filter	11/13th harmonic F2
0.4Mvar	High pass filter	Tune to 24th harmonic F3
0.4Mvar	Capacitor bank	

Table A5: Data for DFIG

Rated power	2 MVA
Power factor	0.98
Voltage	4.16 kV
Frequency	50 HZ
Stator resistance	0.00706 Ω
Stator inductance	171 mH
Magnetizing inductance	2.9 H
Rotor resistance	5m Ω
Rotor inductance	156 Mh
Pole pair	0.013
Converter parameter	
Converter maximum power	0.5
Grid side coupling inductor	0.15 pu
Grid side coupling resistance	0.0015 pu
Nominal DC bus capacity	1000 μF
Nominal DC voltage	1200 V
Coupling inductor current	[0 90]
Voltage regulator parameter	
Grid voltage ref	1.0 pu
Grid side converter ref	0
Grid voltage regulator k_p	1.25
Grid voltage regulator k_i	300
Droop	0.03

Table A5.1: Dynamic load parameter

Dynamic load	
Nominal load and p.f	2.2e6 and 0.9
Modulation: [Amplitude (Arms) Frequency (Hz)	2000 5
Modulation timing : [Ton Toff]	[0.15 1]*100
Nominal voltage (V)	4.160

Table A5.2 Measured IEEE 13-bus system

Bus No	Phase A	Phase B	Phase C
632	1.0025	1.0013	1.0004
633	1.0071	1.0013	1.0008
634	0.9747	0.9999	0.9999
645	0	1.0008	1.0004
646	0	1.0004	1.0008
671	0.9992	1.0037	0.9867
692	0.9908	1.0008	0.9808
675	0.9904	1.0021	0.9792
684	0.9971	0	0.9863
611	0	0	0.9863
652	0.9958	0	0
680	0.9992	1.0037	0.9867

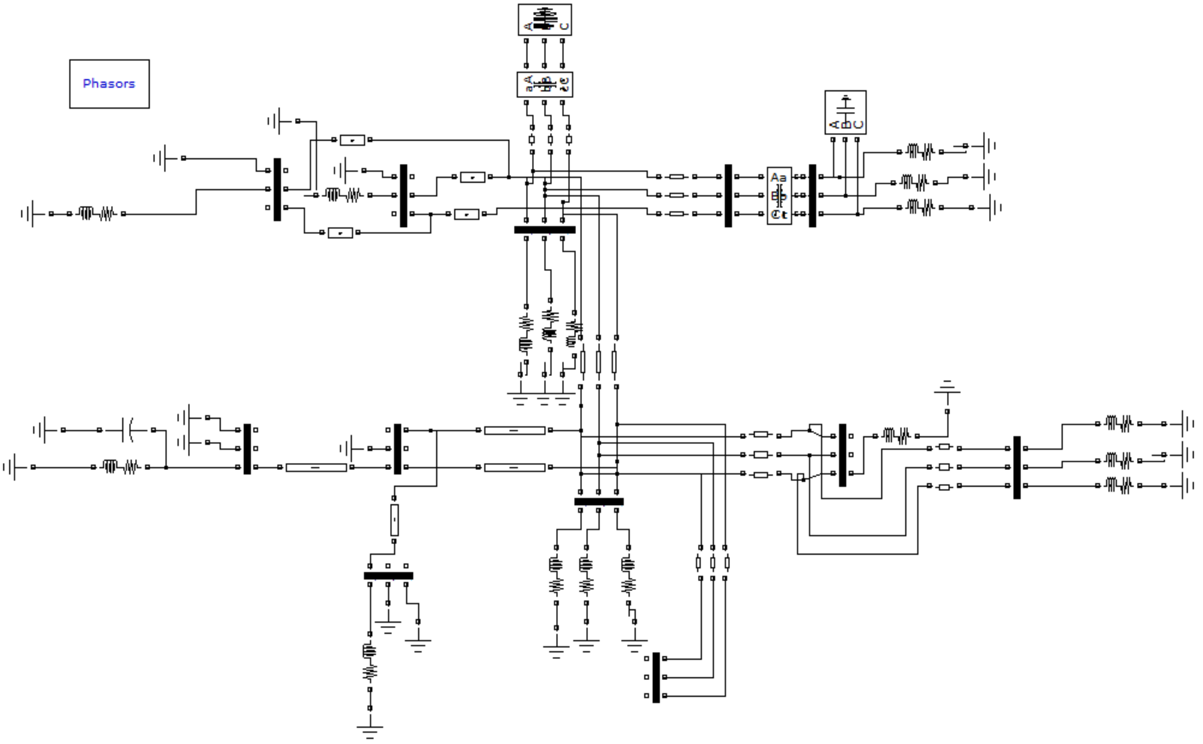


Figure A1: IEEE 13-bus test feeder in MATLAB/SIMULINK

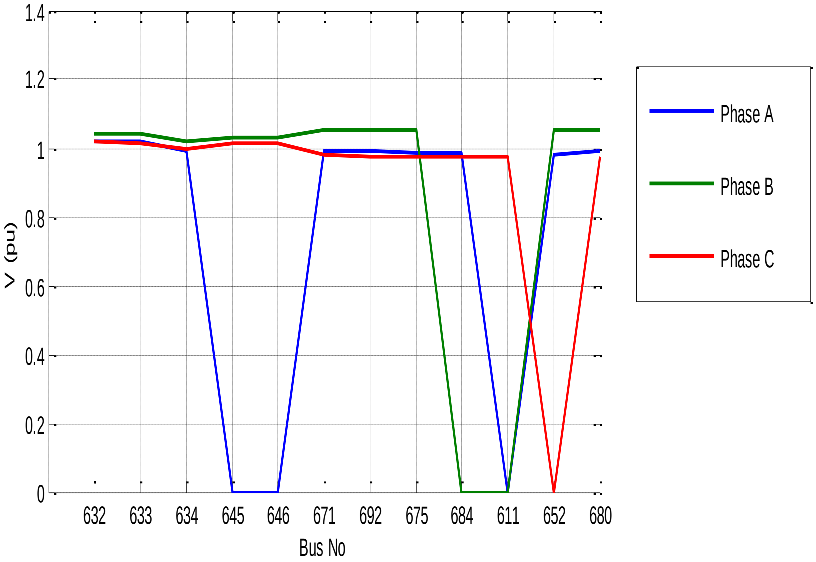


Figure A3: Simulated IEEE 13-bus voltage profiles

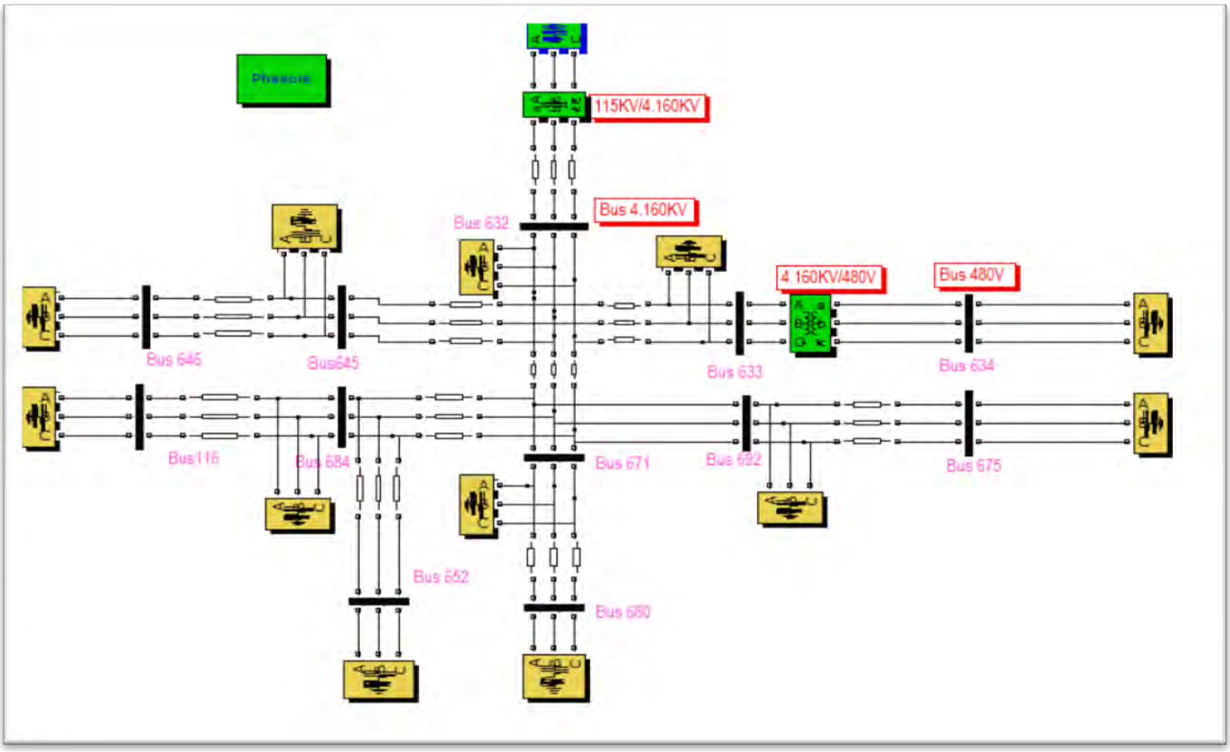


Figure A2: Modified IEEE 13 node test feeder in MATLAB/SIMULINK

Comparison tables

Table A6: Phase A measured voltage for IEEE 13 bus feeder (power flow)

Bus No	IEEE	Phase A Simulated	Diff % Simulated	CYMD Diff %
632	1.02	1.00	0.02	0.00
633	1.02	1.01	0.01	0.00
634	0.99	0.97	0.02	0.00
645	-	-	-	-
646	-	-	-	-
671	0.99	0.99	0	0.00
692	0.99	0.99	0	0.00
675	0.98	0.99	0.01	0.05
684	0.99	0.99	-	0.01
611	-	-	-	-
652	0.98	0.99	0.01	0.05
680	0.99	0.99	-	0.00
%Max			0.02	0.05

Table A7: Phase B measured voltage for IEEE 13 bus feeder (power flow)

Bus No	IEEE	Phase B Simulated	Diff % Simulated	CYMD Diff %
632	1.04	1.00	0.04	0.00
633	1.04	1.00	0.04	0.01
634	1.02	1.00	0.02	0.02
645	1.03	1.00	0.03	0.01
646	1.03	1.00	0.03	0.01
671	1.05	1.00	0.05	0.01
692	1.05	1.00	0.05	0.01
675	1.06	1.00	0.06	0.03
684	-	-	-	-
611	-	-	-	-
652	-	-	-	-
680	1.05	1.00	0.05	0.01
%Max			0.06	0.03

Table A8: Phase C measured voltage for IEEE 13 bus feeder (power flow)

Bus No	IEEE	Phase C Simulated	Diff % Simulated	CYMD Diff %
632	1.02	1.00	0.02	0.04
633	1.01	1.00	0.01	0.02
634	0.99	0.99	0.00	0.00
645	1.02	1.00	0.02	0.05
646	1.01	1.00	0.01	0.04
671	0.98	0.98	0.00	0.02
692	0.98	0.98	0.00	0.03
675	0.98	0.98	0.00	0.02
684	0.98	0.98	0.00	0.02
611	0.97	0.98	0.00	0.02
652	-	-	-	-
680	0.98	0.98	0.00	0.02
%Max			0.02	0.05

Table A10: Data for SVC and STATCOM

Power rating	5 MVA
Voltage (L-L)	4.16 kV
Base power	5 MVA
Reactive power limit	2e6 – 1e6
Average time delay	4e-3
Control parameter	
Voltage ref	1.0 pu
Voltage regulator	[0 0.03]
Val control	0.0

Table A9: Voltage profile in MATLAB/SIMULINK

Line		Phase A	Phase B	Phase C
650-632	V	2408 < 27.70°	2405 < -92.10°	2403< 147.57°
	I	2.745 < 177.24°	10.58 < 57.97°	18.79 < -62.60°
632-633	V	2419 < 27.68°	2405 < -92.12°	2404 < 147.55°
	I	25.18 < 5839°	21.99 < -64.78°	22.62 < 176.08°
633-634	V	269.8 < 51.56°	277.4 < -68.04°	276.9< 171.90°
	I	215 < 80.91°	196< -25.53°	195.7< -145.59°
632-645	V	0.00 < 00.00°	2404 < -92.09°	2403 < 147.56°
	I	0.00 < 00.00°	29.31 < 51.59°	0.00 < 0.00°
645-646	V	0.00 < 00.00°	2403 < -92.13°	2404 < 147.56°
	I	0.00 < 00.00°	36.82 < 58.01°	00.00 < 0.00°
632-671	V	2400 < 26.70°	2411 < -92.04°	2370 < 147.10°
	I	61.49 < 176.95°	61.77 < 58.21°	60.72 < -62.64°
671-692	V	2380 < 26.14°	2404 < -92.37°	2356 < 146.47°
	I	00.00 < 00°	0.00 < 00.00°	30.96 < 104.86°
692-675	V	2379 < 25.98°	2407 < -92.34°	2352 < 146.48°
	I	71.6 < 4.59°	12.61 < -133.77°	48.83 < 110.31°
671-684	V	2395 < 26.56°	0.00 < 00.00°	2369 < 147.07°
	I	0.00 < 00.00°	0.00 < 00.00°	23.43 < 153.75°
684-611	V	0.00 < 00.00°	0.00 < 00.00°	2369 < 147.03°
	I	0.00 < 00.00°	0.00 < 00.00°	23.43 < 153.74°
684-652	V	2392 < 26.51°	2392.20 < 26.51°	0.00 < 00.00°
	I	21.32 < 172.62°	0.00 < 00.00°	0.00 < 00.00°
680	V	2400 < 26.70°	2411 <-92.04°	2370 < 147.10°
	I	0.00 < 00.00°	0.00 < 00.00°	0.00 < 00°

Appendix B

Wind Turbine and component model in MATLAB

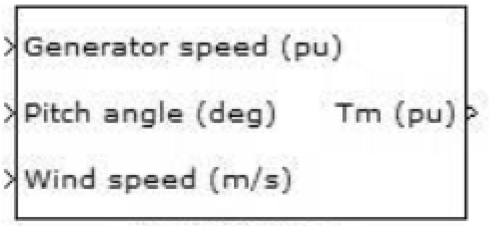


Figure 4: wind turbine block

The block that simulates the wind turbine has for inputs the generator speed, which in the WTIG is the rotor speed of the asynchronous machine. The other two inputs are the angle of the wind turbines blades (pitch angle β) and the wind speed, which can be defined by the user. To compute the pitch angle of the wind turbines blades it’s used a proportional integrator derivative controller, which limits the electric output power to the nominal power. This action only occurs when the electric output power exceeds the nominal power. Until that point the pitch angle is equal to zero. When the nominal power is reached the controller acts by increasing the pitch angle until the nominal and electric output power are equal. The wind turbine has for an output the mechanical torque. The mechanical torque of this turbine will be the input for the induction generator of the WTIG

Static Synchronous Compensator (STATCOM)

Figure A5: STATCOM block

Inputs:

- Trip - This input can be a logical signal (0 or 1). When the input is HIGH, the STATCOM is disconnected and its control system is disabled.
- Vref - This input will only be visible if the option External control of reference voltage Vref is checked.

Outputs:

- m - Output vector containing many internal signals. Each of these signals can be accessed individually using a Bus Selector. The signals are:

1. Va_prim (pu), Vb_prim (pu) and Vc_prim (pu) - The first three signals of the output vector contain the phasor voltages (phase to ground) Va, Vb and Vc at the STATCOM primary terminals;
2. Ia_prim (pu), Ib_prim (pu), Ic_prim (pu) - These three signals contain the phase currents Ia, Ib and Ic flowing into the STATCOM;

3. Vdc (V) - DC voltage;
4. Vm (pu) - Positive-sequence value of the measured voltage (pu);
5. Vref (pu) - Reference voltage;
6. Qm (pu) - STATCOM reactive power. A positive value indicates inductive operation;
7. Qref (pu) - Reference reactive power;
7. Id (pu) - Direct-axis component of current (active current) flowing into STATCOM. A positive value indicates active power flowing into the STATCOM;
9. Iq (pu) - Quadrature-axis component of current (reactive current) flowing into STATCOM. A positive value indicates capacitive operation;
10. Idref (pu) - Reference value of direct-axis component of current flowing into the STATCOM;
11. Iqref (pu) - Reference value of quadrature-axis component of current flowing into the STATCOM;
12. modindex - The modulation index m of the PWM modulator. A positive number (m) between 0 and 1. When m equals to 1 it means that the VSC (Voltage-Sourced Converter) is generating the maximum voltage without over modulation;

- A, B and C - The three terminals of the STATCOM

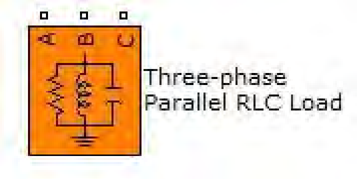


Figure A6: 3-phase load

The three-phase parallel RLC load block models a three-phase balanced load as a parallel combination of RLC elements. Its inputs and outputs are the three-phase terminals A, B and C.
This load absorbs active and reactive power proportionally to the square of the applied voltage to its terminals. The impedance value is constant for a specified frequency.

The user can define the nominal phase-to-phase voltage, the nominal frequency, the active power of the load and the inductive and capacitive reactive power, positive and negative Var, respectively.

The connection of the three phases of the load can also be defined with the following options:

- Y (grounded) - Neutral is grounded;
- Y (floating) - Neutral is not accessible;
- Y (neutral) - Neutral is made accessible through a fourth connector;
- Delta - Three phases connected in delta.

This block also gives the possibility to measure the three voltages across each phase of the Three-Phase Parallel RLC Load block terminals. The measurements can be accessed through a Multimeter block.

If the Branch voltages option is selected, the three voltages across each phase of the block are measured. For a Y connection, these voltages are the phase-to-ground or phase-to-neutral voltages and for a delta connection, these voltages are all phase-to-phase voltages.

If the Branch currents option is selected, the three total currents (sum of R, L and C currents) that flow through each phase of the load are measured. For a delta connection, these currents are the currents flowing in each branch of the delta.

Finally, if the Branch voltages and currents option is selected, the three voltages and three currents of the load are measured.

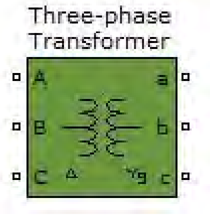


Figure A7: Three-phase transformer

The block implements a mode of a three-phase transformer using three single-phase transformers. It has as inputs and outputs the three-phase terminals (A, B, C, a, b and c).

The transformer is based on three single-phase transformers that can be either linear transformers or saturation transformers. This option can be made in the transformer's parameter menu. In this test platform, linear transformers were used for the simulations.

The two windings of the three-phase transformer can have one of the following connections:

- Y;

- Y with accessible neutral;
- Grounded Y;
- Delta (D1), delta lagging Y by 30 degrees;
- Delta (D11), delta leading Y by 30 degrees;

If the Y with accessible neutral option is selected, a new output will appear with the label N.
The parameters that can be defined are the nominal power, the frequency, the magnetization resistance and inductance and, for each winding, the phase-to-phase voltage, the winding resistance and the leakage inductance

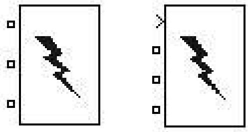


Figure A8: Three-phase fault blocks.

The block can simulate a three-phase fault in a network. It implements a three-phase circuit breaker where the opening and closing times can be controlled either from an external Simulink signal (if the external control mode is selected) or from an internal control timer (if the intern 86 control mode is selected). If the intern control mode is selected, the user can define the transition times in the parameter menu. As inputs and outputs, this block has the three-phase terminals that can be connected to the network and has as a possible input, the external control signal as mentioned before.
The Three-Phase Fault block uses three Breaker blocks that can be controlled individually, depending on the kind of fault that the user to simulate. The faults can be phase-to-phase, phase-to-ground or a combination of phase-to-phase and ground faults.

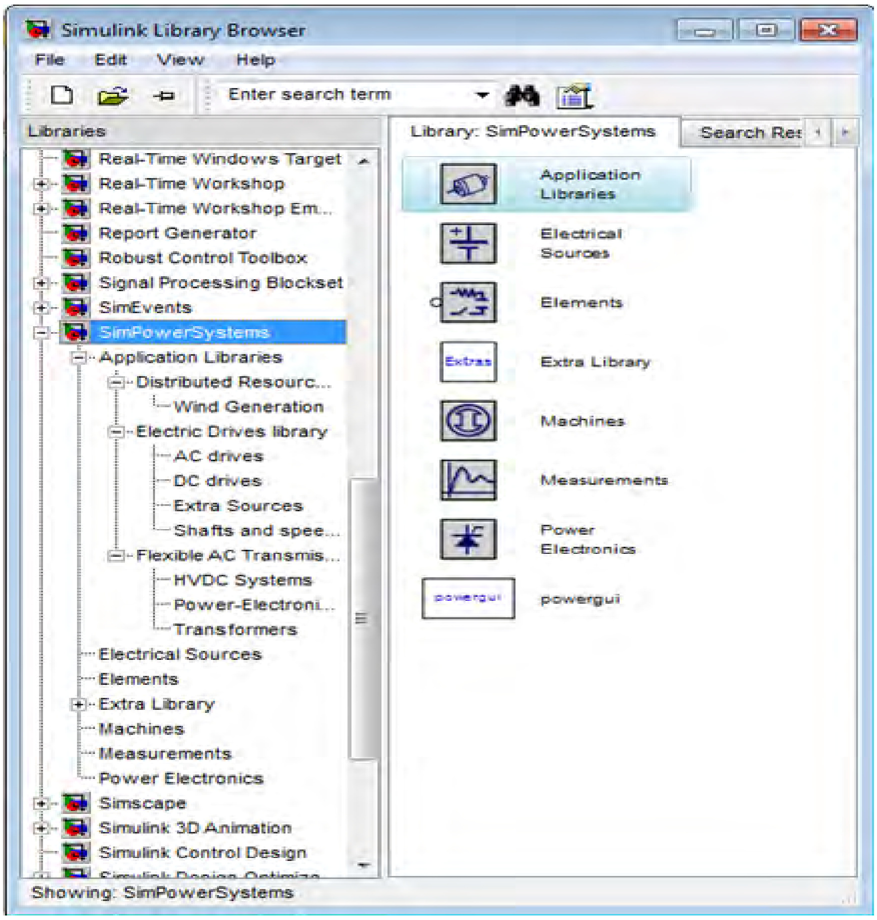


Figure A9: Modelling in MATLAB/SIMULINK

In building an electrical Circuit with powerlib Library, the grouped of an electrical components are contained in a library called powerlib, graphical user interface makes use of the Simulink functionality to interconnect various electrical components together. The following steps can be followed

- Open the SimPowerSystems main library by entering the command at the MATLAB prompt powerlib, the command displays a Simulink window showing icons of different block libraries. From the File menu of the powerlib window, open a new window containing your first circuit and save it. Open the Electrical Sources library and copy electrical source (e.g. Voltage source, current source, programmable source) block into the circuit window.
- Select any electrical component needed from the library element, machine and application library. Name and resize the block, interconnect the blocks by dragging lines from outputs to inputs of appropriate blocks.
- The voltage measurement block can be copied to measure the voltage; a display system (scope) is needed, which can be copied from the Simulink Sinks library.

Powergui block

For any simulation to be performed in the Simulink using elements from the SimPowerSystems library, Powergui block must be added to the model, it is necessary for the simulation of any Simulink model containing SimPowerSystems blocks. It is used to store the equivalent Simulink circuit that represents the state-space equations of the SimPowerSystems blocks The presence of Powergui in the circuit designed allows different simulation solution. However, the simulations included in this thesis use the phasor solution method for the Wind Turbine Doubly-Fed Induction Generator

- Continuous method, which uses a variable step Simulink solver;
- Ideal Switching method;
- Discretization of the electrical system for a solution at fixed time steps;
- Phasor solution method.

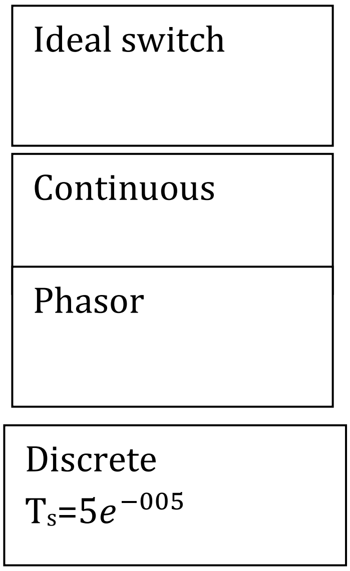


Figure A10: possible appearances of the Powergui block.

Load model

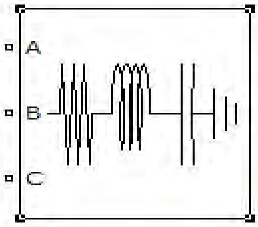
The Three-Phase Series RLC Load block implements a three-phase balanced load as a series combination of RLC elements. At the specified frequency, the load exhibits constant impedance. The active and reactive powers absorbed by the load are proportional to the square of the applied voltage

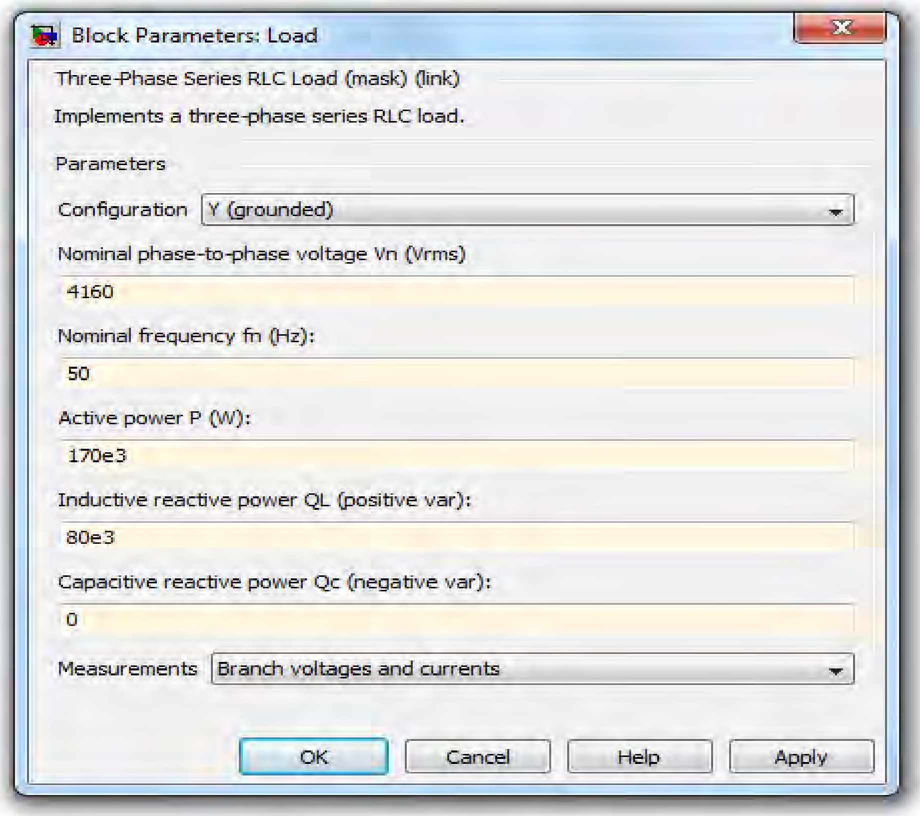
Nominal phase-to-phase voltage: The nominal phase-to-phase voltage of the load, in volts RMS (Vrms).

Nominal frequency: The nominal frequency, in hertz (Hz).

Active power: The three-phase active power of the load, in watts (W).

Inductive reactive power: The three-phase inductive reactive power QL, in vars. Specify a positive value, or 0.
Capacitive reactive power: The three-phase capacitive reactive power QC, in vars. Specify a positive value, or 0.
Measurements: Branch voltages can be selected to measure the three voltages across each phase of the Three-Phase Series RLC Load block terminals. For a Y connection, these voltages are the phase-to-ground or phase-to-neutral voltages. For a delta connection, these voltages are the phase-to-phase voltages. Branch currents can be selected to measure the three total currents (sum of R, L, C currents) flowing through each phase of the Three-Phase Series RLC Load block. For a delta connection, these currents are the currents flowing in each branch of the delta





Three-Phase Series RLC Load (mask) (link)

Implements a three-phase series RLC load.

Parameters

Configuration: Y (grounded)

Nominal phase-to-phase voltage Vn (Vrms): 4160

Nominal frequency fn (Hz): 50

Active power P (W): 170e3

Inductive reactive power QL (positive var): 80e3

Capacitive reactive power Qc (negative var): 0

Measurements: Branch voltages and currents

Figure A11: Three phase measurement and Bus bar

The Three-Phase V-I Measurement block is used to measure three-phase voltages and currents in a network. When connected in series with three-phase elements, it returns the three phase-to-ground or phase-to-phase voltages and the three line currents. The block can output the voltages and currents in per unit (pu) values or in volts and amperes. If voltage and current are to be measured in pu, the Three-Phase V-I Measurement block does the following conversions:

$$V_{abc}(pu) = V_{abc}(pu) = \frac{V_{abc}(pu)}{\frac{V_{baseLL}}{\sqrt{3}} \times \sqrt{2}}$$

$$I_{abc}(pu) = \frac{I_{abc}(pu)}{\frac{P_{base}}{V_{base}.\sqrt{3}} \times \sqrt{2}}$$

Where VbaseLL is the base line-to-line voltage in volts RMS and Pbase is the three-phase base power in volts-amperes. The two base values VbaseLL and Pbase are specified in the Three-Phase Measurement block menu. Three phase measurement block can use to make bus bar model, this is done by clicking on “used a label” inside the three phase measurement block and try to reduce the block to a desired block.

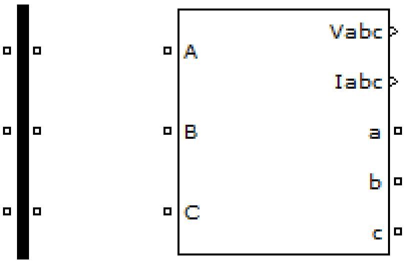
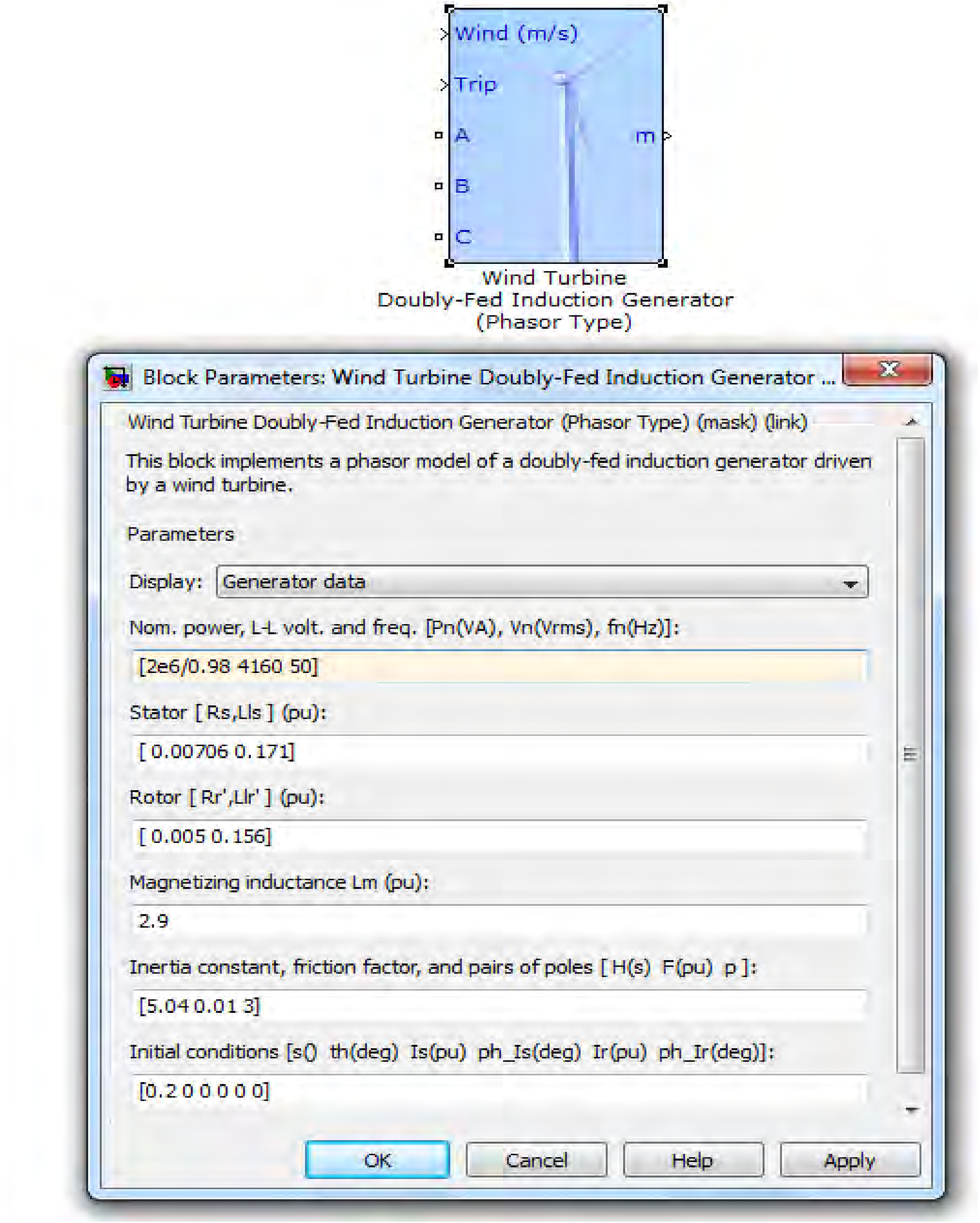


Figure A12 three phase measurement

Representation of DFIG in Simulink (power tool box)

The Figure below shows the representation of DFIG in the power system tool box, the wind turbine and the generator has been built together as one unit. Parameters of the wind turbine and the generator can only be input into the system.



Wind Turbine Doubly-Fed Induction Generator (Phasor Type) (mask) (link)

This block implements a phasor model of a doubly-fed induction generator driven by a wind turbine.

Parameters

Display: Generator data

Nom. power, L-L volt. and freq. [Pn(VA), Vn(Vrms), fn(Hz)]: [2e6/0.98 4160 50]

Stator [Rs,Lls] (pu): [0.00706 0.171]

Rotor [Rr',Llr'] (pu): [0.005 0.156]

Magnetizing inductance Lm (pu): 2.9

Inertia constant, friction factor, and pairs of poles [H(s) F(pu) p]: [5.04 0.01 3]

Initial conditions [s() th(deg) Is(pu) ph_Is(deg) Ir(pu) ph_Ir(deg)]: [0.2 0 0 0 0 0]

Figure A13: Simulink block for the DFIG

Input

- **Wind (m/s)** - Input of the wind speed can be either a function or a constant. One can use an interpolation of several wind velocities to simulate the wind evolution over time. If the option External mechanical torque is selected, the wind velocity input will not be visible;
- **Trip** - Command signal of the wind turbine protection system. When the value of the trip is zero (LOW) the protection system isn't active. The protection system will be activated when the trip value is equal to one (HIGH), which will happen when any of the generator's measurements exceeds the reference values that were established.

When the system is activated, the wind turbine is turned off, which means that the generation of active and reactive power is equal to zero;

- **Tm** - This input will only be visible if the External mechanical torque option is selected. The mechanical torque must be negative for power generation. This input should be used with an external turbine model;
- **Vref** - This input is only visible when the Mode of operation parameter is set to Voltage regulation or when the External grid voltage reference is selected. We can define this reference value;
- **Qref** - This input is only visible when the Mode of operation parameter is set to Var regulation or when the External generated reactive power reference is selected. We can define this reference value;
- **Iq_ref** - This input is only visible when the parameter External reactive current Iq_ref for grid-side converter is selected. We can define this reference value.

Outputs:

1. **M** - Output vector which contains 8 signals from the Wind Turbine Doubly-Fed Induction Generator (WTDFIG). Each signal can be accessed individually using a Bus Selector. The signals are:

- Iabc (complex) (pu) - Phasor currents Ia, Ib e Ic, that flow in the WTDFIG terminals;
- Vabc (complex) (pu) - Phase to ground voltages Va, Vb e Vc at the WTDFIG terminals;
- Vdq_stator (pu) - **d** and **q** components of the stator voltage. Vd_stator and Vq_stator are respectively the real and imaginary components of the positive sequence voltage of the stator;
- Iabc_stator (complex) (pu) - Phasor currents Ia, Ib e Ic that flow in the stator;
- Idq_stator (pu) - **d** and **q** components of the stator current. Id_stator and Iq_stator are respectively the real and imaginary components of the positive sequence current in the stator;
- Vdq_rotor (pu) - **d** and **q** components of the rotor voltage. Vd_rotor and Vq_rotor are respectively the real and imaginary components of the positive sequence voltage of the rotor;
- Idq_rotor (pu) - **d** and **q** components of the rotor current. Id_rotor and Iq_rotor are respectively the real and imaginary components of the positive sequence current in the rotor;

- wr (pu) - Generator rotor speed in pu;
- Tm (pu) - Mechanical torque applied to the generator in pu;
- Te (pu) - Electromagnetic torque in pu
- Vdq_grid_conv (pu) - **d** and **q** components of the grid side converter voltage. Vd_grid_conv e Vq_grid_conv are respectively the real and imaginary components of the positive sequence voltage of the grid side converter
- Iabc_grid_conv (complex) (pu) - Phasor currents Ia, Ib e Ic that flow in the grid side converter
- P (pu) - Output active power of the WTDFIG in pu. If this value is greater than zero in means that there is generation of active power
- Q (pu) - Output reactive power of the WTDFIG in pu. If this value is greater than zero in means that there is a generation of reactive power
- Vdc (V) - DC voltage in the WTDFIG
- Pitch_angle (deg) - Pitch angle of the blades o the WTDFIG in degrees.
- A, B and C - The three terminals of the WTDFIG.

IEEE 13 bus feeder impedances conversion to positive, negative and zero sequence using MATLAB code

```
 %Title: Calculating the positive, negative and zero sequence impedances
 %------------Input the impedance values given------------------------------
Zaa=input('Enter the value for Zaa: ');
Zab=input('Enter the value for Zab: ');
Zac=input('Enter the value for Zac: ');
Zbb=input('Enter the value for Zbb: ');
Zbc=input('Enter the value for Zbc: ');
Zcc=input('Enter the value for Zcc: ');
 %-------------Forming the original impedance matrix------------------------
Z1=[Zaa Zab Zac];
Z2=[Zab Zbb Zbc];
Z3=[Zac Zbc Zcc];
Zabc=[Z1;Z2;Z3];
 %-------------Formation of the transformation matrix,A--------------------------
a=-0.5+ (sqrt(3)/2)*1i;
a2=-0.5- (sqrt(3)/2)*1i;
A1=[1 1 1];
A2=[1 a2 a];
```

```
A3=[1 a a2];
A=[A1;A2;A3];
 %------------Calculating the sequence impedance matrix-------------------
I=eye(3);
Ainv=A\I;
 %------------Displaying the sequence impedance matrix--------------------
Z012=Ainv*Zabc*A;
```

Self inductance = $L_{ii} = 2\times10^{-7}\ln\frac{1}{GMR}$ (H/M)
Mutual inductance = $L_{in} = 2\times10^{-7}\ln\frac{1}{D}$ (H/M)
Phase inductance = $L_i = 2\times10^{-7}\ln\frac{D_{eq}}{GMR}$ (H/M)
Phase reactance = $x_i = w.L_i = 0.12134\times L_i$
$Z_{positive} = R + j0.1213.\mathrm{In}\,\frac{D_{eq}}{GMR}\,\Omega/mile$
$Z = \sqrt{R + (X_L + X_C)}$
R = conductor resistance (from Table)Ω/mile
$D_{eq} = \sqrt[3]{D_{eq}.D_{eq}.D_{eq}}$ (ft)
GMR = conductor geometric mean radius (ft) (from Table)
D = distance between the conductor

```
Z1=[Zaa Zab Zac];
Z2=[Zab Zbb Zbc];
Z3=[Zac Zbc Zcc];
```

Zaa = Zero sequence
Zbb = Positive sequence
Zcc = Negative seguence
or
Self impedance = $z_s = \frac{1}{3}.z_{aa} + z_{bb} + z_{cc}$
Mutual inpendance = $z_m = \frac{1}{3}.z_{ab} + z_{bc} + z_{ca}$
Zero sequence = $z_{oo} = z_s + 2.z_m$
Positive sequence = $z_{11} = z_s - z_m$

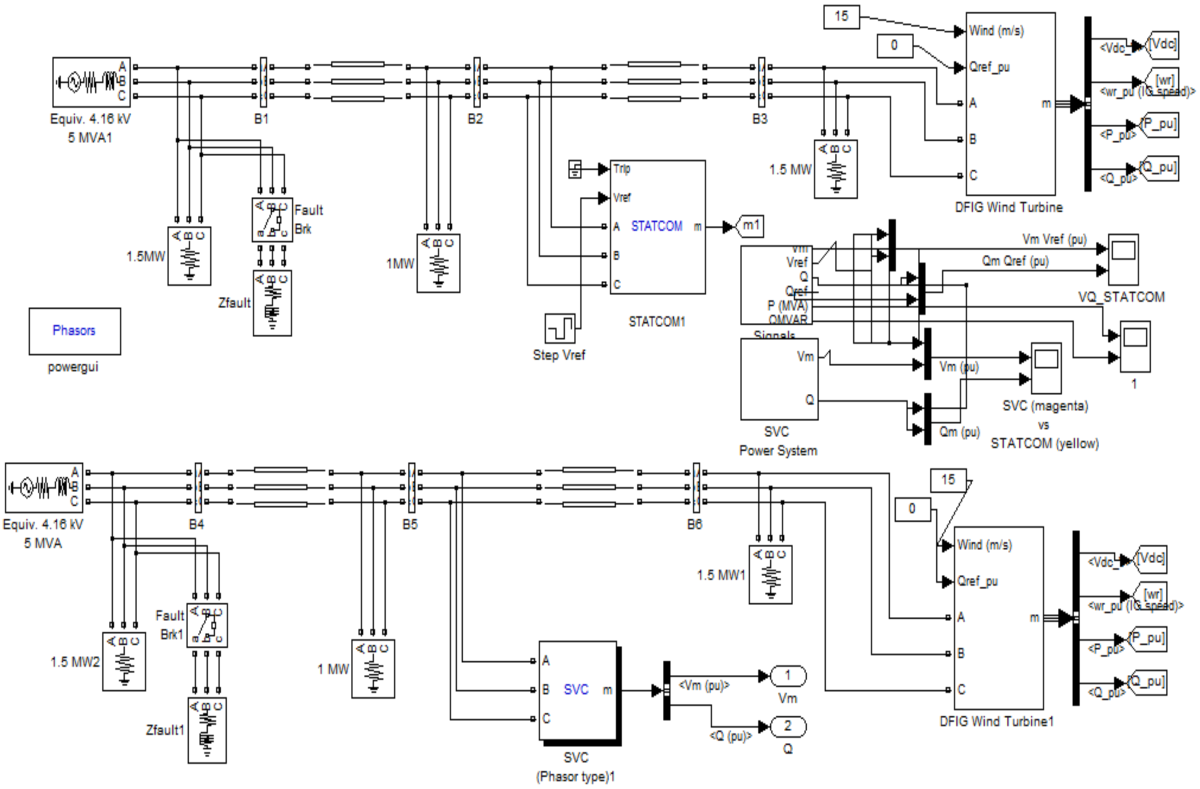


Figure A14: Comparison of SVC and STATCOM diagram layout in MATLAB/SIMULINK

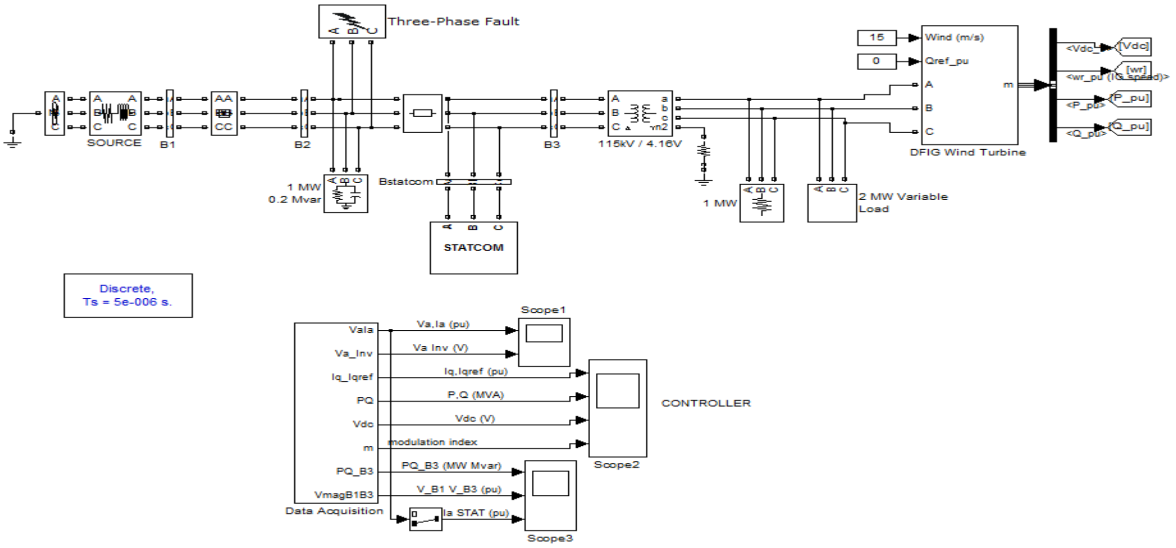


Figure A15: Voltage dips and flicker mitigation by STATCOM diagram layout in MATLAB/SIMULINK

Appendix C

Turbine and Wind Speed Blocks in PSCAD

The wind speed block is built with components in PSCAD/EMTDC library as seen in Figure 1, and is comprised of a mean wind component, a gust wind component, a ramp wind component and a noise wind component. The turbine block which consists of a rotor model, a shaft model and a pitch system are implemented, the output of this block is the torque and it is directly input to the generator block. The trip signal is used in emergency conditions to switch off. Pitch System turns the blades in required angles to decrease the power output of the turbine whenever this signal is received.

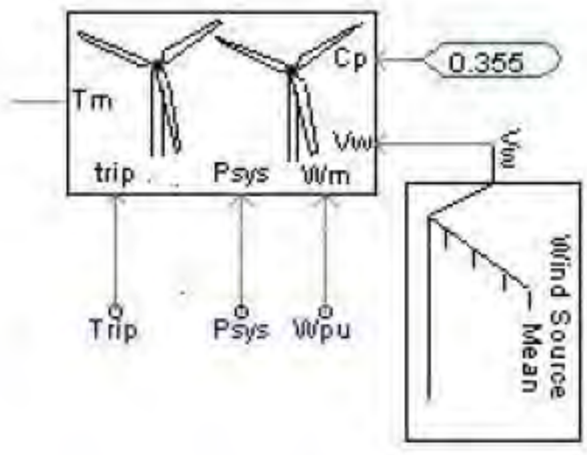


Figure A16: Block Diagram of Turbine and Wind Speed Model in PSCAD

Generator Block

The wound rotor induction generator available in PSCAD/EMTDC main library is used to represent DFIG block. The generator can be operated in either 'speed control' or 'torque control' modes. Generally, the machine is started in speed control mode with the *W* input set to rated per-unit speed and then switched over to torque control via the selection input, *S*, after the initial transients of the generator die out. The block provides 3-phase terminals for stator connection to the grid and 3-phase terminals to rotor windings for rotor side converter connection. The block can internally provide rotor position, mechanical and electrical torques and the shaft speed as output signals.

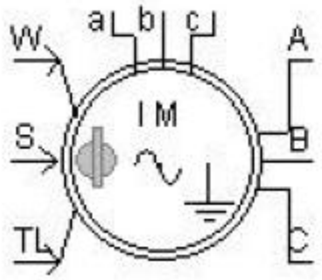


Figure A17: Diagram of the DFIG in PSCAD

Converter Blocks

Grid-side and rotor-side converters are shown in Figure below,

Vga, Vgb, Vgc are the reference inputs to the grid-side controlled voltage sources sent by grid-side controller and Vra, Vrb, Vrc are the reference inputs to the rotor-side controlled voltage sources sent by rotor-side controller, the grid-side converter is connected to the grid through a filter circuit

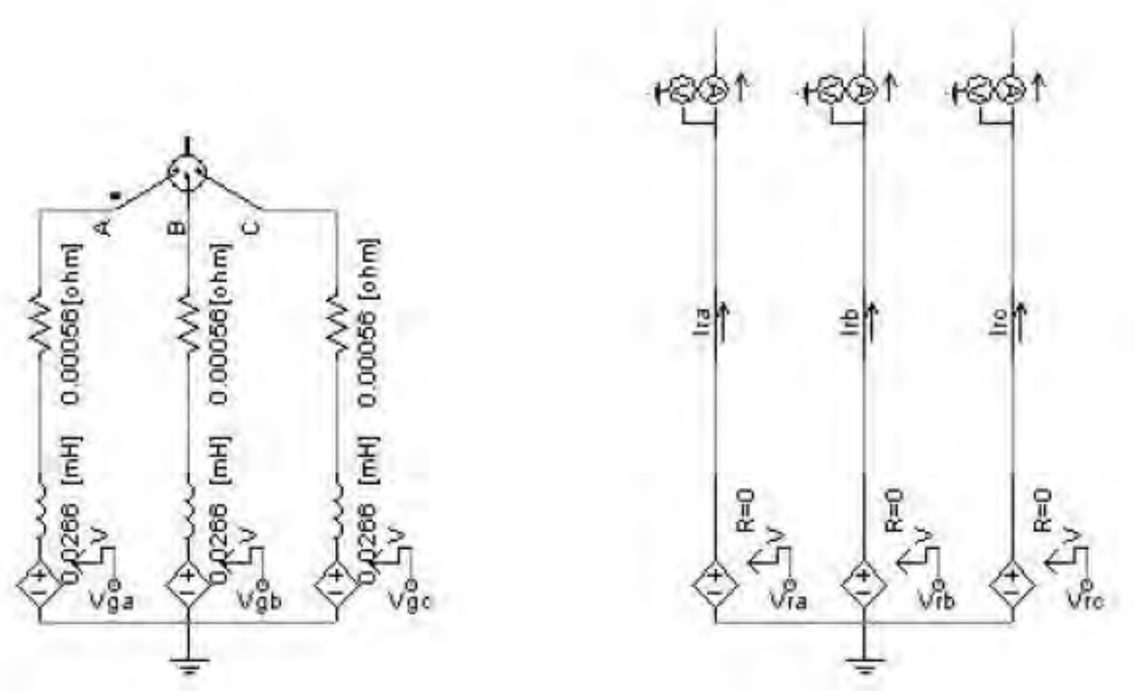


Figure A18: Grid side and rotor side converter in PSCAD

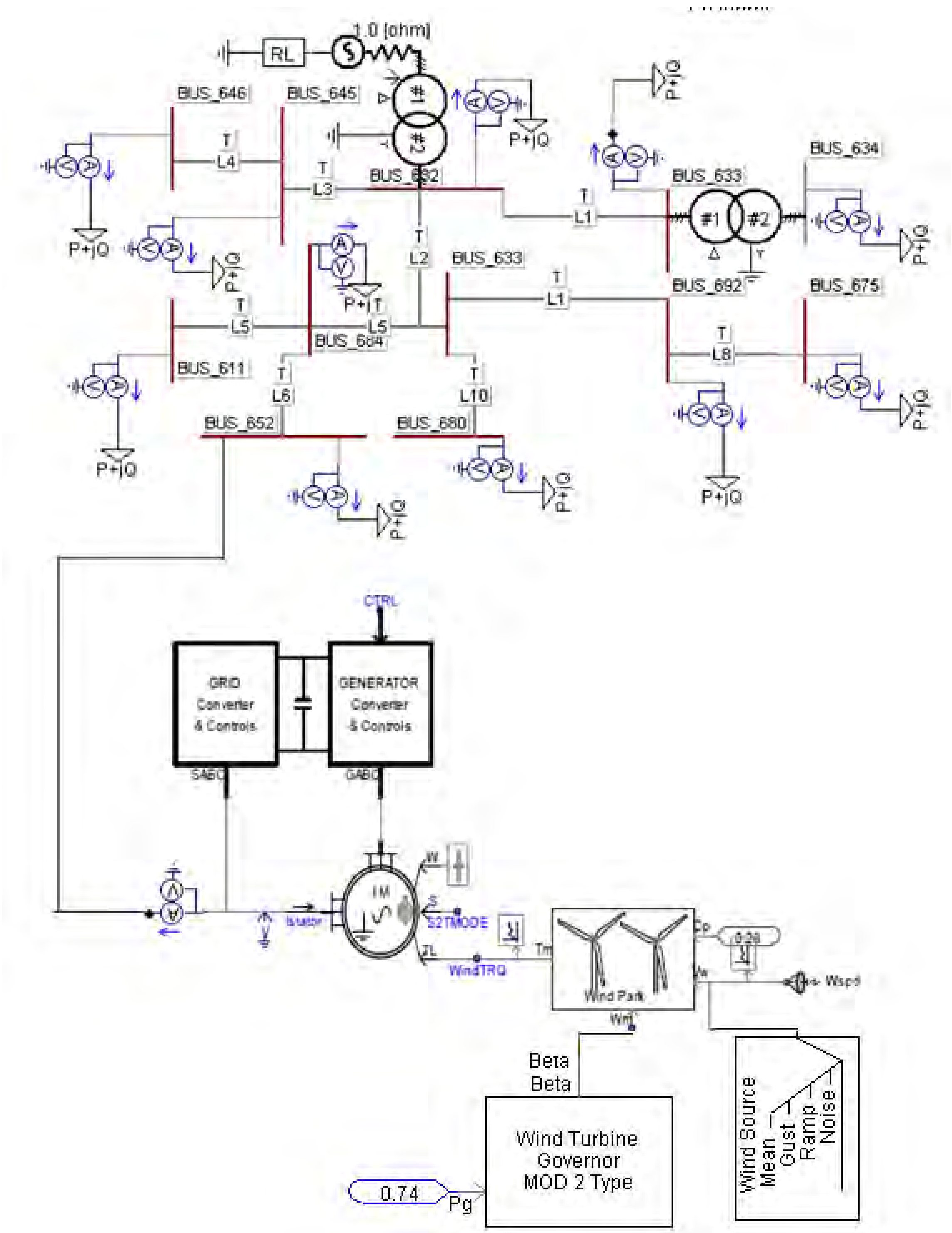


Figure A19: Wind farm

APPENDIX D

Simulation similarity in MATLAB/SIMULINK and PSCAD

The simulation result showed below similar to each other.

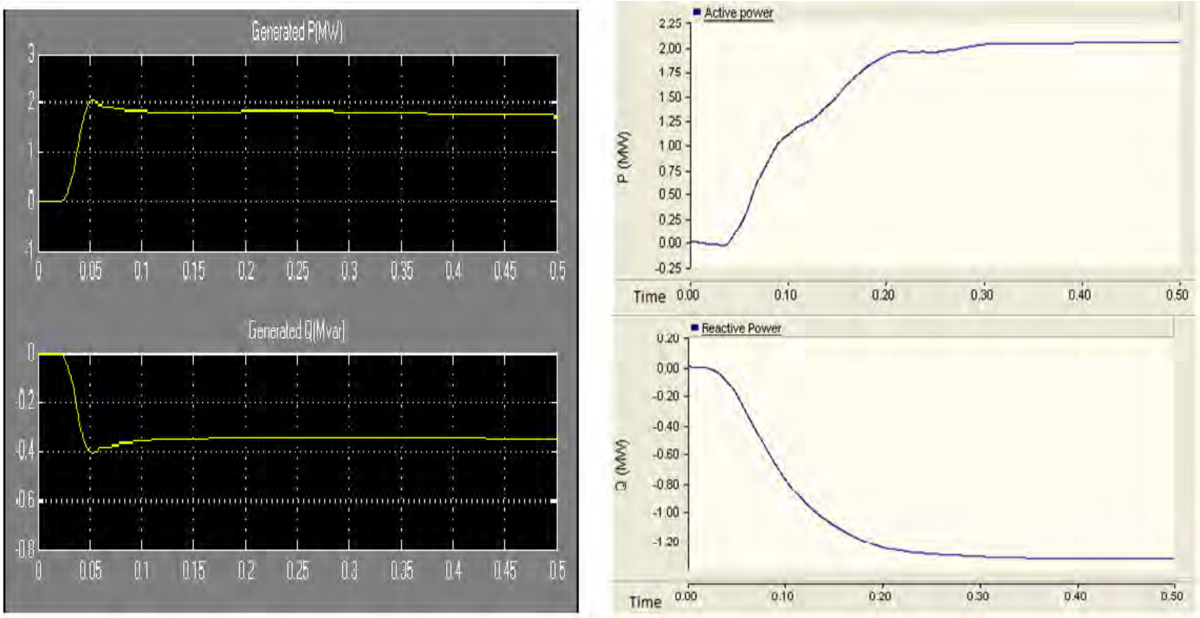


Figure A20: Active and reactive power in MATLAB/PSCAD