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INTEGRATION OF WIND ENERGY SYSTEMS INTO THE GRID: POWER QUALITY AND TECHNICAL REQUIREMENTS

BY

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THESIS SUBMITTED IN FULFILLMENT OF THE REQUIREMENTS FOR A MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

MARCH 2010

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DECLARATION

I, Taru Madangombe hereby declare that the work contained in this thesis is my own work. All information obtained from reference material has been properly acknowledged. I declare all simulations and analysis carried out in this thesis was conducted by me without the help of anyone. Guidance was however provided by Prof. K.A Folly, Dr Sebitosi and Prof Pillay

The conclusions are based on my own understanding of the literature and results of the simulation studies conducted.

Signature: Date:

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Taruziwa Madangombe

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ACKNOWLEDGEMENTS

Firstly, I would like to that the Lord God for giving me the strength and support in guiding me throughout all my work to this point of my academic career. It has been a long and insightful journey but thank God, He has made it possible.

My sincere gratitude is due to my supervisor, Prof. K.A Folly for his guidance, financial support and supervision throughout my MSc Project. Moreover, i wish to add my extended thankfulness to my co-supervisors Prof P. Pillay and Dr Ben Sebitosi for their knowledgeable input and analytical assistance with regards to shaping up my research.

I would also like to express my extended thankfulness to my colleagues and research groups, the AMES and Power System Research Group.

Furthermore, I wish to extend my sincere gratitude to Mr Riaan Smit from Eskom Western Region, for his untiring efforts and support during my research work.

I would like to thank the following people who have supported me during my research:

- Ake Larson
- Bernard Magoro, NERSA
- DIgSILENT Support Centre

Finally, I would like to thank my mum and the rest of the family, my girl friend and my close friends for giving me the love and moral support I needed when the going went tough.

SYNOPSIS

The integration of wind energy into the utility network has increased significantly over the past years largely as a result of the increasing environmental concerns arising from the use of fossil fuels, coupled with the anticipated global increase in oil. In South Africa, the wind energy industry is still in its infancy, with the Klipheuwel (about 3.2 MW) and Darling (about 4.2 MW) wind farms being the only grid connected projects in the country. However, grid integration studies carried out in [1] have shown that there are over 7 000 MW potential ideas for wind power in the Western Cape alone and this is a clear indication that there is a growing interest in wind development locally. The Government has also set a 4% target for the development of the renewable energy in the country by 2013 [2]

In light of the above, this thesis discusses some of the technical requirements and power quality issues that need to be addressed in order to fully integrate wind power into the network without adversely affecting the operation of the grid. These have been researched through reviewing the various standards and grid codes for wind power that have been implemented in other leading countries, in order to identify some of the requirements that can be adapted to suit our local integration process.

Some of the main technical issues that are discussed in this thesis include the strength of the grid (fault levels), permitted penetration levels, choice of wind turbine and the reactive power requirements of the network. All these issues contribute towards the resolution of the impact of wind turbines on the power quality of the network, especially at the point of common coupling or connection (PCC). Various power quality phenomena were discussed in the literature but the ones that were further investigated included the voltage level profile, harmonic distortions as well as reactive power requirements from the wind turbines. These were determined both during the steady operation of the network and during a network disturbance.

The fixed speed wind turbine (FSWT) and the variable speed wind turbine (VSWT) are two main types of wind turbine technologies that have been investigated. The FSWT were the earlier technologies to be manufactured during the development of wind energy and they are equipped with induction machines that are directly coupled to the grid and operate over a fixed speed range. The VSWT however are the modern turbines with more aerodynamic efficiency which allows them to operate over a broad range of wind speeds [3]. The variable speed wind turbines (e.g. doubly-fed induction generator (DFIG) and full converter-driven synchronous generator) are highly favoured over the fixed speed wind turbines (e.g. squirrel cage induction generator (SCIG)) mainly due to their power electronic devices which enable them to control the speed and reactive power of the generator [3], thereby demonstrating better power quality characteristics.

Having described the various wind turbine models used for power quality analysis, the impacts of DFIG and SCIG on the grid were investigated by carrying out computational simulations using the DIgSILENT software package. A simplified network of the proposed 100 MW Juno Wind Farm which mostly consists of existing data from Eskom was modeled and used as a basis for most of the studies conducted in this thesis. The studies involved connecting the DFIG and SCIG at various penetration levels (between 0 – 100 MW, though in some cases the generated power was increased beyond 100 MW so as to establish worst case conditions) in order to compare their impacts on the power quality of the network. As expected, the studies showed that the DFIG performed better than the SCIG in terms of controlling the voltage profile at the point of common connection. This is attributed to its power electronic converter that controls the reactive power to the network as compared to the SCIG which draws reactive power from the network. The SCIG should always be fitted with a capacitor bank (in this case it was found to be about 25% of its MW rating of the wind farm, i.e. 500kVar for every 2 MW of SCIG) in order to maintain the voltage levels within the acceptable limits.

Additional findings from the literature indicate that a fairly large number of areas along the Cape west coast which have a higher density of wind and are located closer to an MV networks which happen to be typified by remote and long transmission lines, a characteristic of weak grid networks [4. The impacts of the grid strength on the operation of the wind turbines were performed to figure out the likely effects of wind turbines connected in weak grids. The strength of grid was determined by calculating the short-circuit power levels (fault levels) using the DIgSILENT software tool. The simulations showed that the fault level contributions from the simulated 100 MW wind farm of both DFIG and SCIG were fairly noticeable with a contribution of about 27% and 17% respectively. However, in practise these values seem inflated as we would expect very minimal fault level contribution from a 100 MW farm connected to a stronger part of the grid. Other interesting observations showed that the DFIG had higher fault level contributions as compared to the SCIG, possibly due to the DFIG's partial interface with the grid through electronic power converters.

The proposed point of common connection between the wind farm and the rest of the grid (at the 132 kV busbar) was found to be the stronger part of the grid and was least affected by the connection of the 100 MW wind farm. Studies performed showed that the voltage profile problems became more apparent when the wind farm was connected at relatively weaker parts of the network. This may be due to higher voltage drops and increased losses resulting from the limited power transfer capability of weaker networks.

Even though DFIG have shown to have better reactive power and voltage control as compared to SCIG, they do have a tendency to inject unwanted harmonic currents into the grid as a result of some unexpected defects in the switching of their converters [5]. These harmonic currents may cause harmonic distortions on the network and thus the percentage total harmonic distortions (%THD) at the point of common connection were calculated in DIgSILENT. It was found that the proposed 100 MW wind farm contributed 3.79% THD which was less than the 8% specified in the European Standard, EN 50160. However, a further increase in penetration levels may cause the %THD to go outside the permissible limits. This would require a harmonic filter to be installed in order to mitigate the harmonics. A worst case scenario was presented which showed the %THD level rising above the allowable limits and a simple design of a single-tuned filter was connected to the grid which eventually reduced the harmonic distortions to acceptable limits. This exercise was performed additionally to show the design requirements and mitigation capability of a filter. Otherwise modern wind turbines have power electronic devices that are capable of reducing the harmonic distortions to near zero [6].

With the higher penetration levels of wind power into the network, wind power may be required to provide support to the network during grid disturbances such as faults [7]. The behaviour of wind turbines during a system was investigated by applying a fault and removing it after 100ms. The study showed that the DFIG wind turbine had a faster voltage recovery as compared to the SCIG and more over, its voltage level after the fault was cleared and returned almost to its pre-fault voltage (0.99p.u) as opposed to the SCIG (0.95 p.u.). In addition to this, voltage drop during the fault was less for a DFIG (0.75p.u) as compared to that of SCIG (0.45.pu). All these investigations support the fact that the DFIG has a better performance during a disturbance as compared to a SCIG. However, when a voltage controller is added to the SCIG, its performance improved significantly.

Currently in South Africa, there are no formal guidelines or regulations available for the connection of wind turbines into the grid. Therefore based on the findings from the literature, as well as simulation studies carried out in this thesis, the author identified some requirements to be recommended to the future grid.

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LIST OF SYMBOLS AND ABBREVIATIONS

DFIG	: Doubly-fed Induction Generator
FSWT	: Fixed Speed Wind Turbines
GTO	: Gate Turn-Off thyristor
HD	: Harmonic distortion
HVDC	: High Voltage Direct Current
IEC	: International Electrotechnical Commission
IGBT	: Integrated Bipolar Transistor
MOSFET	: Metal Oxide Semiconductor Field Effect Transistors
MW	: Mega-Watts
PCC	: Point of common connection
PU	: Per unit
RES	: Renewable Energy Sources
RMS	: Root mean square
THD	: Total harmonic distortion 0
VSWT	: Variable Speed Wind Turbines
SCC	: Short circuit current
SCIG	: Squirrel Cage Induction Generator
VSC	: Voltage Source Converter
WT(s)	: Wind Turbine(s)

1 INTRODUCTION

This research seeks to investigate the technical issues associated with the integration of wind energy into the utility grid. The main area of concern involves the impact of wind turbines on the power quality of the grid. Of key interest is the impact these wind turbines have on the voltage quality of the utility network, mainly at the point of common connection.

The Government of South Africa, in collaboration with Eskom and other related stakeholders are aggressively promoting renewable energy in South Africa. This is necessary because of the recent power supply problems experienced in South Africa as a result of the increasing load demand caused by South Africa's economic growth.

Some of the renewable energy interventions that Eskom is planning on pursuing include the project on the Cape West coast to install 100 MW (with the intention to increase to 200 MW) of wind energy [7]. This is a major initiative by the local utility and it will be interesting to investigate the power quality issues that would be associated with the integration of wind farms into the grid

In this thesis, a number of studies have been conducted in order to investigate the power quality concerns that are associated with integration of wind turbines into the network. From the literature conducted, it emerged that voltage quality issues were of notable concern at the point of connection of the wind turbine to the grid and these were extensively investigated in this thesis.

1.1 Background and objectives

A global trend shows an increase in the integration of renewable energy into the grid over the last couple of years, with a number of small to medium scale renewable energy technologies being connected onto the grid [8]. The growing global need for environmentally friendly energy resources as well as the anticipated shortage of the oil resources coupled with oil price hikes has facilitated the need to move into alternative sources of energy. The most common renewable energy technologies that have been of interest include wind, solar, wave, ocean and biomass, just to mention a few. Wind energy seems to be growing extensively, with leading countries which include Germany (with over 7% penetration levels i.e. over 20 GW of wind capacity connected), Denmark (with over 20% contribution to total power capacity), Spain and the United State of America just to mention a few [8]. The growth of wind energy in Germany from a mere 100 MW to over 20 GW in a period of over ten years is a strong indication that wind energy is growing fast and that it is possible to integrate more wind energy onto the grid as long as proper guidelines are followed [8] .

In developing countries, like South Africa, wind energy is not yet fully integrated on to the grid. The general move towards wind energy and other renewable energy is still in its infancy and hence Eskom and its stake holders have decided to put more emphasis on promoting the use of renewable energy locally. The target of over 4 % of electricity to be generated from renewable energy by 2013 is one such drive which has strengthened the need to focus on grid connected renewable energy, with wind being one of the main subjects of interests [2].

The research basis should mainly focus on technical characteristics that distribution planners may consider as a selection criteria to assess requests by customers that are willing to connect their wind power plants into the grid. At the time of publication of this thesis, this had not yet been established in South Africa and more work is still in progress to develop a guideline for grid-connection of wind energy.

Studies conducted in South Africa have shown that the highest concentration of wind is on the coastal areas (mostly in the Western Region) and it has been predicted that over 7 GW of wind energy potential can be harnessed in the region [1]. With this development in mind, many proposals are being considered from wind power plant operators willing to connect to the grid. The, interconnection of wind power into the existing grid may pose some technical challenges to the network. Some of these challenges have been considered in this research, with the long-term aim of advising or recommending to distribution planners or developers, the procedures associated with wind integration.

In order for wind energy resources to be incorporated into the grid, certain technical requirements and guidelines need to be met before interconnection, so that the wind energy sources may not adversely affect the normal operation of the network. This along with power quality associated with wind energy integration should also be investigated in order to come up with guidelines that will be universally applicable in our local context.

1.2 Problem Statement

The unavailability of formally defined integration guidelines is contributing to the slow progress in the development of the wind industry in South Africa. The Distribution Network Code was established with the main objectives of setting out the basic rules of connecting to the distribution system as well as specifying the technical requirements to ensure the safety and reliability of the distribution system [9]. However, wind farm requirements were not set out in the existing transmission or distribution grid codes as they were drafted at a time when there was minimal or no wind generation on the network

Since wind energy sources have different operational characteristics and technologies as compared to conventional synchronous generators, there are concerns arising from connecting them to the grid. In addition, the fact that a form of generation is being connected to the distribution part of the network may give rise to safety, reliability and other power quality concerns.

Studies have shown that connecting wind turbines to the grid may cause power quality problems. These could result from the variable and unpredictable nature of the wind power output or the type of wind technology that is used. Also, as the penetration levels of wind connected turbines increase, the power quality impacts are likely to be more severe, as compared to low penetration levels.

It is also believed that the impact of the level of power quality that these wind turbines have, is dependent on the strength of the grid (described by its short circuit power level or fault level). The power quality problems are more pronounced in relatively weaker grids (usually associated with lower short circuit power levels). The injection of wind power into the power system may affect the voltage quality of the network, and this shall be determined at the point of common connection. The level of impact of these power quality issues also depend on the strength of the network as well as the active and reactive power flows of the wind generators [10].

Another problem with wind generators is that induction machines used in most wind turbine technologies are known to be major consumers of reactive power from the grid, which eventually results in voltage quality problems on the grid. However, the latest technologies of wind turbines, the variable speed turbines, are known to improve the voltage quality issues of the turbine interaction with the grid [10]. Conversely, they have a tendency to introduce harmonics (due to the power electronic controls they have) into the grid that may affect the shape of the voltage waveform at the point of common connection with other loads.

This thesis is mainly concerned with the investigation of power quality issues associated with wind energy integration that need to be considered so as to recommend guidelines that will be universally applicable to all grid-connected wind systems in the South African network. Since there was no existing guideline at the time when this research was conducted, recommendations to the local guideline for wind integration shall be presented at the end based on the findings from the literature as well as the power quality studies performed in this research.

1.3 Research Approach

An extensive literature review was done on the different countries that have integrated wind energy into their power system networks. The guidelines and standards used by these countries to implement their wind energy systems were studied and examined to note the most critical and important issues to consider for inclusion in the recommendations to the proposed guidelines.

Different network topologies were studied to investigate the power quality issues. A network model of the proposed 100 MW Juno Wind Farm on the Cape west coast has been the main subject of study. Network parameters and data of transformers, lines, busbars and generators were obtained from the Eskom stuff.

Since there are no practical measurements which can be taken from the wind turbines (since the project has not yet been implemented), most of the findings are based on the simulations performed using the DigSilent package. Some of the network data was made available by Eskom. The network parameter data are realistic although some engineering assumptions where made on parameters that were not provided.

Doubly-fed induction generators (DFIG) and squirrel cage induction generators (SCIG) have been used in the investigations carried out in this thesis. This is because they have a history of being the most commonly used technologies globally as they are considered to be economical.

The following other methods have also been used to explain some of the research problems in this research project:

- Load-flow studies performed in DIgSILENT – to investigate the impact of wind turbines on the network power flows and voltage quality.
- Harmonic load-flows (also performed in DIgSILENT)- to investigate the influence of harmonics at the point of common connection
- Filter design – to mitigate harmonic distortions
- Fault studies - to investigate the behaviour of the wind turbine during a network disturbance

1.4 Thesis Outline

Chapter 1 gives an introduction to the research work being investigated and introduces the scope of the work to be covered. The general background and objectives of this study are discussed in detail, furthermore, highlighting key studies and investigations to be performed in this thesis. The research approach followed in this thesis is also presented together with the overall contribution of this thesis to the integration of wind energy in South Africa

Chapter 2 reviews the research related to the integration of wind energy. This includes addressing some of the technical issues relating to grid-connected wind turbines as well as reviewing some of the standards and grid codes related to wind integration used by other countries worldwide.

Chapter 3 describes the theoretical concepts of wind power generation and the different turbine technologies and concepts used in wind power systems.

Chapter 4 further discusses the concept of power quality on grid connected wind turbines, with more emphasis being placed on the voltage quality concerns (voltage variations and harmonics). The objective of this chapter is to review the different power quality aspects that may affect grid connected wind turbines so as to consider the relevant issues to be carried out in the later investigations of this thesis.

Chapter 5 reviews the literature on modeling the network for power quality studies. The different models of wind turbines used in this thesis to carry out the DIgSILENT simulations are described in detail, with mathematical expression to validate the theory behind the modeling. The SCIG and DFIG models for power quality studies are described and compared, with reference to their impact on the network.

Chapter 6 deals with issues related to the integration of wind energy in South Africa. The distribution of wind power in South Africa is described, with a brief description of the Klipheuwel and Darling wind farm projects. The proposed Cape West coast wind farm is described and introduced as the main area of focus for this thesis.

Chapter 7 describes the analysis of the SCIG and DFIG wind turbines on the network during the normal steady state operation of the network. The influence of wind turbines on the voltage quality of the network is investigated, in relation to penetration levels, technology choice, strength of the grid and reactive power compensation.

Chapter 8 explores the influence of current harmonics caused by DFIG wind turbines on the total harmonic distortions at the point of common connection (PCC). This is investigated in relation to grid the strength of the grid and penetration levels. Furthermore, the mitigation of these harmonic distortions is described.

Chapter 9 provides an analysis of the behaviours of wind turbines during a grid disturbance. The impacts of squirrel cage induction generators and doubly-fed induction generators during a fault are compared in order to investigate which amongst the two behaves better under grid disturbances.

Chapter 10 presents some of the critical grid connection requirements that have been recommended for incorporation into the future wind grid code of South Africa. These proposed requirements are based on findings from studies carried out in this thesis.

Chapter 11 outlines the conclusions and recommendations based on the overall findings from the thesis.

1.5 Contributions to the thesis

This thesis contributed the following:

- It strengthened the importance of interconnection standards for grid-connected wind turbines in South Africa. This aspect is of great significance with the increasing wind power penetration levels.

- The thesis assists in identifying some of the technical issues to be considered before a wind farm can be connected into the grid. This will assist wind farm developers in their project design

- From the results obtained in this thesis, it was observed that the proposed 100 MW wind farm can be safely connected to the grid without compromising the integrity of the network.

- Typical power quality issues in most networks were investigated to identify their potential impacts on the South African grid

- The impacts of the DFIG and SCIG technologies on the grid were investigated in order to recommend the most suitable choice.

2 INTERNATIONAL EXPERIENCE ON WIND ENERGY DEVELOPMENT

This chapter is aimed at reviewing the experience of wind energy development in leading countries worldwide. It is intended to give an insight into some of the issues related to grid code and technical standards that should be taken into consideration before wind energy can be connected into the network. Some of the grid code requirements in selected global utilities are also discussed with the aim of deciding which, amongst these connecting requirements should be adopted to suit our local connection of wind turbines in South Africa without compromising the security of the grid

2.1 Overview of global wind energy developments

Wind energy integration expanded rapidly globally in the last couple of years, with the USA, Germany Spain, China, India, UK and Denmark representing some of the leading countries in the wind energy industry as shown in Table 2.1. This increased growth is mostly attributed to the growing environmental concerns about use of fossils fuels which has resulted in new environmental and economical and policies that are promoting the use of renewable energy such as wind [11]. Moreover, this growth in the wind industry is largely as a result of the subsidies and tax allowances made by the government to the private sectors in the industry [11].

Table 2.1 Global Wind Energy Capacity, 2009 [12]

Continent	Country	Capacity in 2008 [MW]	New Capacity added in 2009 [MW]	Capacity end 2009 [MW]	% Wind penetration
EUROPE	Germany	23,903	1,917	25,820	~7%
	Spain	16,689	2,459	19,148	~12%
	Denmark	3,163	334	3,497	~21%
	UK	2,974	1,077	4,051	~5%
	Portugal	2,862	673	3,535	~9%
	Ireland	1,027	233	1,260	~8%
NORTH AMERICA	USA	25,237	9,922	35,159	~2%
	Canada	2,369	950	3,319	~4
ASIA	China	12,104	13,000	25,104	~5
	India	9,655	1,271	10,926	~9
AFRICA	Egypt	365	65	430	~0.7
	Morocco	134	119	253	~0.3
	South Africa	8	0	8	~0.025%
LATIN AMERICA	Brazil	341	264	605	~0.9
	WORLD TOTAL	**120,550**	**37,466**	**158,016**	

From Table 2.1, we notice that as from 2009 the USA has overtaken Germany in having the highest capacity of wind power installed. However, even though the USA has the highest wind capacity installed, this contributes to about 1% of its total installed generation capacity [12].

On the other hand, even though Denmark has only just about 3 500 MW of wind connected, 20% of its generation capacity comes from wind power and this figure is projected to reach a level of 50% penetration by end 2010 [11]. This could be as a result of the strong interconnection system that is linking Denmark to other countries like Norway, Germany and Sweden [11]. These large interconnected systems are known to be strong grid connections which can allow for more wind power penetration levels to be added.

The wind industry in South Africa is still small as compared to the other leading countries and we would therefore expect the local wind integration issues to be different from the ones currently experienced by the other established industries. However, there is a lot to learn on how these other countries got to establish themselves in the wind industry.

With the integration of wind energy being a relatively new phenomenon in most distribution networks globally, and especially here in South Africa, there is a need to understand some of the issues associated with the interconnection impacts and procedures.

Some of the impact of integration of wind turbines on the network may include power quality aspects such as voltage variations, harmonic distortions, flicker and reactive power requirements [11]. These impacts however depend on the penetration levels of the wind power on the systems network capacity as well as the choice of turbine technology being used [11].

Generating interconnection guidelines would help wind farm developers, utility network planners and wind turbine manufacturers in having common ground with regards to what would be suitable for the development of grid-connected wind energy in South Africa.

In most cases, when discussing penetration levels, we generally consider the total amount of wind power installed in comparison to the total power capacity produced by the utility. However, there are a several indices that may be used to describe wind penetration levels and these have been described in [8] (see Appendix A5)

According to [13], there is no particular limit for penetration levels as there are various factors that may influence it. These may include the size of the existing conventional generating plants as well as the capacity for storage available on the network. Most interconnected systems, through their importing and exporting of generating capacity have the advantage of having higher penetration levels [13]. However, not many countries have wind penetration levels greater than 5%, except for the leading countries like Denmark, Germany, Spain and Portugal to mention a few [13]. The penetration levels were calculated by comparing the installed wind capacity with the total installed power capacity on the overall system.

From Table 2.1 above, it can be seen that it is possible to integrate large volumes of wind power into the grid as long as proper guidelines and procedures are followed. However, it is also important to point out that most of these areas with higher penetration levels wind power are part of the strongly interconnected, large national and multinational systems which will facilitate large volumes of wind to be integrated to the system without having a significant adverse impact [3]. It is believed that Denmark, for instance can actually have its wind penetration level beyond 50% at some point during the operation of the grid [13].

Some of the challenges associated with wind integration into the grid are mainly because of [3]:

- The variable nature of wind (intermittency) owing to its unpredictability
- Technology types used in wind turbines (e.g. squirrel cage and doubly-fed induction generators-DFIGs) which are different from the conventional synchronous generators used in well-established power systems.

Some of the challenges associated with the varying wind penetration levels on the grid in areas where wind contributes significantly to the total capacity may involve the following cases [7]:

- Low wind penetration levels versus high load demand
- High wind penetration levels versus low demand

These challenges normally become more significant in weak grid systems as compared to strongly interconnected systems.

2.2 Global experience on technical standards and integration issues

Most of the technical standards that are used by nearly everyone in the wind industry, especially the most developed countries like United State of America, Europe and Asia are based mainly on the existing standards developed by the IEEE (Institute of Electrical and Electronic Engineers) or from the IEC (International Electrotechnical Commission) [3]. The IEEE and IEC standards are used as a basis from which most countries or regions can develop their regulations and are thus mainly references that can be recommended to different utilities seeking to connect wind power to the grid. Most of the standards began with recommendations for connecting wind systems into the distribution network and gradually, as the penetration levels of wind energy increased dramatically, it was decided to look into connecting on the transmission side of the grid [3]. These standards can further be broken down into technical interconnection regulations as well as power quality requirements. The power quality standards mainly give permissible limits that should be taken into consideration when connecting to the utility grid.

The most popular of these standards is the IEEE 1547 Series of Standards – *Standard for Interconnecting Distributed Resources with Electric Power Systems* [14]. This standard establishes technical requirements for the electrical power systems connected with distributed generators such as wind generators and many other forms of distributed generators. Since wind is of particular interest in this thesis, we shall consider its technical requirements more carefully. The IEEE 1547 standard, places more emphasis on the technical specifications, and the testing of the interconnection procedure as a whole [14]. It includes the general requirements, response to abnormal conditions as well as power quality issues amongst other issues [14]. For some of its power quality regulations, it does make mention of the American National Standards Institute (ANSI), C84.1-1995 document as well as other IEEE standards [14].

The most common standard which has been reproduced by most leading wind energy countries globally is the IEC 61400-21 Standards - *Measurements and Assessment of Power Quality Characteristics of Grid Connected Wind Turbines* [IEC, 2001] [15]. Other common standards include IEEE 519 - *Recommended Practices and Requirements for Harmonic Control in Power Systems* [IEC, 1992] [16].

Having mentioned the standards above, it should be emphasized that the different utilities will integrate these standards differently mainly as a result of differences in their electric power systems topologies or composition. For instance, the different penetration levels of the wind power on the overall systems capacity may influence some of the power quality characteristics that have to be considered.

One of the main concerns of most utilities with regards to wind integration is to keep the voltage quality for the loads (customers) at the point of common connection within the acceptable limits. Thus, according to [3], the main influence of wind turbines on the power quality of the grid mainly involves voltage changes or fluctuations and harmonics at the point of connection. Reactive power and flicker concerns are also part of the problem, but with the development of power electronic devices, these issues are no longer a major cause for concern. Most of these issues will covered in the investigations carried out in this thesis.

Another important issue that is understood to limit the higher levels of wind power into the utility grid is the unavailability of properly defined and approved guidelines or technical regulations to be followed before and during the integration process. These guidelines are set up to specify the relevant requirements and procedures for connecting wind turbines into the grid.

According to [11], the major grid connection characteristics that are considered in most grid codes include:

- The behaviour of wind turbines during faults or transients in a system (fault ride through capabilities)
- Active power control
- Reactive power control
- Voltage and frequency operating limits
- Other requirements such as
    - Power quality
    - Short circuit current levels
    - Protection
    - Communication

As mentioned in chapter 1, the fault ride-through capability is a major change to the modern grid codes that are being developed. This concern comes about when there are large wind penetration levels, where a disconnection of the wind farms, as a result of low voltage conditions may create a serious threat to the stability of the network if the wind power is cut off concurrently [11]. However, in this thesis, not all these grid codes have been investigated fully and most of the emphasis has been placed on the power quality requirements. The other requirements shall be discussed as a form of comparison of different standards so as to come up with recommendations for a South African wind energy grid code.

2.2.1 Low voltage ride through capability

The low voltage ride-through (also known as fault ride through (FRT) capability) allows the voltage stability of a network to be maintained throughout a disturbance and it becomes a very significant requirement when there is a high local concentration of wind generation [17]. The untimely tripping of the numerous wind turbines due to local disturbance can additionally compromise the stability of the system and therefore wind turbines would be required to remain connected during power systems disturbances [17].

For instance, the low voltage ride through requirements for wind turbine generators connected to the Irish network system were specified in WF1.4.1 [17] Wind Farm Transmission Grid Code Provision as follows, "*A wind farm shall remain connected to the transmission system for voltage dips on any or all phases, where the transmission system voltage measured at the HV terminals of the grid connected transformer remains above the heavy black line shown in Fig 2.1 below*" [17].

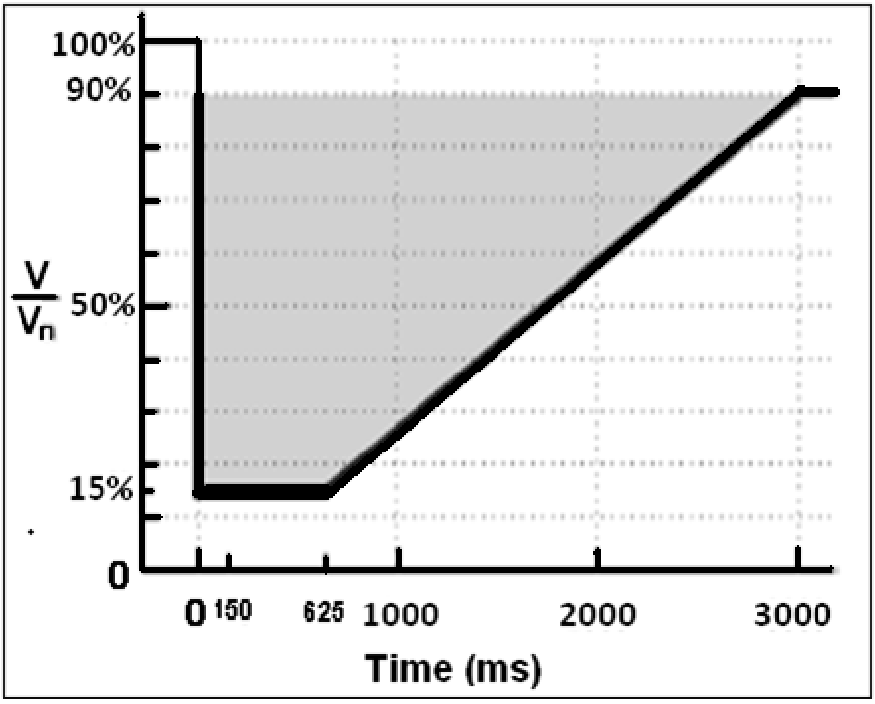


Figure 2.1 Fault ride through requirements for wind turbines in Ireland [11]

The fault ride through requirement varies for different network places or grids. For instance, in Ireland the fault ride through requirement curve is shown in Figure 2.1. It was formulated by determining the minimum voltage that different nodes or regions on the network experience every time there is a fault on the grid. The minimum voltage retained by the grid was found to be about 5% of the line voltage so the grid code developers decided to allow for a 5% retention voltage for 0.2s and 50% for 0.6s [18]. This was aimed at allowing the wind turbine to remain connected to the system even under low voltage. This was however not possible to attain by the manufacturers of wind turbines and the best they could attain was worked out to be 15% under-voltage and this is illustrated in Figure 2.1 [18]. Other countries have also different fault ride through capabilities depending on the extent of the common faults.

2.2.2 Active power control

For the power system network to operate accordingly, there has to be a balance between the generated power and the load (or/and losses). Changes in this equilibrium of power flow may result in a temporary or permanent stability on the power system that may affect the power plants and the customer loads [3]. The active power requirements enable the power system to maintain stability as it ensures that the frequency remains stable as well as preventing line overloading, voltage imbalances and compliance to the power quality standards [3].

With wind energy rapidly developing globally, the higher penetration levels of wind energy on the system may be cause for concern if not properly monitored and controlled. This may necessitate the need to properly control the amount of wind power production, meaning that suitable forecasting techniques become increasingly important for system operations and these should be followed according to its variability and intermittency [3]. Moreover, this power variability introduced by wind fluctuations may need to be curtailed by the use of appropriate wind technologies that have the ability to control the flow of active power [3].

Besides the need to maintain a constant flow of power from wind turbines, it is also important that there are controls to reduce the power production should this be necessary (i.e. under low loading conditions). The ability of the variable speed wind turbines (e.g. DFIG) to operate under variable wind speed conditions may help improve a wind farm's capability to contribute to the active power being supplied to the grid should there be any power needed from the wind farm. The behaviour of different wind technologies shall be investigated later in this thesis.

2.2.3 Reactive power control

A reactive power balance in a power system should be preserved to maintain a voltage balance in the network [3]. This reactive power production by wind turbines is of great significance during both steady state and fault conditions. It is becoming increasingly popular in most large wind penetration regions where the wind power is expected to provide voltage support to the network by increasing the amount of reactive power supply during network disturbances such as faults [3].

Once again, the choice of technology that is used in a wind farm may influence the balance of the reactive power with the grid. Wind turbines employing fixed speed induction generators connected directly to the grid, consume reactive power from the network (capacitor may have to be used to compensate for reactive power consumption from the grid). However, wind turbines that have converter control systems are capable of controlling the flow of reactive power between the turbine and the grid, although this may be limited by the size of the converter [3]. The reactive power compensation capability of these two different forms of wind turbines shall be investigated in the later parts of this thesis.

For instance, according to the Nordic connection code for wind turbines, a wind plant must have an adequate reactive capacity to be able to operate with zero reactive exchange with the network measured at the point of common connection (PCC), when the voltage and frequency are within normal operating limits [19]. In terms of reactive power control, the wind turbine must be able to control the reactive power exchange with the system. This control is expected to operate automatically and on a continuous basis [19].

The wind turbine should be able to control its reactive power output automatically as a function of the voltage at the point of common connection [19]. This means that the reactive component of the wind turbine should be greatly monitored as it should only provide reactive power when needed by the network

2.2.4 Frequency control

In most leading wind energy producing nations with higher wind penetration levels as compared to the total generation capacity, wind turbines are now expected to provide frequency control, unlike before when it was only expected from conventional generators. The power system's frequency is normally controlled by the inertia of the grid and in most cases; synchronous generators and system load may contribute to power system inertial response [20].

Theoretically, if there is too little generation on the system as compared to the system's load, the frequency will drop and too much generation will result in frequency rising. There is therefore a need to create a balance between the amount of the power generated and the load for the frequency to be within acceptable limits. However, it is believed that if there is a significant amount of wind energy contribution to the total network capacity it may also detect the system frequency [20]. . This issue is currently being investigated by other researchers [20].

Frequency control is used to keep the grid operating frequency at or near the nominal value. Frequency control requires generators to regulate their power output so as to adjust the frequency or speed of the grid [21]. This is due to the fact that frequency is directly proportional to output power. Table 2.2 shows some of the generic frequency range requirements of the European grid codes that were used in countries like Denmark, Germany, Ireland, Scotland and UK [22]:

Table 2.2 Frequency range requirements for European grid codes [22]

Generic frequency range requirement	
Frequency	Code of operation
52 Hz to 53 Hz	3min
51.5 Hz to 52 Hz	Continuous operation
51.0 Hz to 51.5 Hz	Continuous operation
50.5 Hz to 51.0 Hz	Continuous operation
49.5 Hz to 50.5 Hz	Continuous operation
49.5 Hz to 47.5 Hz	Continuous operation
47.5Hz to 47.0 Hz	20 sec
Below47.0 Hz	20 sec

This frequency range requirement table is used as a guideline for designers of generator plant system equipment and wind turbine technologies are expected to operate within this range [22].

For instance, in Ireland, the grid code specifies various requirements in relation to frequency control [18]. The normal frequency operating range is 49.8Hz to 50.2Hz for 99.9% of the time [18]. All synchronous generators are expected to operate at optimum rated output power over this frequency range. However, wind generators are given a less strict frequency range of continuous operation over the 47.5Hz -52Hz range for 60 minutes and for 20 seconds in the 47Hz – 47.5Hz range [18].

2.2.5 Analysis of grid codes

Investigations of the literature of interconnection standards have shown that the most developed standards are found in the leading wind energy countries, namely Germany, Denmark, Spain and Ireland [18]. According to [11], a grid code is meant to cover all material and technical aspects relating to the connections, and the operation and use of the electricity transmission or distribution network of a certain utility. Most of these grid codes have been adopted from the technical standards that have been specified in section 2.2.1. and they vary from utility to utility owing to the discrepancy in different electricity networks. Some of the grid codes and standards that are reviewed in this thesis are listed below [11].

- Indian Grid Code
- Ireland Grid Code, *ESB National Grid, 2007*
- Great Britain Grid Code
- NRS 048-062 Standards (South African Power Quality Standards)
- Distribution Network Code (South Africa)
- Nordic grid code, *Nordel, 2006*
- Danish Grid code, *Eltra &Elkraft, 2004*
- Germany grid code, *E.ON Netz, 2006*
- USA/*FERC Regulations, 2005*

According to [23], most utility organizations have prepared their grid codes in such a way that these interconnection standards and requirements fall into different classes.

At present, there are no formal requirements or regulations with regards to the integration of wind energy into the South African grid. However, to speed up the process of increasing wind penetration levels as targeted by Eskom and the Department of Mineral and Energy, a recognized wind energy interconnection guideline must be put in place. One of the objectives of this thesis is to recommend guidelines that can be added to the integration document to be used by planners in accommodating wind energy systems into the network.

3 WIND TURBINE SYSTEMS

3.1 Theoretical overview of wind power production

A wind turbine is a rotating machine that converts the kinetic energy of wind into mechanical energy [3]. Occasionally, the mechanical energy is used directly by the machinery in the form of a pump, e.g. windmills. However, in most cases, when the mechanical energy is then converted into electrical energy, the machine is called a wind generator (or wind energy converter) [3]. Wind turbines are designed in such a way that they exploit the wind energy in a particular location. Denmark happens to be the first country to have used wind turbines for the generation of electricity. This happened around the early 1990s and back then, the size of the units used had capacities of 5 to 25 kW [3].

The common sizes of individual wind turbines are in the range of 30kW to 1.5MW but currently on the market (mainly in Europe); there has been talk of a huge turbine with capacity of up to 10 MW [3]. The horizontal axis propeller type with three blades is the most common category of wind turbine used [3]. The components of a wind turbine include a rotor, generator, turbine blades and drive devices [3]. The hub height can reach up to 80 metres with rotor diameters of up 60 metres [3].

When it comes to the output power produced by the wind turbine, the following equation [3] can be used to describe the dependence of the wind output power as a result of the instantaneous wind speed:

$$P = \frac{1}{2}.\rho.\mathrm{A}.v^3 Cp \tag{3.1}$$

where:

- P is the power,
- ρ is the air density
- v is the wind speed
- A is the cross-sectional area cut-off by the turbine rotor

The measure of the fraction of energy in the wind that is extracted by the turbine is given by Cp, the power co-efficient. It is said that the Cp has a theoretical Betz limit of 59.3% [3]. However, in most commercial scale wind turbines, the real value is approximately 44% (in wind speeds of about 10m/s) [3].

From equation 3.1, we observe that the output power produced by the wind turbine increases with the cubic ratio of the wind speed until the rated output power level of the turbine is reached. Basically this means that a 10% increase in wind speed may eventually lead to output power increasing by 30% [3].

Normally, wind turbines start operating at cut-in wind speeds of about 4m/s and the power increases with the cube of the wind speed until it is limited to a rated power at wind speeds that are about 12m/s [24]. The following graph, figure 3.1 illustrates the power curve of a wind turbine versus wind speed.

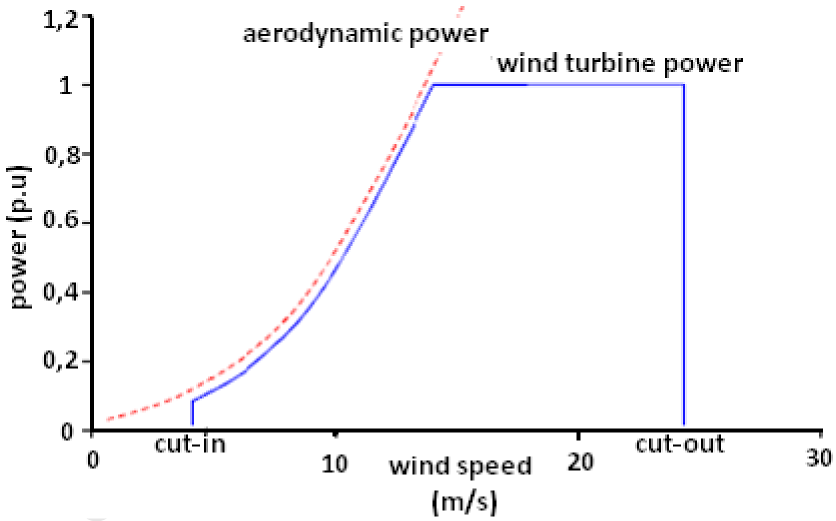


Figure 3.1The power curve of a wind turbine [24]

From Figure 3.1, it can be seen that the output power of the wind turbine is restricted to a rated output power at wind speeds exceeding 12m/s. The methods used to limit the power output are briefly described as follows [24]:

- Pitch regulation – this occurs when the turbine blades are pitched away from the wind mechanically. Most of the latest variable speed wind turbines use this mechanism such that the turbine produces as much power as possible when operating below rated speed owing to the pitch angle control which allows for maximum energy capture [24]. The pitch angle is adjusted when the wind speed is above rated value, thereby maintaining the turbine to operate at rated power [24].

- Stall regulation – this occurs when the output power of the turbine is limited by the aerodynamic limitation of the power.

However, at wind speeds above 25m/s, often called the cut-out speed, most wind turbines are designed in such as way that they automatically shut down to avoid damage [24].

As mentioned earlier, the generator’s output power is correlated to the speed of the rotor which is turn is determined by the wind speed and figure 3.2 (a) and (b) aims to shows this correspondence. In general, an increase in speed, results in an increase in generator output power and vice versa. However, this may not necessarily be true, depending on the generator technology that is in use. Other generators can maintain their output power even during low speed conditions and this shall be discussed in the following sub-sections.

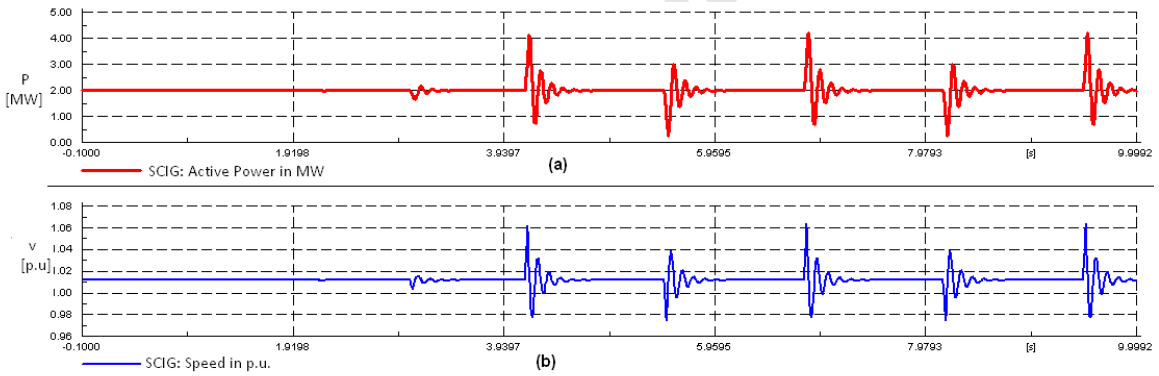


Figure 3.2 (a): Variation of generator active power with time (b) Variation of generator speed with time

3.2 Wind Turbine Topologies

3.2.1 Fixed Speed Wind Turbine (FSWT) systems

This system seems to be the simpler way of connecting wind power into the electric grid and most manufacturers of fixed speed wind turbines use induction generators. These turbines run at a relatively fixed mechanical speed [24]. These were the first topology of wind turbines to be implemented as early as the 1990's [24]. In terms of its operation, the wind turbine's rotor speed is fixed and determined by the frequency of the supply grid. They are equipped with induction machines (notably the squirrel cage or wound rotor that are directly connected to the grid [3]. Soft starters and capacitor banks are normally connected to it, the former being used to limit the inrush current, and the latter facilitating the reactive power compensation of the generator [3]. This is illustrated in figure 3.3.

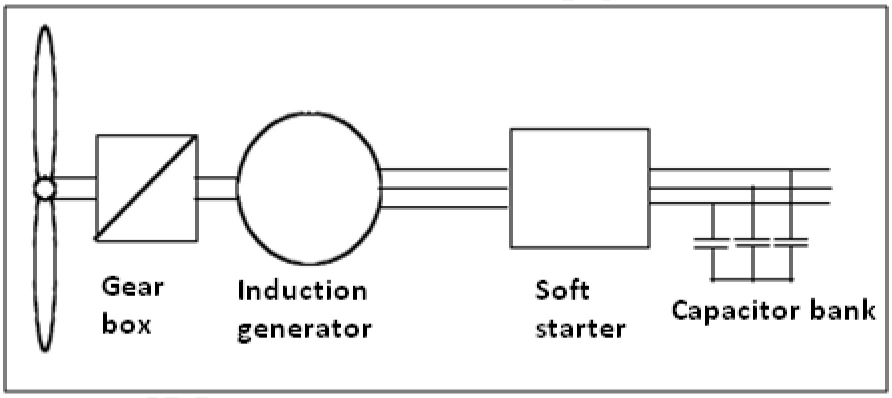


Figure 3.3 Electrical system of a fixed speed wind turbine [19]

Some of the reasons for the FSWT being widely used globally are that it is simple to design, robust, reliable and well proven and is generally cheaper compared to variable speed turbines [24]. A squirrel cage induction generator is a typical example of a fixed speed wind turbine.

However, its flaws include its inability to control reactive power consumption, mechanical stress as well as its contribution to most power quality defects, namely the voltage fluctuations on the nominal voltages, especially at the point of common connection. This occurs due to wind speed fluctuations being transmitted in the mechanical torque and further into the electrical power on the grid, which can lead to large voltage variations on the grid, which may contribute to line losses [24]. Figure 3.4 gives an illustration of the measure of reactive power consumption, Q, of an induction generator as a function of the active power, P.

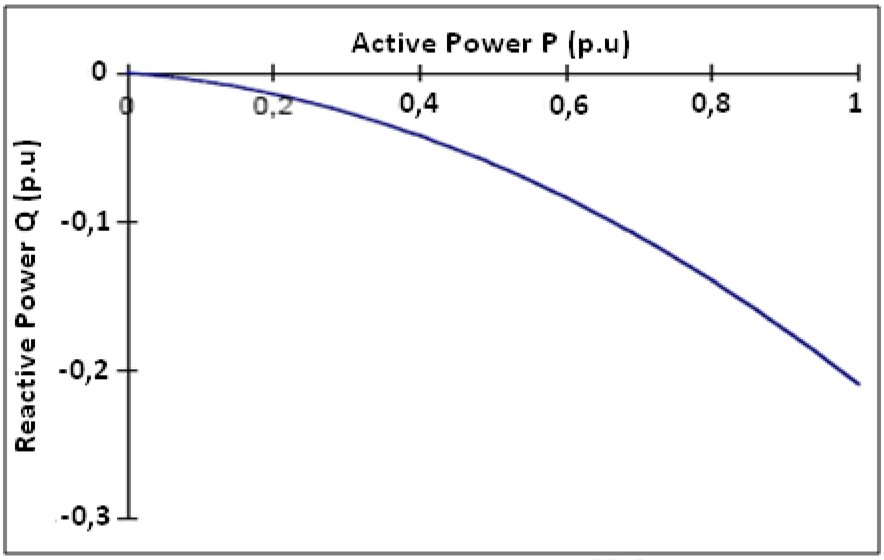


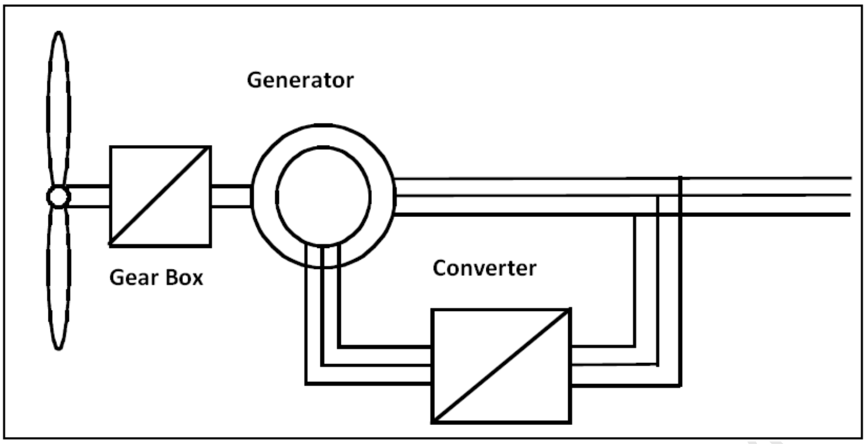
Figure 3.4 Reactive power as a function of active power [24]

Figure 3.2 shows that as the active power supplied by the generator increase, its reactive power also increases, at close to an exponential rate.

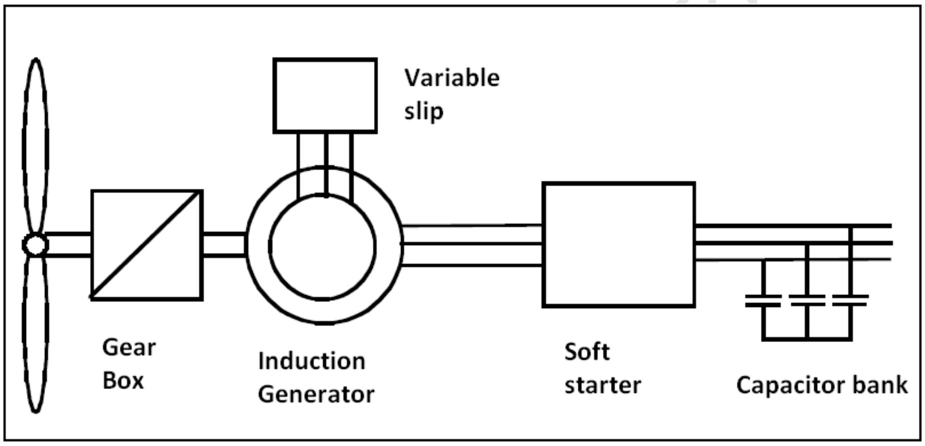
3.2.2 Variable Speed Wind Turbine (VSWT) Systems

Variable speed wind turbines have become the dominant form of wind turbines used lately as they are designed to attain maximum aerodynamic efficiency over a broad range of wind speeds [24]. What makes it more favourable than the FSWT is its capability to absorb wind changes by varying the generator speed and thereby allowing it to operate better under variable speed conditions [24]. The synchronous or the induction machine can be used for this type of wind turbine. Its electrical component is more complicated than that of a FSWT and may contain power electronics to connect it to the grid [3]. These power electronic devices control the speed of the generator [24]. Owing to these added electrical characteristics, the VSWT has much better power quality characteristics compared to the FSWT.

A doubly-fed induction generator (DFIG) is a typical example of a variable speed wind turbine and shall be further analysed in this thesis. Figure 3.5 (a) and (b) shows an illustration of this type of wind turbine.



(a)



(b)

Figure 3.5 (a) Variable speed wind turbine with (a) a doubly-fed induction generator with a converter connected to the rotor circuit, (b) controllable rotor resistance [24]

The added power electronic devices connected to a VSWT allow it to perform better than the FSWT in terms of improved energy capture and power quality characteristics [3]. The power fluctuations caused by the variable nature of wind are absorbed mainly by the changes in the rotor generator speed which in turn is absorbed by the wind turbine rotor speed, hence the voltage fluctuations are not as prominent as those resulting from the FSWT [3].

However, its shortfalls include the power losses in the power electronic devices as well as the increased costs that are associated with the added power electronic features. The power losses can be kept at minimum when the voltage across the device is zero (during the ON state) and when no current flows through it (during the OFF-state) [23]. This would favour the use of higher efficient devices in order to reduce these losses [23]. This cost trend however seems to be declining because of reduced costs owing to the advances in technology and increased economies of scale [3].

Other variable speed wind turbines that have been reviewed but not considered in this thesis include the full-scale converter-driven generator which operates under full variable speed ranges to control the reactive power compensation and further produce a smoother power output quality (e.g. wound rotor synchronous generator or permanent magnet synchronous generator.

3.3 Wind Generator Concepts

Several types of generators can be used to manufacture wind turbines for grid-connected systems. Some of these are described below [3]:

3.3.1 Synchronous generators

These are extensively used by some wind turbine manufacturers as they allow independent control of real and reactive power over a wide range. The only problem is that they have to be carefully synchronized with the network before connection. For the generator and the grid to be considered synchronous, both systems must be operating at the same frequency and also the phase angle between the systems must be zero [24]. This phenomenon requires both synchronizing relays and accurate control of the speed of the generator. Examples of synchronous wind generators include the permanent magnet synchronous generator (PMSG) and the wound rotor synchronous generator.

The PMSG has been highly recommended because of its self-excitation property which allows it to operate at a high power factor and a high efficiency [24]. However, as much as the PMSG is more efficient than the induction generator (excitation is provided without supplying it with energy), the materials used during its manufacture are expensive and difficult to work during build-up [24]. Power converters are also required to adjust the voltage and frequency of generation and the magnetic component being temperature sensitive, losing its magnetic qualities in times of high temperatures resulting from faults on the network [24].

3.3.2 Induction generators

Induction generators have been a widely used form of electrical machinery in most wind turbine generators due to the simplicity of their construction. As opposed to the synchronous generator, it does not require synchronism with the grid before connection, which is a complicated mechanism. The ability to produce the generator in large quantities as well as its robustness, favour its application in most grid connected systems, globally. However, the induction generator cannot be excited by drawing excitation current from another source and thus consumes reactive power in the process [24]. This is the reactive power that can be supplied by the grid or any other power electronic system.

In this thesis, the SCIG and the DFIG have been used to carry out most of the simulations studies.

3.3.2.1 Squirrel Cage Induction Generator (SCIG)

Most of the biggest wind power producers globally, namely Germany, Denmark and Spain, have primarily used the SCIG for most of their wind power plants. This widespread preference resulted from its mechanical simplicity and low maintenance requirements as well as low production costs. The SCIG functions under constant or fixed speed operation and is equipped with a soft-starter mechanism and reactive power installation to cope with the reactive power compensation, since it consumes reactive power [3].

A significant drawback of the SCIG is that it has torque speed characteristics, which allow the fluctuations in wind power to be transmitted directly to the grid, hence causing voltage variation problems. The large damping torque provided by the prime mover makes them suitable for fixed speed application. As shown in figure 3.3, the fixed speed is connected to the grid through a gearbox to try and match the different operating speeds of the wind turbine rotor and generator.

3.3.2.2 Doubly-fed Induction Generator

The doubly-fed induction generator has grown to be the preferred choice of wind turbines globally and its market share has increased significantly over the past years [3]. It utilizes wound rotor-rotor induction machines with an ac-dc-ac converter between the stator and rotor terminals as shown in figure 3.5. The term 'doubly-fed' signifies that the voltage on the stator is applied from the grid and the voltage on the rotor is induced by the power converter which facilitates variable operations over a large range [22]. As shown in figure 3.5 (a), the grid side and rotor-side converters make up the overall converter but they are controlled separately [22], with the rotor side controlling the active and reactive power by controlling the rotor current components , while the grid-side converter controls the DC-link voltage to ensure operation at an almost unity power factor [3]. This power electronic structure allows the DFIG to control its reactive power consumption by independently controlling the rotor excitation current [25].

Besides controlling reactive power consumption, the DFIG can also generate reactive power that can be delivered to the stator by the grid-side converter [24]. This reactive power control is essential for voltage level control and this makes the DFIG even more favourable in weak grid systems as discussed in section 3.4.3.

In the most typical cases, the partial scale frequency converter connected to the rotor side is normally rated at about 30% of the nominal generator output power [3]. Controls within the DFIG have the ability to hold electrical torque constant, allowing rapid fluctuations in mechanical power of the turbine to be contained and temporarily stored as kinetic energy, thus reducing voltage fluctuations and consequently improving the power quality of system [25]. These power electronic devices facilitate the control of voltage and phase angles of the rotor's current thereby controlling the output voltage and its corresponding power factor [3].However, DFIGs are known to be emitters of harmonics and this shall be discussed in Chapter 4. DFIGs have since been used in some parts of this research to perform harmonic load-flow simulations on the different networks using the DigSilent simulation tool.

3.4 Power Electronics of wind turbines

With wind power energy growing dramatically, more stringent requirements demanding the accurate reactive power control and voltage regulations capabilities has led to integration of power electronic converter devices in most of the wind turbines designs, as discussed in the above sections (i.e. DFIG and WRIG). These power electronics devices are designed to facilitate improved overall control of the generator (in terms of both active and reactive power control). This happens by regulating the turbine's output voltage whilst maintaining the power factor close to unity [3]. Some of the common power electronic devices are briefly described below [3]:

- Soft starter – reduces the inrush current (normally about 7-8 times the rated current) that is being drawn by the generator, which may result in voltage disturbances as well as damaging the turbine itself due to excessive heating. The soft starter is normally used in fixed speed generators during connection to the grid and it is simple and cheap to operate.
- Capacitor bank – also commonly used in fixed speed wind turbines to compensate for reactive power requirements of the induction machine so as to reduce the reactive power absorbed from the grid. Capacitor banks can operate under static operations where a single capacitor is switched on once the turbine is running, regardless of the reactive power requirements. Another form of operation is through active/dynamic compensation where a certain number of capacitors are switched on and off continuously depending on the reactive power demand of the wind turbine.
- Rectifiers/ inverters – The two types of power electronic converters used by wind turbine systems are classified as grid-commutated or self-commutated converters [3]:
    - Grid-commutated – These are very cheap and dependable but have a tendency to consume reactive power and introduce low order harmonics, which are difficult to filter.
    - Self-commutated – These emit high order harmonics, which are relatively easy to filter out. Self-commutated inverters such as pulse-width-modulation (PWM) and pulse-amplitude-modulation (PAM) based controllers have the capacity to improve the quality of generated energy [23].

According to [25], *a PWM converter model represents a self-commutated, voltage sourced AC/DC converter* and this general model is illustrated in Figure 3.4.

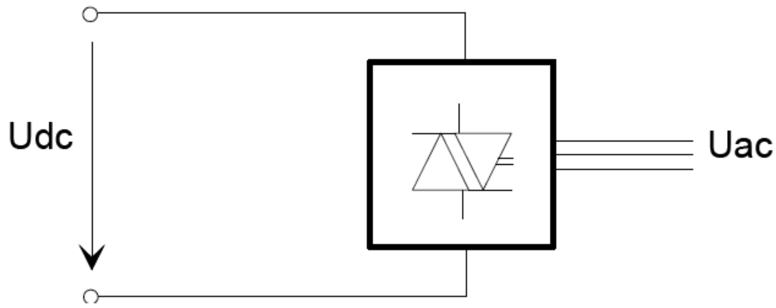


Figure 3.6 Simplified model of a PWM Converter [26]

This PWM converter model is normally used in most DFIG applications where it connects the rotor circuit of the generator to the grid [26]. These self-commutated PWM converters that are generally used in most modern wind turbines normally consist of IGBTs with higher switching frequencies than classical GTOs [26].

As mentioned previously, the DigSilent PowerFactory application package has been used to perform studies. To perform the load flow studies, there are different converter control modes that have been made available. These include:

- Vac-phi: Specifies magnitude and phase of the AC-terminal. It is a typical control mode for motor-side converters in variable speed drive applications [26]
- Vdc-phi: Specifies the DC-voltage and the AC-voltage phase. No typical application
- Vdc-Q: Specifies DC-voltage and reactive power. Typical applications: STATCOM, shunt-converter of UPFC, grid-side converter of doubly-fed induction machines, VSC-HVDC applications [26].

A harmonic voltage or current source control can be used for PWM converters, with the harmonic current source control giving the more realistic representation of the converter as it describes the harmonic current amplitude and angle [26].

From the wind turbine's point of view, the power electronics incorporated into it make it possible to actually apply the variable speed concept in VSWT resulting in increased efficiency through optimal power production as well as actively controlling the flow of power, thus improving its power quality [3]. However, as previously discussed, these power electronic may have issues with emitting harmonic currents into the grid.

3.5 Factors to be Considered when Connecting Wind Turbines to the Electricity Network

Connecting wind turbines to the grid may raise certain issues which may depend on the local grid to which they are connected, or on the choice of wind turbine technology that is to be used [27]. Some of the basic factors that are considered before wind generators (or turbines) can be connected to the grid, include network voltage level, terminal ratings, strength of grid and power quality issues [27].

3.5.1 Network Voltage Level

Most electricity systems were designed to transfer power from the large conventional generators located on the high voltage side towards the distribution side on the lower voltage part of the grid where most customers are connected [27]. With the connection of wind generators on the distribution side of the network, it is likely that voltage levels or range problems (over-or under voltages) might be experienced [27]. These are as a result of electrical parameters of the generators and this will be discussed in more detail in chapter 4. So, to guarantee good quality of electrical supply, the impact of the wind turbines output power capacity needs to be analysed [27].

3.5.2 Thermal Ratings

Just like any other form of generators, it is obvious that when a wind farm is to be connected to the grid; power will be transported to the main grid via overhead lines, cables, transformers and other electrical equipment [27]. Since the main grid's electrical systems' equipment have been designed to carry a certain level of electrical power ratings, having more power supplied by the wind farm to the same equipment may damage it due to overheating (exceeding thermal ratings) [27]. So, the thermal ratings of the equipment should be carefully considered. Reinforcements of the grid in the form of adding more transformers, transmission lines etc. may be necessary to try and strengthen the grid and improve its power transfer capability. For instance, for the Cape West Coast Wind Farm, Eskom has made a proposal to reinforce the grid by building a new substation for the wind farm [88]. A new double-circuit line connecting the proposed substation to the rest of the grid has been projected as well as two new transformers to cope with the new wind farm will be discussed in Chapter 5 [1].

3.5.3 Strength of the Grid

Another area of interest with regards to the power quality of all distributed generators (in this case wind turbines) connected to the grid is the issue of grid strength. The strength of the grid can be described in the following terms:

3.5.3.1 Short-circuit Power Level (Fault Level)

The fault level is defined as a measure of the current that will flow in a network when there is a fault in a system that has a wind power plant installed already. It is normally used to describe the strength of the grid. It thus needs to ensure that the fault current contributed by the wind power plant is small and does not affect the system's equipment (transformers, cables, etc.). There is therefore a need to ensure that the resulting fault level remains below the network design limits. However, high current levels will be experienced only if the integration of wind turbines (and other renewable energy systems) on our systems happen to increase significantly to contribute substantially to the overall grid capacity [28].

The short circuit power of the grid at the PCC is also an important aspect when considering the power quality issues on the grid. This is defined as the apparent power that would flow through the short circuit at the PCC as shown in Figure 3.7 [28].

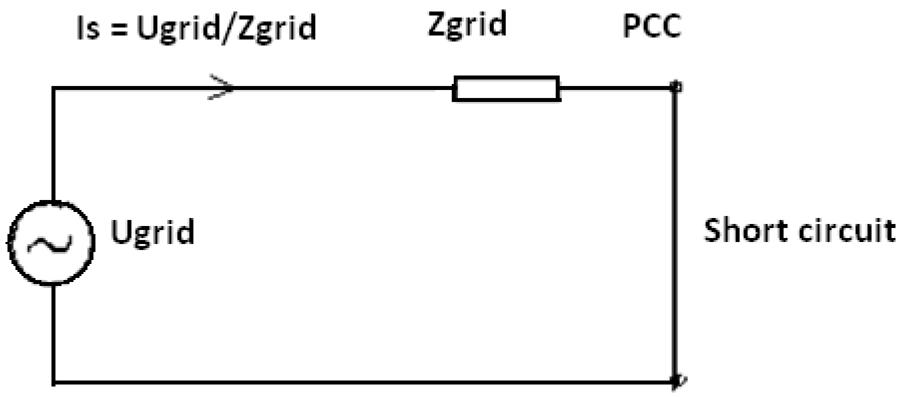


Figure 3.7 Hypothetical short circuit at the PCC to calculate short-circuit power [28]

Assuming that the load and turbines have an insignificant effect on the short circuit power level, the S_{sc} is given by [28]:

$$S_{sc} = U_{grid} \; I_{sc}^{\;*} = \frac{U_{grid} . U_{grid}^{\;*}}{Z_{grid}} = \frac{\left|U_{grid}\right|^2}{Z_{grid}} \qquad (3.2)$$

Where:

- U_{grid} is the grid voltage
- I_{sc} is the short circuit current
- Z_{grid} is the Impedance of the grid
- S_{sc} is the Short circuit power level

The wind turbine is also assumed to be connected in parallel with the load as shown in figure 3.8.

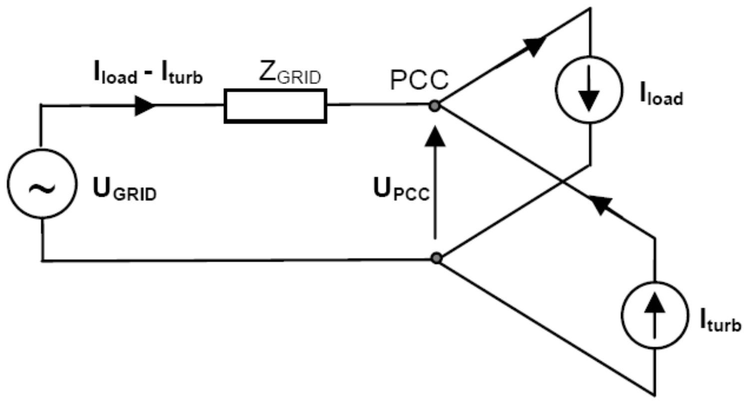


Figure 3.8 Grid equivalent model with two users at the PCC [28]

Since S_{SC} is inversely proportional to $Z_{GRID,}$ the voltage at the PCC during the normal operation of the grid can be given by the following equation 3.3 [28]:

$$U_{PCC} = U_{grid} - (I_{Load} - I_{turb}).Z_{grid} \quad (3.3)$$

Where:

- U_{PCC} is the Voltage at the PCC
- I_{Load} is the current through the load,
- I_{turb} is the current through the turbine
- Z_{grid} is the Impedance of the grid

This equation shows that the lower the impedance of the grid, the less impact the load and turbines are likely to have on the voltage at the PCC. The assumption made is that far away from the point PCC, the voltage is taken as constant; meaning the conditions at PCC will not influence it.

This thus brings about the issue of grid strength. A higher short circuit power level implies a stronger grid meaning that the variation of loads and turbine power output make an insignificant contribution to changes in the voltage at the PCC [29]. The short circuit power level is therefore an indication of how strong the grid is. It is believed that the ability of the grid to absorb disturbances is directly related to the short-circuit power level at the point in question [28].

Power quality impacts are also dependant on the strength of the grid and we would thus expect to experience significant power quality effects on a relatively weaker grid (with a lower short circuit power level). This would help us identify what harmonic levels would be permitted on a certain grid point, without causing severe harmonic disturbances.

Therefore when intending to connect wind power to the grid it is always advisable to connect it to the relatively stronger parts of the grid so as to reduce sensitivity to the other customers as a result of wind plant power quality issues. The lower ends of the distribution network are believed to be the weaker parts of the grid. There is a general rule of thumb regarding the connection of a wind farm into the grid amongst most European countries and it states that [29]:

"*The ratio between the short circuit capacity of the grid and the installed wind turbine power should be at least 20 times (or even 40 in some regions)"*

However this is dependent on the network topology or size of each country or region. For instance some regions in Poland have ratios of up to 50 [29]. According to the research done in this area, there are different perspectives with regards to how this ratio comes about and there has not been any solid explanation for these values.

3.5.3.2 Fault Level Contributions of the Wind Turbines

Most distribution networks are characterised by a design short-circuit (fault level) capacity which represents the maximum fault current that must not be exceeded [30]. This short-circuit capacity is related to the rating of the distribution equipment such as circuit breakers, switchgears as well as the thermal capacity of other equipment on the network [30]. Thus, connecting any form of distributed generator on the network may contribute to the total fault level of the network, therefore fault level contribution from wind turbines are required not to cause the total fault levels on the network to go beyond the design values [30].

With an increasing penetration level of wind turbines expected in South Africa in future, this issue would become an important consideration in determining the amount of wind turbines that can be connected with the current installed equipment ratings [30].

The short circuit current contributions of the wind turbines depend on the generator type and technology (synchronous or induction, directly connected or connected via power electronic converters) that that is used [31]. For most conventional generators this is given by [30]:

$$I_k'' = \frac{c_{\max} U_n}{\sqrt{3}(Z_G + Z_T + Z_L + Z_R)} \tag{3.4}$$

Where:

- I_k'' represents the initial symmetrical short-circuit current (RMS) (p.u)
- U_n represents the nominal system voltage (p.u)
- c_{max} represents the voltage factor (assumed to be 1.1 for maximum short-circuit currents)

- Z_G represents the impedance of the generator (p.u)
- Z_T represents the impedance of the transformer (p.u)
- Z_L represents the impedance of the interconnecting line to the substation (p.u)
- Z_R represents the impedance of the reactor (if any) (p.u)

This equation assumes that the wind generator is connected to the proposed connection substation via a unit transformer and a series reactor connected to the transmission line. All these component impedances determine the faults current that flows into the connection substation.

The initial symmetrical short-circuit power, S_k'', which represents the fault level contribution is given by [89]:

$$S_k'' = \sqrt{3} I_k'' U_n \tag{3.5}$$

It is known that the short-circuit contribution of the converter-based turbines are generally low, mainly determined by the thermal limit of the semiconductors (about 2p.u. of the nominal current) [31].

The IEC 60909 International Standard is applicable for the calculation of short-circuit currents in three-phase systems operating at 50 Hz frequency [31].

3.5.3.3 The X/R ratio

As seen from equation 3.2, to determine the short-circuit calculations one needs to establish the total impedance of the circuit from the utility source, through the transmission lines and transformers down to the point in question. All circuit elements have their various impedances (reactance, X, and resistance, R) which are often referred to as “complex impedance” [32]. This complex impedance value can be represented by plotting the X vs. R as shown in Figure 3.8.

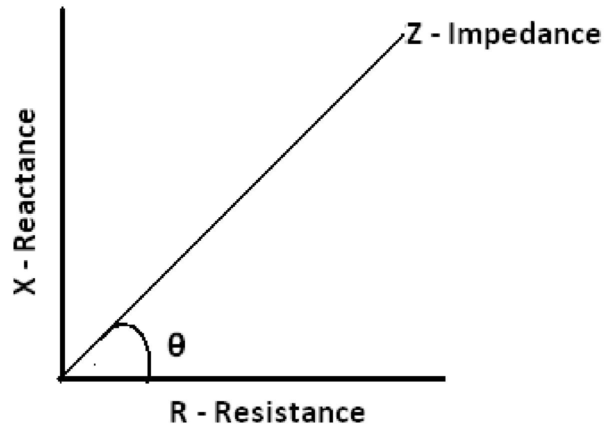


Figure 3.9 Representation of the impedance angle [32]

As seen from Figure 3.9, the X/R ratio represents the impedance angle. If the grid impedance is small, then the short circuit power level (or fault level) is large, meaning that the voltage variations are likely to be less significant or lower on the network. Thus, if the grid impedance is high, then the voltage variations will be relatively significant leading to a weak grid.

One should bear in mind that weak and strong grid are relative terms and can only be used when comparing different points on the network. The short circuit capacity power ratio of the grid as compared to that of the installed wind power is mostly used to illustrate the grid strength. Usually, 20 to 25 short circuit ratios may imply strong grids and below 8 to 10 times may mean that the grid is relatively weak [32]. However depending on the technology of the wind turbine in use, they can operate successfully under weak conditions [32].
The issue of the X/R ratio may become increasingly significant on the low voltage distribution side of the network as these are usually referred to as a weak grid.

Unfortunately most of the favourable wind areas in South Africa are mainly in the remote areas which are usually associated with weak grids and connecting the wind farm to weaker parts of the grid may require some reinforcements of the network. All this shall be discussed in more detail in chapter 5.

3.6 Comparison of power quality impacts of wind turbine technologies

Wind power introduced into the grid may result in power quality issues on the network. Table 3.1 is provided to show the various power quality concerns of the wind turbines [33].

Table 3.1 Comparison of power quality impacts [33]

	Steady state voltage impact	**Dynamic State Voltage impact**	**Harmonic Distortion of the grid [THD]**	**Voltage disturbance during start up**
Fixed speed (stall regulated)	Uncontrolled	average	nil	high
Fixed speed (Active stall regulated)	Uncontrolled	average	nil	average
Fixed Speed (pitch regulated)	Uncontrolled	high	nil	average
Variable speed (induction generator with rotor resistance control)	Uncontrolled	average	nil	average
Other variable speed systems (e.g. DFIG)	Controlled	low	Average to high	low

From the above assessment, one can safely assume that the fixed speed turbine exhibits more power quality problems associated with voltage quality as compared to variable speed turbines. However, the variable speed turbines with a power electronic converter contribute harmonic distortion to the grid as show in Table 3.1. These impacts range from average to high depending on the power electronic converters used. The above analysis will help us in identifying the modeling requirements of some of the wind turbine systems for our simulations studies.

The thesis investigated the voltage quality issues of the fixed speed generators (mainly the SCIG) and compared them to those of the variable speed generators (i.e. DFIG). This assessment will help us investigate the effect that these technologies may have if they are to be connected in some parts of the South African network. Harmonic distortion investigations were also performed for a DFIG system.

4 POWER QUALITY ISSUES IN GRID-CONNECTED WIND GENERATORS

4.1 Overview of Power Quality

Power quality seems to be an issue of ever increasing importance and concern. Good power quality of an electrical system generally means that the voltage waveform is almost perfectly continuous and sinusoidal when it is operating under a constant frequency and amplitude [24]. Most electrical utilities strive to meet the power demand of their customers all the times and under all conditions.

Various definitions of power quality exist and they may all reflect different points of view, making the term not necessarily restrictive, depending on the point in context. For instance, a good power quality for a utility may mean that they are supplying voltage at the permissible limits whereas to an end –user, it might mean the availability of power to use their equipment. The power quality of the system is essential because most grid connected equipment and devices are designed to operate under certain specified voltage and frequency conditions and any deviation from these may result in a malfunction or damage of the equipment.

According to [24], power quality can be expressed in terms of voltage, frequency and interruptions. This relationship has been illustrated in Figure 4.1 and it shows how the various power quality factors are interlinked. The power quality standards and regulations are used to guide network planners and customers so as to ensure that they follow acceptable limits.

The regulations may vary from country to country, or region to region. The power quality phenomena may be broken down as shown in Figure 4.1.

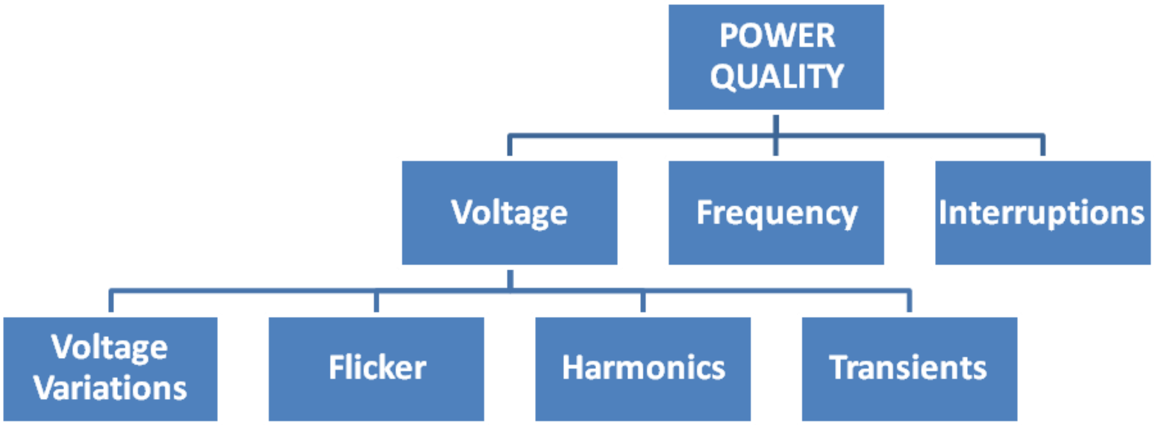


Figure 4.1 Classification of different power quality phenomena [24]

Looking at Figure 4.1, voltage seems to be a major characteristic used to determine the power quality nature of a power system. In most cases, when describing the subject of power quality, it is essentially the quality of voltage that is being addressed. This means that the voltage quality is expected to conform to the predetermined standards or regulations for a country or region. For instance in South Africa, this means that they should follow the NRS 048-2 [34]. In Europe the standards are defined in the EN 50160 and in America, they are clearly specified in the IEEE STD 1250 and P1453.

4.2 Characteristics of Power Quality Phenomena

The following phenomena may need to be considered during the investigation of power quality.

4.2.1 Voltage sag or dip

According to the NRS 048-2 [34], voltage sag or dip can be described as a short term reduction in RMS voltage for a period of between 20ms to 3 seconds. *The duration of the voltage dip is the time measured from the moment the R.M.S. voltage drops below 0.9 per unit of declared voltage up to when the voltage rises above 0.9 per unit of the declared voltage* [34]. The most common causes of voltage dips on a system are faults on the network, increased load demand and transitional events such as motorised starting of large machines or occasionally the sudden start up of wind turbines which may not have a generator soft start [35]. Figure 4.2 gives an illustration of a voltage dip caused by a single-line-ground (SLG) fault on a power system. For instance, figure 4.2 shows that when a dip occurs on the network after 0.15 seconds, the voltage level drops to about 20% of the nominal voltage before the system recovers.

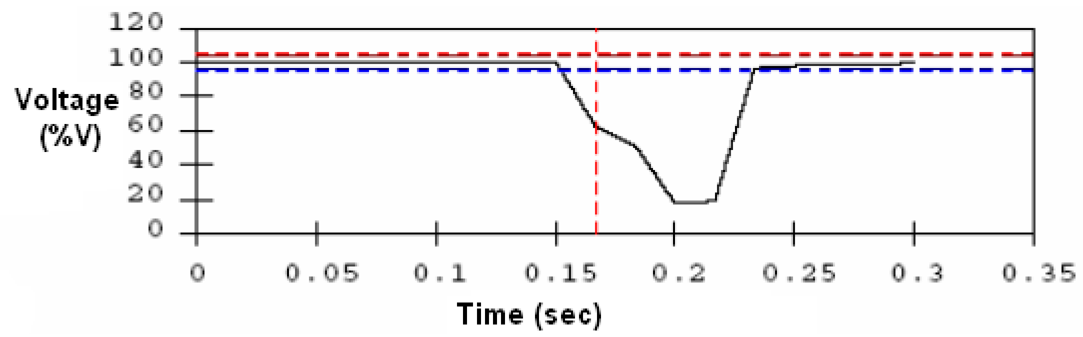


Figure 4.2 Illustration of a dip caused by a single-line - ground fault [36]

4.2.2 Over-voltages

This refers to a measured voltage having a value greater than the nominal voltage for a period greater than 1 minute [24]. According to IEEE standard 1159-1995 [37], the typical values are 1.1 to 1.2 p.u. It is believed that over-voltages can occur due to the switching operations on a system, i.e. switching off of large loads or as a result of discrepancies in reactive power compensation [36]. Other causes of over-voltages include inappropriate system voltage regulation capabilities as well as incorrect tap settings of transformers [36]. Figure 4.3 illustrates a characteristic over-voltage scenario which may last for a minute or longer.

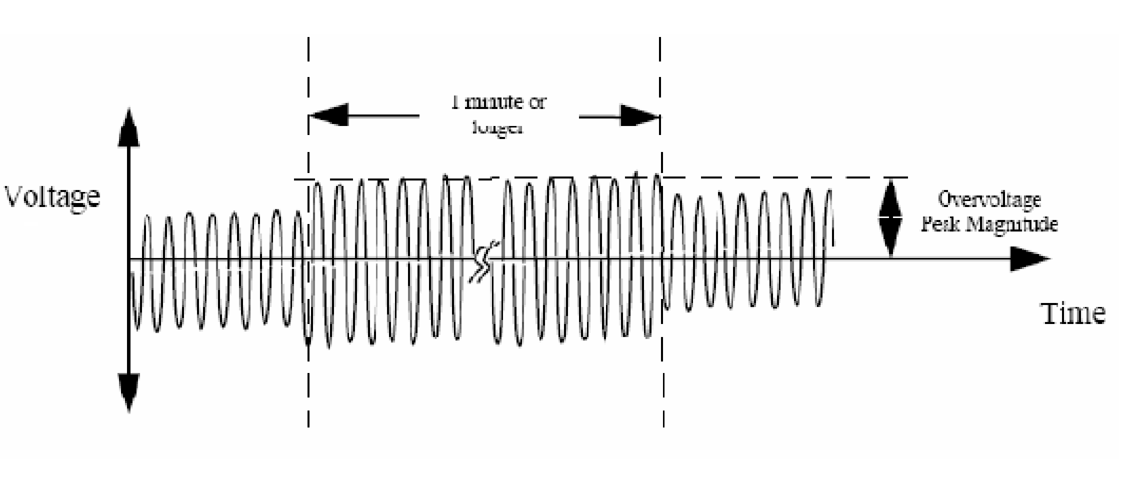


Figure 4.3 A characteristic over-voltage waveform [36]

4.2.3 Under-voltages

These may occur on a network as a result of the events which are the reverse of the events that cause over-voltage e.g. when switching on load or under overloaded circuit conditions [36]. An under-voltage can be described as a voltage having a value that is less than the nominal voltage for a duration of greater than 1 min according to the IEEE STD 1159-1995,with typical values being 0.8 - 0.9p.u. [36]. The switching off of capacitor banks can also lead to under-voltage conditions [36].

4.2.4 Transients

A transient can be described as a momentary deviation of the supply voltage or load current [35]. Most often, the transients are known to take place at some point in the switching operation of wind turbines (mainly fixed speed wind turbines), during the starting up and shutting down of the turbine. During start up of a fixed speed generator, a large rush of current flows through the machine, so a soft starter is normally used to avoid this. This voltage transient may be responsible of unsettling sensitive equipment connected to the same grid [24]. Lightning is another common cause of voltage transients. The connection of shunt capacitor banks leads to a large inrush peak current occurring as shown in Figure 4.4.

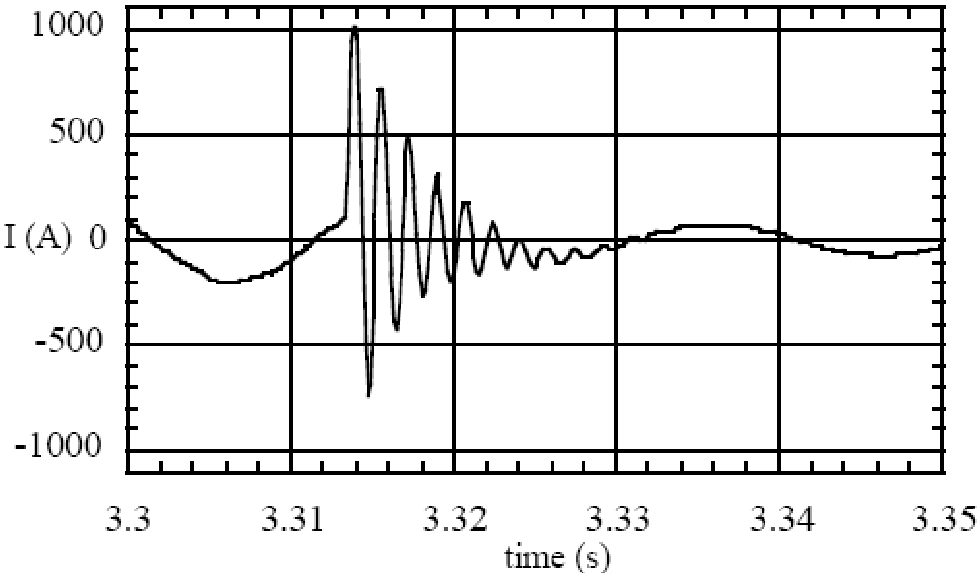


Figure 4.4 Transient current caused by connection of a shunt capacitors during start up of a 225 kW wind turbine [24]

4.2.5 Voltage Unbalance

This phenomenon normally occurs when the phase voltage (or line) magnitudes and angles are different and or out-of phase [36]. This is due to the unbalanced conditions on the network (i.e. due discrepancies in system impedances as well as unequal distribution of single-phase loads) and is regarded as a power quality issue on most electricity distribution networks [36]. The network becomes less stable and is bound to incur more losses when the voltage on the network is are not balanced [36].

4.2.6 Voltage Variations

These can be described as changes in the RMS value of the voltage occurring in a time span of a few minutes or more [24]. These occur during the normal operation of the grid and may be as a result of variations in load and power production units. Most national standards have permissible limits (generally within ±95% of the nominal voltage) that need to be met over a certain period of time, normally 24 hours [24]. Owing to wind output variability and intermittency, the output power of wind may also vary considerably resulting in voltage variations. A more detailed analysis of voltage variations emanating from power produced by wind turbines shall be described in section 4.3.1.

Voltage fluctuations are a result of sudden or periodic variations caused by loads drawing current. This fluctuating current that is drawn from the supply results in additional voltage drops in the power system leading to fluctuations in the supply voltage [38]. Examples of loads that may cause voltage fluctuations include [38]:

- Arc furnaces and welders
- Frequent motor starts (fans, air-conditioning and induction generators.).
- Motor drives and equipment with excessive motor speed changes.

It is believed that the most frequent causes of voltage fluctuations are as a result of motor starting operations [38].

4.2.7 Flicker

Voltage flicker is defined in the European standards (CEIEN50160) as "*The impression of unsteadiness of visual sensation induced by a light stimulus whose luminance or spectral distribution fluctuates with time*" [39]. This happens because of abrupt changes in the load or switching operations in the system. A flicker-meter is used to measure flicker and the method used to measure it is based on measurements of voltage variations in the voltage magnitude. The permissible magnitude of flicker is usually regulated by international standards based on sensitivity criteria. The measurements and determination of flicker are normally given in the IEC 60868 Standard and Amendment 1 [39] for most European utilities and locally, the NRS 048-1, 2 standards [34]. The following curve, Figure 4.5 gives an illustration of the magnitude of the allowable voltage limits for a sinusoidal curve with respect to the number of voltage changes per second as given in the IEC 60868 Standard [24].

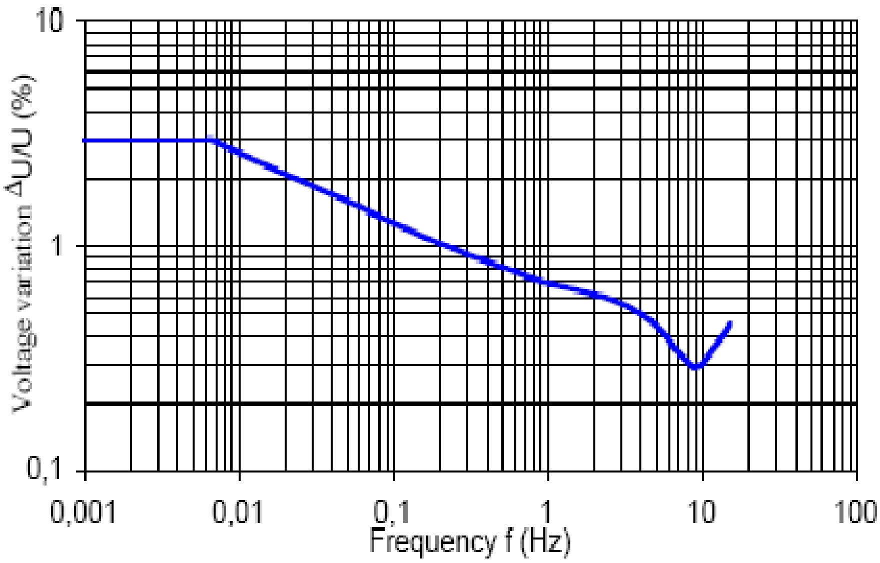


Figure 4.5 Flicker curve according to IEC 60868 [24]

Figure 4.5 is normally referred to as a flicker curve and it normally represents *"the short term flicker values of 1.0 for various frequencies of rectangular voltage fluctuations"* [35]. The basis for this curve is taken from the rectangular voltage variations (although uncommon under normal settings) which help in determining the threshold of irritability of the average observer [38]. This curve is based on the measurements that have been carried out using the 60W incandescent light bulb [38]. The acceptable limits for the flicker (or voltage variations) should lie in the region below the flicker curve shown in Figure 4.5 [38].

Wind turbines are believed to contribute to voltage flicker on the distribution network as a result of some of its switching operations. This may end up degrading the power quality of the system and this phenomenon shall therefore be described in the following sections so as to give an understanding of flicker contribution by wind turbines.

4.2.8 Harmonics

Harmonics are generally described as periodic sinusoidal distortions in voltage and current waveforms and may lead to degradation of the equipment [24]. Other effects may include overheating and interference with the communication circuits [24].The most common sources of harmonic emissions in a network are non-linear loads, power electronic devices such rectifiers and inverters [24]. These non-linear devices produce current, which is not proportional to the applied voltage. Rotating machines are also considered as sources of harmonics owing to the configuration of their windings affecting the magnetic-motive force of the machine [41]. However, these harmonics are considered insignificant as compared to those from other sources such as power electronic devices (converters etc.).

Harmonics are components with frequency multiples of the fundamental supply frequency. For instance, here in South Africa, the operational frequency is 50Hz and thus 100Hz , 150Hz up to over 2000Hz form part of the nth order harmonics. It is believed that the variable speed wind turbines contribute significantly to the amount of harmonics on the grid as compared to fixed speed wind turbines. This could be attributed to the power electronics that make up the turbine. Figure 4.6 shows a typical representation of a measured harmonic spectrum with different components. It shows an illustration of the harmonic components on a voltage waveform. The fundamental waveform seems to be distorted by the 5^{th} and 7^{th} order harmonics, resulting in the total waveform shown by the darkest line [41]. It is understood that the higher order harmonics (above the range of the 25^{th} to 50^{th} order harmonic, depending on system) are negligible for systems analysis [42]. One of the reasons behind this, is that although they may cause interference with low power electronic devices, they cause minimum damage on the system [42].

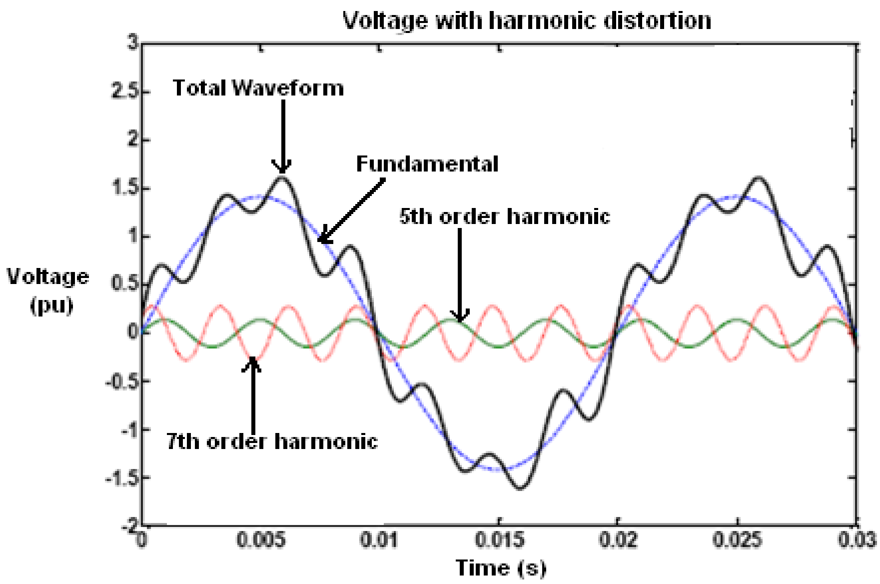


Figure 4.6 Voltage with harmonic distortion [41]

Harmonic distortion in a waveform could mean any or a combination of the following [42]:

- The harmonic voltages are too high for the control to properly establish the firing angles
- Harmonic currents are too high for the capacity of some devices in the power systems supply
- Harmonic voltages are too high because the harmonic currents produced by the source are too strong for the given system's condition.

According to Roger C. Dugan *et al* [42], the voltage distortion is normally understood to be as a result of distorted current passing through the linear, series impedance of the power system. Thus, what actually causes the harmonic voltages is the harmonic current that flows through the impedance of the system, thereby causing a voltage drop for each harmonic [42] and hence voltage distortions at the point where the harmonic source is connected to the grid. In the case of wind turbines contributing harmonics to the grid, the point of common connection is the one that is of interest in the investigation of these harmonic distortions.

Using Ohm's law, we can see that the amount of voltage distortion depends on the impedance of the grid as well as the current flowing through it. With this in mind, one can safely see that although the harmonic source may be emitting a specific current harmonic spectrum, the amount of voltage distortion it causes may be dependent on its location on the power system. This means that the grid impedance at the point of common connection plays a vital role in determining the outcomes of the harmonic distortion. Knowledge of the short circuit level at the point of connection is therefore of significance.

4.2.9 DC Injection

The injection of DC current into the AC grid can be as a result of defects in grid-connected power electronic converters [43]. DC injection has the potential to increase the saturation of transformers which may lead to power system distortion. This is a major contributor of harmonics currents from the grid connected systems with inverter/converter devices. Transformers are normally connected on the interface of the DC bus and the grid to absorb these DC injections. Some inverters do not have these transformer interfaces and therefore are susceptible to these current injections.

4.3 Effect of Wind Turbines on Power Quality

It is believed that every device or piece of equipment that is connected to the electric grid needs to meet standardized power quality requirements so as to guarantee the steady operation of the grid without any disturbances. Power quality has grown to be a technical concern for most power utilities that are planning on integrating large wind power systems into the grids. It has been widely mentioned that the initially undersized wind power plants (in the ranges of less than 1MW to 10MW) that were integrated into the utility grid had hardly any significant impact on the grid [44]. With the increase in turbine power as well and wind power plant sizes (some in the ranges of over 1GW – 10GW), it is argued that this may raise some noticeable power quality issues concerning the grid [44]. This may vary depending on the different sizes and structures of the various utility grids. It has also been proven, during the early wind integration periods, that the initial power quality stability problems were as a result of lack of standards, or regulations that governed the implementation of these wind power plants [44].

Wind energy sources, like any other distributed generation sources, are widely expected to affect the power quality of the network to which they are connected. Most utilities strive to make sure that these wind plants that are connected to the utility's grid, actually maintain the power quality that is required to guarantee the safety, stability and reliability of system [44]. Most power quality effects introduced by wind turbines are best mitigated at the point of common connection.

With voltage quality being an important characteristic in determining the power quality of a system, most equipment connected to the grid is designed and expected to operate in such a way that it functions in satisfactory way within the permissible power quality limits. Inappropriate supply of voltage may result in poor performance of the equipment or damage as well as increasing in distribution losses which may lead to a decrease in revenue for the utility [45].

The power quality effects of wind turbines in this thesis are investigated both under normal operation as well as under grid disturbance circumstances. Under normal operating conditions of the turbine, the steady state voltage impact, dynamic variations and the harmonic distortions are of particular. During disturbances, the voltage recovery of the turbine as well as the voltage level on the grid's point of common connection is also considered, and flicker contributions as well though to a lesser extent.

4.3.1 Analysis of Voltage Quality

Voltage variations are usually described as random variations that influence the magnitude of the supply voltage as a result of changes in the real and reactive power drawn by the load [14]. The characteristics of these voltage fluctuations can be affected by some the following parameters [45]:

- Load type
- Load size
- Penetration levels.

It is believed that the voltage waveform demonstrates the variations due to the fluctuating nature or intermittent operation of the connected loads [45]. Wind generators connected to the grid may also draw reactive power from the grid or provide reactive power to the grid. This may result in voltage fluctuations. The variable nature of the wind together with its intermittency may also contribute to the voltage variations occurring at the point of common connection of the grid. The relationship between the voltage gradient and the flow of active and reactive power on a system is given by the following expression [46]:

$$\Delta U = \frac{(R_g * p - X_g * q)}{U} \tag{4.1}$$

Where:

- ΔU is the voltage gradient, and *U is the nominal voltage at the PCC*
- p is the active power fed by the turbine
- q is the reactive power consumed by the turbine
- R_g and X_g are the resistance and reactance of the grid respectively

Voltage level problems represent another form of voltage quality concerns during the normal operation of grid-connected wind turbines as a result of reverse power flows along the feeder [46]. This may eventually lead to voltage level decrease or rise depending on the turbine technology in use. This shall be described in more detail in chapter 5.

Equation 4.1 illustrates the significance of the X/R ratio on the impact of the wind turbines and the voltage level of the grid at the point of common connection. Assuming *P* and *Q* to be constant, the voltage gradient would also be constant, and thus easily compensated for by means of fixed capacitors. Unfortunately this is not the case, since the flow of active and reactive power is not constant owing to the fluctuating mechanisms associated with wind power which lead to equivalent fluctuations in voltage levels at the point of connection [46].

A simple model of the power system given in Figure 4.7 can be used to briefly describe the relationship between reactive power and voltage variations on the network.

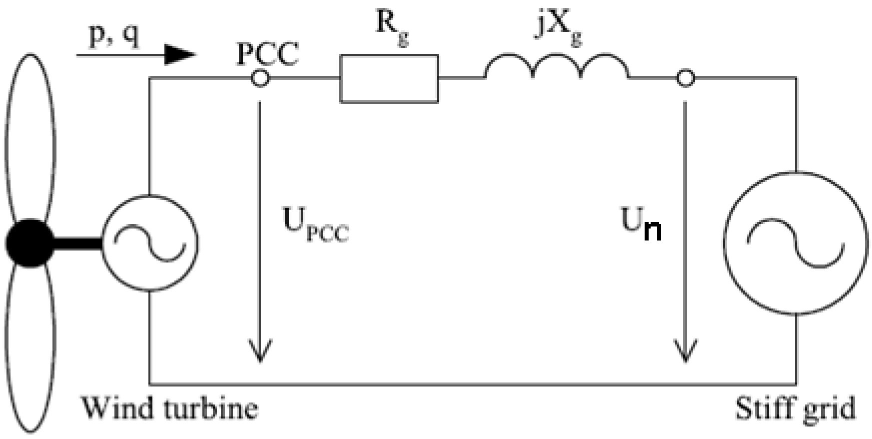


Figure 4.7 Simple Model of a Wind Turbine connected to the Grid [35]

It is believed that the voltage fluctuation problem caused by wind turbines is similar to the steady state problem resulting from load variations and this phenomenon can well be described using real and reactive power distribution on the network [47].

As mentioned previously, the exchange of reactive power between the wind turbine and the grid depends on the type of wind turbine used; thereby influencing the voltage levels at the point of common connection, U_{pcc} [47] and the following equation 4.2 is used to describe this relationship (assuming the load at the PCC remains constant)[47]:

$$U_{PCC} = R_g \frac{p}{U_n} + X_g \frac{q}{U_n} + U_n \quad (4.2)$$

Where :

- U_{PCC} is the voltage at the point of common connection (PCC)
- R_g is the grid resistance
- p is the active power produced

- U_n is the nominal voltage
- X_g is the grid resistance
- q is the reactive power consumed

With higher wind power produced by the turbine, there will be an increase in voltage drop over the grid resistance and a resultant increase in the voltage at the point of common connection (PCC) [47]. However, if the turbine consumes more reactive power, there would be a significant increase in the voltage drop over the grid reactance and a consequent decrease in the voltage at the PCC [47].

This is bad for the power quality of the grid and would call for dynamic compensation of reactive power to be used. For induction generators, the reactive power consumption is a function of its loading and increases as the active power output increases [46]. It is believed that the power factor of induction generators at rated load is normally in the range of 0.85-090, implying that the consumption of reactive power is typically about half the active power generation [46]. It is considered that reactive power consumption related to no load conditions is compensated for by means of fixed capacitors connected next to the wind turbine plant. In cases where there is no capacitive compensation, this will result in reactive power being drawn from other parts of the grid, and may thus result in voltage level instability on the network.

According to [38], equation 4.1 can further be expanded into the comparing the voltage at the point of common connection (PCC) to the reactive power. Assuming that *Un* is on the stronger part of the grid and thus remains constant, and *Rg* is negligible (like in most MV to HV networks), then the reactance X_g =1/Fault level, leading to equation (4.3)

$\Delta U_{PCC} = -\Delta Q/$Fault level…………………………………………………………. (4.3)

Where:

- ΔU_{PCC} is the change in voltage
- ΔQ is the change in reactive power

This could be interpreted as the voltage at the point of common connection being a function of the reactive power variation of the turbine and supply system characteristics [38].

However, on some distribution networks where the R is relatively large, the real power may also contribute to voltage changes at the point of common connection [38].

It is mentioned [38] that voltage changes introduced by a certain load will not be a problem to a single customer, but will also spread to others connected to the point of common connection of the distribution system. There is therefore a need to look carefully into this phenomenon to avoid affecting other parts of the network.

The same is true for a wind generator connected to the grid. The voltage variations as a result of the wind power injected into the grid may cause fluctuations on the network which can also be propagated to other loads or customers connected to the grid. Therefore the amount of wind power that is connected at a certain point needs to be carefully managed. Once again, the strength of the grid at the place where the wind power is to be connected may also affect the voltage variations experienced at that point i.e. at the stronger parts of the network, which are normally associated with high fault levels , there will be less influences on the voltage levels as a result of wind integration.

Load flow calculations that are performed in the DigSilent PowerFactory simulations package can be used to determine voltage variations caused by wind turbines on the network. Alternatively, an analytical method that has been discussed in section 4.3.1 above can be used to calculate the simplified voltage variation calculations [24].

4.3.2 Analysis of Harmonic Emissions

Harmonic distortion problems are becoming gradually more important with most power electronic and converter driven wind turbine systems. As much as modern power electronic devices are widely recommended to solve most power quality problems as compared to conventional control methods, their main drawback is the harmonic emissions generated onto the power system's network. The harmonics produced are increasing all the time and becoming a significant problem to the utility since these harmonics are transmitted freely from the low-voltage distribution system towards the high voltage side closer to the transmission system [48]. This transmission of harmonics may end up affecting other loads connected to different voltage levels on the network due to THD limits being exceeded. There is therefore a need for it to be assessed.

In order to make sure that wind turbines do not contribute harmonics that will have an adverse impact on the grid, it is suggested that the overall harmonic emissions from the wind farm should be kept within the permissible limits which have been described in the standards (i.e. IEEE 519). In order to facilitate this, the harmonic distortion (HD) together with the total harmonic distortion (THD) of the overall wind power plant or wind farm should be assessed before interconnection to ensure that the installed wind farm operates within the acceptable harmonic emission levels accepted in the various power quality standards [26].

4.3.2.1 Harmonic Distortion

The harmonic distortion (HD) of a voltage or current waveform can be described as follows [26]:

$$HD_I(f_i) = \frac{|I(f_i)|}{|I(f_1)|} \tag{4.4}$$

where $I(f_i)$ is the component of the current at frequency, f_i *and* f_1 represents the fundamental frequency which in this case is 50 Hz.

The harmonic distortion is merely a ratio of each individual harmonic contribution to the fundamental frequency of a waveform [26].

4.3.2.2 Total Harmonic Distortion

This is specified as a measure of the effective value of the harmonic components of a distorted waveform [42]. Its index can be calculated as follows:

$$THD_U = \frac{\sqrt{\sum_{h=2}^{\infty} {U_h}^2}}{U_1} \tag{4.5}$$

Where:

- U_2 to U_h represent individual harmonic components (h=2, 3, …n)
- U_1 represents the fundamental component of the frequency.

In the DIgSILENT modeling tool, the voltage or current THD calculations can further be represented by the following expression [26]:

$$THD_1 = \frac{1}{I_{ref}} x \sqrt{{I_{rms}}^2 - I^2(f_1)} \tag{4.6}$$

Where I_{ref} is the reference value of the current [10], *Irms* is the root-mean-square current and *I is the nominal current*

The RMS value of the distorted waveform is given by [42]:

$$RMS = \sqrt{\sum_{h=1}^{h_{max}} M_h^2} = M_1\sqrt{1+THD^2} \tag{4.7}$$

Where M_h can either be the current or voltage harmonic component.

The THD index is useful in quantifying how much additional loss is caused by the current flowing through a conductor and is mostly used to describe voltage harmonic distortions i.e. the voltage total harmonic distortion [42]. Basically, the THD is a measurement of the harmonic distortion present in a waveform. It is given as a measure for determining the quality of the waveform and it is used to quantify the effects of the harmonic injection on our system.

4.3.2.3 Voltage Harmonic Distortion Limits

As mentioned previously, it is always important to make sure that during the course of the harmonic simulations, the harmonic load-flow results are compared to the limits set by the international standards [40]. This allows for a better assessment of the harmonic impact on the network for various mitigation procedures, should the harmonic distortion limits be exceeded.

Several international standards have been used to assess the level of harmonics that wind turbines may contribute to the grid. One such standard is the IEEE standard 519 "IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power

Systems" [16]. They specify the allowable THD limits and therefore the corresponding harmonic distortion limits as given in Table 4.1.

Table 4.1 IEEE 519 Harmonic voltage limits [42]

Bus Voltage (kV)	Maximum individual harmonic content (%)	Maximum THD (%)
0-69	3.0	5.0
69-161	1.5	2.5
>161	1.0	1.5

These limits should be met by all equipment or loads connected to the grid so as to allow for smooth operation of the grid without significant impacts on the voltage quality.

On the other hand, the European power quality standards, EN 50160, specify 8% as the limits for the percentage THD on the voltage supply [3]. Since wind turbines are also connected to the grid and most likely closer to the other customers, they are also expected to meet these limits at the corresponding voltage levels.

4.3.3 Harmonic Sources in Wind Turbines (Three phase power converter*)*

In most recent cases, a generator feeds electrical power into the grid through a power electronic converter. Power electronic converters may allow for two directional power flow and this can interfere with the load or generator and the systems grid [49]. The two different types of converters are the [49]:

- Grid commutated – mainly thyristor converters with 6, 12 or more pulses which may produce integer harmonics that may require harmonic filters. These thyristor have the disadvantage of not being able to control the reactive power consumption [49].
- Self Commutated – these are mainly PWM converters which are composed of IGBTs (Insulated Gate Bipolar Transistor). These are capable of controlling reactive power on the system. Depending on the converter topology, the high frequency switching of these converters may result in harmonics in the range of a few kHz and these high switching frequencies are easy to filter [49].

These converters can either be connected in to single phase or three phase systems, with the most variable speed wind turbine generators mainly incorporating the latter. Three phase converters are contributors of harmonics on the power system. Unlike single phase converters, they do not generate the third harmonic current (which usually contributes a greater share to the THD) [42]. Voltage source inverter drives, which are of PWM –type can also contribute significantly to higher distortion levels [42]. The six pulse diode rectifier/ PWM inverter emits low order current harmonic such as the 5^{th}, 7^{th}, 11^{th}, etc. [46]. More so, work done on a distribution network in [40] has shown that the highest magnitude of harmonics measured in most substations where mainly in the range of low order components such as 5^{th}, 7^{th}, 11^{th} and 13^{th}. These are typical of three-phase 6-pulse converter systems [40].

It is widely known that in most wind turbine applications, the induction generators and the step-up transformers are connected in three phases in the form of Wye or Delta connection, which eliminates the flow of the 3^{rd} and the even harmonics (including its multiples) [40]. The most common harmonics existing are the odd harmonics (h= 5, 7, 11, 13….etc.) [40].

4.3.3.1 Wind Energy Converters

With the evolution of power electronic systems over the last 30 years, their applications in most modern wind turbine systems have been increasing rapidly. It must however be mentioned that the developments in the power electronic devices have been guided by the following concerns; *reliability, efficiency and cost* [49]. Looking at these parameters, the cost seems to be a major factor for most manufacturers but due to the increased economies of scale, their cost is decreasing by 2-5% annually for the same output performance [49], The most common devices used for the power electronic converters are shown in figure 4.8. This depicts the trend in which the power devices have developed from [49].

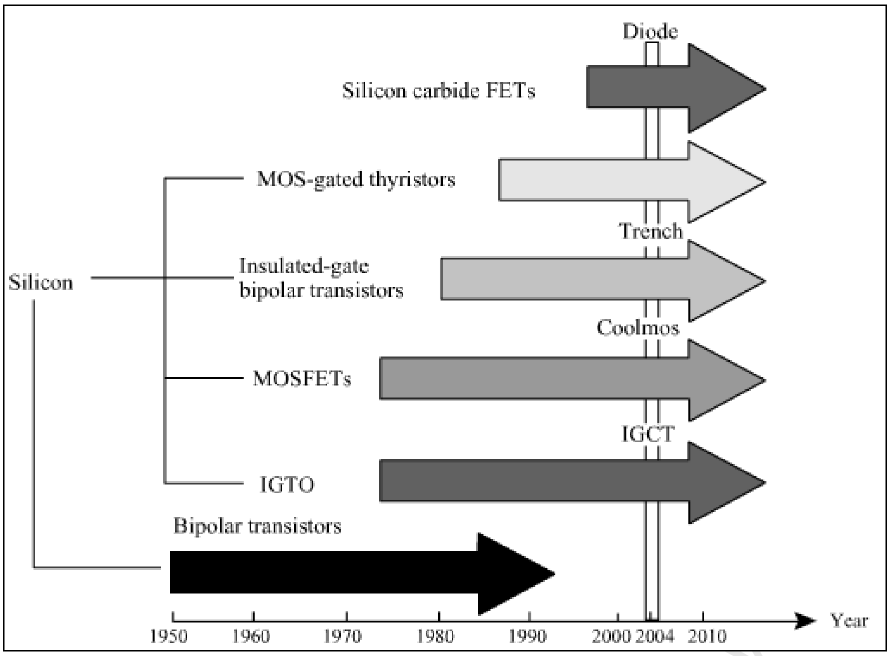


Figure 4.8 Trend-line for the development of power electronic converters [49]

As seen in figure 4.8, the modern power electronic devices that are preferred include the IGBTs and the MOSFETS just to mention a few [49].

4.3.3.2 Harmonic Spectrum

The harmonic spectrum of a wind turbine is basically a spectrum with harmonics whose frequencies are whole number multiples of the fundamental frequencies, notably 50Hz in South Africa. Different harmonic spectra of various wind turbine types have been analysed by Sokratis T. Tentzerakis *et al* in [50] and of particular interest where those of the common DFIG technologies. Figure 4.9 shows some of these common spectrums.

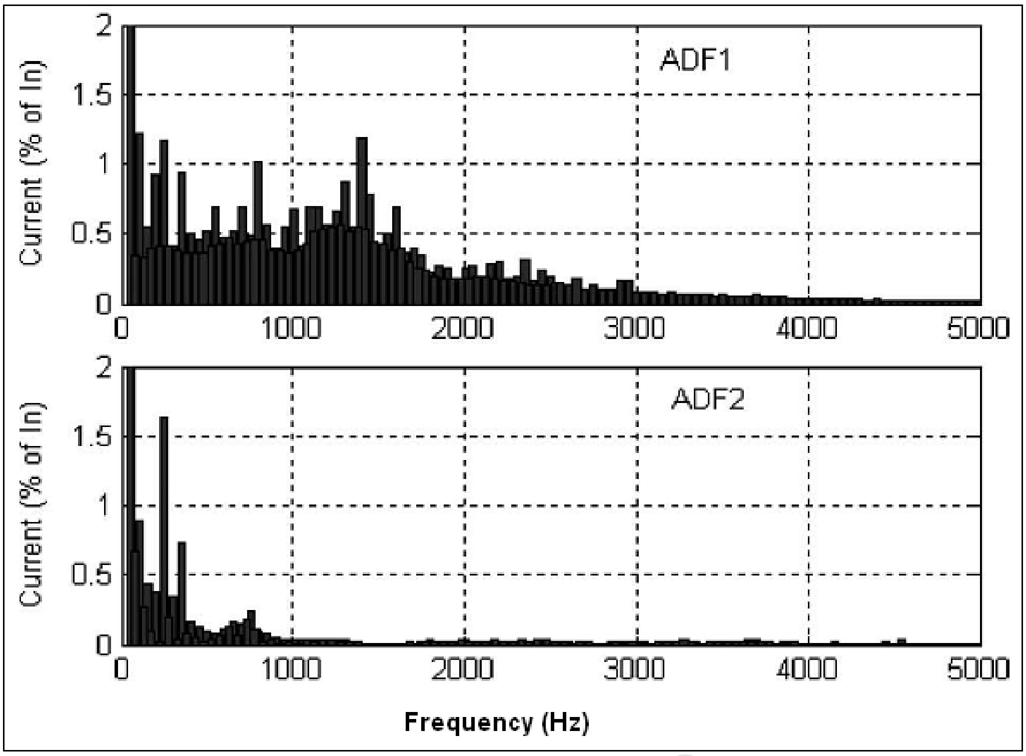


Figure 4.9 Harmonic spectrum of DFIG wind turbines [50]

The shape and frequency range of the harmonic spectrums of these wind turbines are largely dependent on the characteristics and control of the power electronic converter employed, as well as the internal filters that may be incorporated into the wind turbine [50]. The variation in switching frequencies of these controls may bring about different harmonic spectrums. The low-order harmonics are generally dominant in the spectrum of most wind turbines, especially in large sized wind turbines due to unbalanced terminal voltages which result in low-order current harmonics due to the converter control systems [50]

As seen in Figure 4.9, there are two different types of doubly-fed induction generators presented. Type ADF1 mainly consists of a DFIG with a carrier-based PWM scheme implemented in it. This PWM system is controlled in such a way that it emits a high-frequency pattern of a spectrum [50]. On the other hand, the Type ADF2 is a DFIG assumed to have been incorporating a converter scheme consisting of a carrier-based PWM system [50], with its dominant harmonics corresponding to the lower order spectrum. The characteristic of a six-pulse line commutated converter is explained in section 4.3.3.1.

While most modern wind turbines (DFIGs with PWM converters) having harmonic spectrums extending up to a few kHz, there are still PWM converters available which emit lower order harmonics which are very prominent on the overall spectrum [50]. It is thought that the presence and dominance of these low order harmonics are recognized as a result of some of the following issues [50]:

- Terminal voltage imbalances which may lead to the generation of low-order current harmonics due to the control system employed in the converter or sometimes as a result of the induced low-frequency distortion of the dc voltage.
- The low-order harmonics existing in the grid that result in low-frequency harmonic currents. This mainly affects the stator circuitry of the DFIG which is connected directly to the grid via the PWM converter control circuit.
- The auxiliary loads connected to the turbine (controllers, motors, lighting etc.) which also contribute low order harmonics to the overall output current distortion.

In most of these cases, the harmonics are present both on the stator side and on the rotor side and also from the DC-current side of the circuitry [51]. The dc-current harmonics are a result of the harmonic frequencies on the dc-side of the 6 pulse naturally commutated converter [51]. The rotor current harmonics are due to the switching of the diode rectifier (mainly low order harmonics) whereas the stator current harmonics are induced by the rotating magnetic fields emanating from the rotor current harmonics [51].

The most common source of harmonics in wind energy systems are the three-phase converters. This is because of the commutation on the dc-side current between the three ac-phases [24]. The levels of harmonic emissions may vary in accordance with the power inverter used, as well as the interconnection configuration [52]. The most common harmonics current injections limits for most network power quality requirements are derived from the IEEE 519-1992 Standards for Distributed Generators which are illustrated in Table 4.4 [52]

Table 4.2 Harmonic Injection Requirements for Distributed Generators per IEEE 512-1992 [52]

Harmonic Number	**Allowed level relative to fundamental frequency**
< 11th	4%
<11th to < 17th	2%
<17th to <23th	1.5%
<23th to <35th	0.6%
35th or greater	0.3%
Total Harmonic Distortion	5%

Some DFIG based wind turbines are still available which still emit lower order harmonics (even though most of them are emitting higher order harmonics which are not so difficult to filter) which are difficult to filter [50]. It is these low-order harmonics that will mainly be investigated in this research work.

4.3.3.3 DFIG and Harmonic Emissions

The power electronic converters e.g. the PWM converters in modern wind farms are installed so that they can control the real and reactive power flow in the grid so as to balance the loads with the generation capacity. In most cases, the voltage source pulse width modulation (PWM)-converters are used [3]. These PWM converters have switching frequencies that are limited by the loss of the power electronic switches which may result in non-ideal shapes of the output voltage waveforms at the point of common connection [53]. Harmonics are in some cases generated by these distortions of the waveforms. In this report, we are mainly interested in considering the harmonics generated by the converter system of a doubly-fed induction generator (DFIG).

The generated electrical power in a DFIG is controlled by the rotor side converter whereas the controls of the grid-side converter maintain a fixed dc-link voltage [49]. Since these converters (grid-side and rotor-side) are mainly voltage source converters, they are bound to introduce harmonics into the systems grid [49].

On a DFIG system, the distortions are mainly on the stator side. These originate from the harmonic transmission of the rotor side harmonics to the stator. These rotor side harmonics are generated by the rotor inverter but their frequency is modulated by the operating slip of the generator as discussed in [51]. Figure 3.2.2(a) shows this direct connection of the stator and an inverter coupled rotor. It is recommended that the harmonics be measured from the wind turbine' output, including both the rotor and stator circuit contributions [50]. A more detailed analysis of how these harmonics are produced in the converter controls is given in [51] and [54].

4.3.3.4 Mitigation of Harmonics

A filter is expected to act as a reactive power compensator at fundamental frequencies (50Hz), in the same way as a usual capacitor bank [45]. Three phase harmonic filters may offer an optimum solution to solving voltage distortion problems [45]. They are designed to filter one or more harmonics from the power system so as to bring the harmonic distortion to an acceptable level. Filters are understood to provide low-impedance paths that can by-pass the harmonics produced at the source. The filter therefore is expected to have zero impedance at the *tuning frequency* so as absorb the harmonics of interest.

There are two general types of filters used, passive and active filters. Passive filters are the most commonly used filters and are mainly composed of capacitors, reactors and resistors which reduce distortions to the required levels. These are used mainly to filter low-order harmonics (5^{th}, 7^{th}, 11^{th}, 13^{th}, etc.) and examples include single-tuned and double-tuned filters. High-pass filters are mainly used to filter out high order harmonics [45]. Meanwhile, active filters are relatively new filtering devices and are based on complicated power electronic systems. They are relatively expensive as compared to passive filters [43].

There are basically four typical types of filters available and these include the series-tuned filters, double band pass filters, damped filters and detuned filters [48]. The most common ones are the series tuned filters. These mainly consist of a series combination of a capacitor and a reactor usually tuned to low harmonic frequencies. The reactance of both the capacitor and the reactor become equivalent at this tuned harmonics frequency thereby making the impedance purely resistive [48] thus enhancing its operation. One special characteristic of this filter is that its impedance is capacitive for low order harmonics and inductive for higher harmonics [48]. The single-tuned filter is the simplest of all the filters. Figure 4.2 shows a single-tuned filter which is being investigated in this thesis.

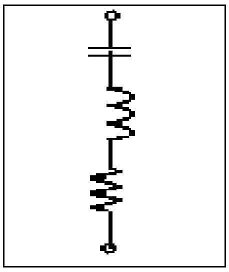


Figure 4.10 The single tuned filter [39]

Single-tuned filters can provide power factor correction in addition to harmonic mitigation [39]. They are connected in shunt with the power system and their low impedance allows harmonic currents to be diverted from the normal flow path towards the filter.

Double-Band-Pass Filters, on the other hand, consist of a series combination of a main capacitor and a reactor connected to a tuning device (consisting of a capacitor and tuning reactor connected in parallel). They are characterized by two tuning frequencies that reduce the impedance of the filter and thus enable its operation [48].

This thesis will mainly investigate the influence of passive filters on the harmonic distortions in the power systems.

The IEEE 1531- "Guide for Application and Specification of Harmonic Filters" [55] has been used as a guideline for the design of filters that are used to mitigate the harmonic contribution of the wind plant at the point of common connection. One of the most general ways of controlling harmonic distortion is to place a passive shunt harmonic filter closer to the harmonic current sources [55].

The point of common connection needs to be appropriately selected for a particular harmonic installation. It can either be at the distribution bus or at an individual harmonic source. Bus-connected harmonic filters are typically a better choice to improve the overall plant power factor [55].

4.3.3.5 Theory on Harmonic Filter Design

Some of the key filter design considerations include [55]:

(i) Reactive power requirements at the nominal voltage

(ii) Harmonic limitations

(iii) Harmonic filter locations

(iv) Normal harmonic filter conditions

4.3.4 Design Equations for Harmonic Filters

Harmonic filters can also be used to provide reactive power for power factor correction purposes. These filters are being designed according to the following equation [56]:

$$Q_c = P(\tan\theta_1 - \tan\theta_2) \qquad (4.8)$$

Where

- Q_c = Capacitor reactive power rating
- P = active power at the load/utility
- θ_1 = Power factor before correction
- θ_2 = power factor after correction

The capacity of the single-tuned filter can be set to Q_c [56]. The capacity of these filters is also designed such that the reactive power it supplies does not exceed a certain value so as to avoid over-voltage rise [56].

Further equations to determine some of parameters of the filter are listed as follows [56]:

$$X_c = \frac{V_c^2}{Q_c} \qquad (4.9)$$

$$X_L = \frac{V_c^2}{Q_c.n^2} = \frac{X_c}{n^2} \qquad (4.10)$$

$$n = \frac{f_n}{f_1} = \sqrt{\frac{X_C}{X_L}} \tag{4.11}$$

$$Q = \frac{n.X_L}{R} = \frac{X_C}{n.R} \tag{4.12}$$

Where

- X_c = capacitive reactance at 50Hz
- X_L= reactor impedance at 50Hz i.e.f_1
- V_c = line to line capacitive voltage
- n = tuned harmonic order
- Q = Quality factor (measure of the sharpness of the tuning frequency determined by the resistance value).
- R = resistance value at 50Hz

Having considered the power quality issues above, the voltage level issues and harmonic distortions seem to be the most interesting issues to investigate, especially in the local context.

5 MODELING OF WIND TURBINES FOR POWER QUALITY STUDY

The aim of this chapter is to present the modeling of wind turbines for power quality studies, thereby allowing us to predict the output of wind turbines during normal operations as well as during a grid disturbance. The models help in the prediction and analysis of the interaction between the mechanical, aerodynamic and electrical components of the wind turbines under the above mentioned conditions.

More emphasis is put mainly on the electrical component of the wind turbine models that have been used in this thesis, notably the SCIG and DFIG.

The development of models that simulate the interaction between wind turbines and the power system are helpful in facilitating the wind farm investors and the utility to perform the necessary preliminary studies (such as power quality and stability) before the integration of the wind turbines into the grid [57]. This in turn reduces the costs involved with wind integration as well as making sure that the wind turbines do not adversely affect the utility grid [35]. The models have been developed using the DIgSILENT simulation tool.

When the steady state voltage level of a wind turbine is taken into consideration, its output (active and reactive power) can be described as a function of the mean wind speed [35]. In this thesis, wind turbines were represented in DigSilent simulation tool as sources of active and reactive power and thus the actual wind speed model concept was not used [35].

5.1 Introduction to DIgSILENT

This simulation package has been developed to analyse complex power system networks on an integrated one-line interface [58]. This package has the ability to perform various power systems operations, but for the sake of this thesis, steady state studies mainly consisting of load flows, rms calculations and harmonic load flows have been performed. A few dynamic studies involving network disturbances, such as faults, were also performed at some stages of the investigation [35]. The accuracy and legitimacy of results that are achieved from this package have been confirmed in most of the work done in the operation and planning of large power systems [58].

DigSilent contains a wide-ranging library of models or electrical elements that can be used for simulating load-flow, harmonic load-flows as well as transient events in a power system [35]. The models and tools that were used in this study are briefly described in the following subsection:

5.2 Wind Turbine Modeling

The model of a complete grid-connected wind turbine consists of the wind model, the aerodynamic model of the wind turbine, the mechanical model of the transmission system, models of the electrical components, namely the DFIG, the SCIG, PWM voltage source converters, transformer, capacitor, and the control system [57]. The way these models connect and interact with each other as a system is illustrated in Figure 5.1.

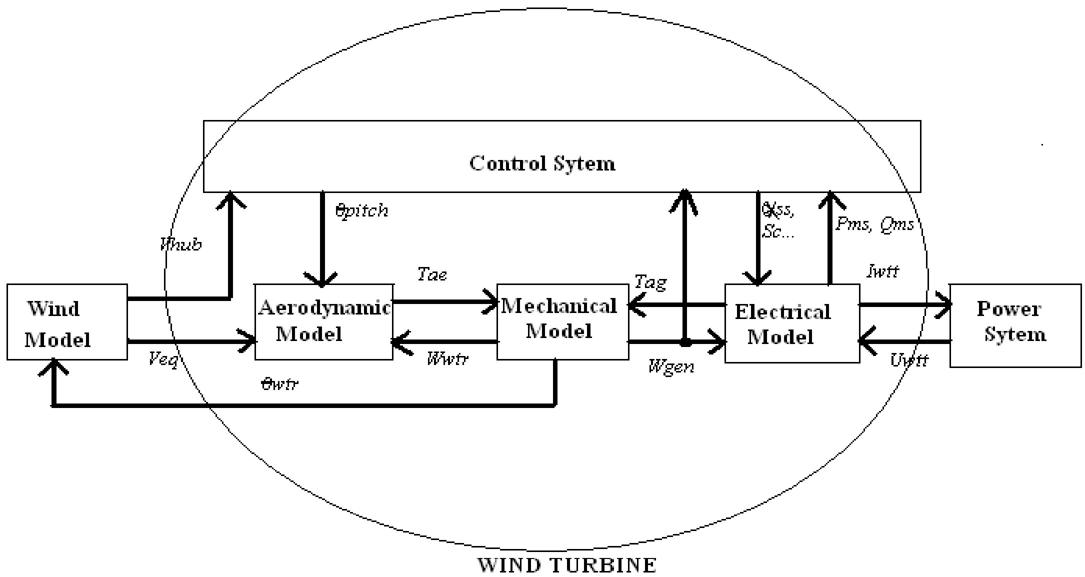


Figure 5.1 Block diagram structure of a basic wind turbine model [57]

Where [58]:

- V_{hub} is the wind speed of the hub
- V_{eq} is the equivalent wind speed
- Θ_{wtr} is the position of the turbine rotor

- α_{ss} , S_c is the soft starter angle and capacitor bank switch signal
- ω_{gen} is the generator angular speed
- P_{ms}, Q_{ms} is the active and reactive power at the main switch
- U_{wtt} , I_{wtt} is the generator voltage and current interfacing with the power system

All these components constitute a basic model of a wind turbine that can be used for power system's analysis, including power quality studies [57]. In most cases, the aerodynamic, mechanical and wind speed models (including some control models) are modeled in the dynamic simulation language (DSL) of DIgSILENT which makes it possible for users to create their own models that are relevant to the studies that are being performed [57]. This DSL modeling language was however not presented in this thesis as it required an external programme and therefore a generic built-in model found in DIgSILENT were used.

5.3 Wind Model

The wind model is meant to give the wind speeds of the wind turbines in the wind farm or wind power plant that is connected to the grid [58]. This model takes into account the interaction of the variable wind speed resulting from turbulence or tower shadow and the corresponding rotor plane of the wind turbine [58]. The wind model mainly consists of [58]:

- Deterministic effects – which contain the mean wind speed and tower shadow variations
- Stochastic effects - which include the wind farm's scale coherence between the wind turbines in a wind farm as well as the effects of rotational turbulence [58].

According to [59], the wind speed, $v_{w,}$ can be described as a four component model as follows:

$$v_w(t) = v_{wa} + v_{wr}(t) + v_{wg}(t) + v_{wt}(t) \tag{5.1}$$

Where [59]:

- v_{wa} is the average value of the wind speed
- v_{wg} is the gust component of the wind speed

- v_{wr} is the ramp component of the wind speed
- v_{wt} is the turbulence component of the wind speed

However, a wind model was not included in the overall wind turbine modeling studies performed in this thesis as it required an external modeling program, DSL (Dynamic Simulation Language). This feature allows for the modeling of non-linear and linear systems such as aerodynamic systems, wind speeds and mechanical systems [26].

In most of the steady state voltage studies made in this thesis, the wind speed was assumed to be constant and in the case where the effects of wind variations needed to be investigated, the following assumptions were made:

- Since wind power output is proportional to wind speeds, the effects of wind power variations was investigated by changing the output power of the wind turbine so that it represented a variation in wind, for instance [59]:
  - When the turbine is operating at optimum speed, this may imply that its power output is almost at rated output hence making each turbine operate at 2MW
  - When wind speeds are low, say at 50% optimal speed (see Figure 3.1), we assume that the turbine is delivering at 50% of its rated power to the grid
  - When there is no wind, we assume that there is no power being delivered to the grid from the turbine (for SCIG).

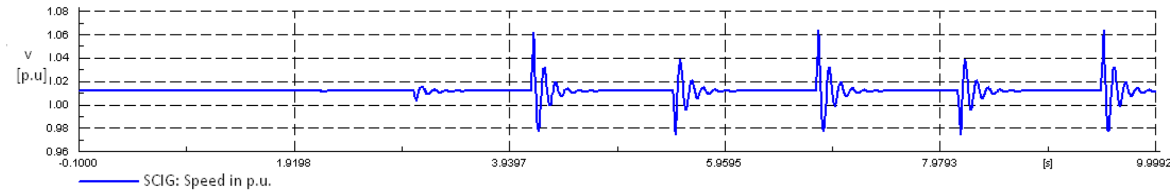


Figure 5.2 Variation of generator speed with time

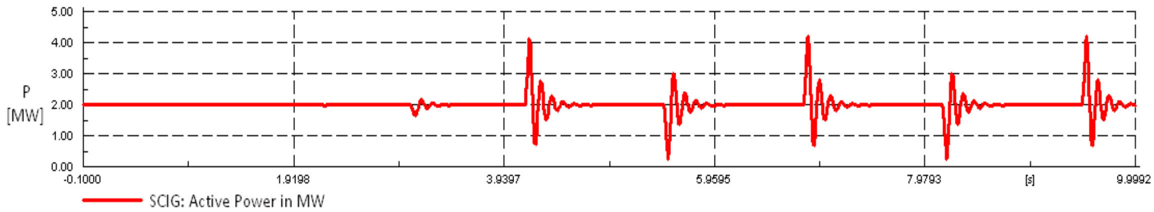


Figure 5.3 Variation of generator active power with time

The above Figures 5.2 and 5.3 show the relations between the speed and the active power produced by the generator with time. There is a correlation between the two and therefore we may assume that varying the output power of a generator can be seen as a way of showing the wind speed variation.

5.4 Aerodynamic Model

The aerodynamic power control of wind turbines is based on the aerodynamic properties of the wind turbine's rotor blade. It is necessary to control or limit the input power to the wind turbine during conditions of high wind and this is done using stall, pitch or active stall control as described in section 3.1 [60]. The most common control system used by most of the latest variable speed wind turbines is the pitch control system [60].

As seen Figure 5.1, the wind speed equivalent, v_{eq} pitch angle, θ_{pitch} from the control system as well as the turbine's rotor speed, ω_{wrt} all together form the basis of the aerodynamic model [58]. The model used in DigSilent simulation tool is based on the aerodynamic efficiency C_p (λ, θ_{pitch}), which is based on the tip speed ratio and the pitch angle [58].

The tip speed ratio, described as the ratio between the blade tip speed, $R\omega_{wtr}$ and incoming free wind speed, v_{eq} is given as [58]:

$$\lambda = \frac{R\omega_{wtr}}{v_{eq}} \tag{5.1}$$

Thus, the relationship between the aerodynamic efficiency, C_p of the wind turbine and the tip speed ratio is commonly used to describe the conversion of wind speed to shaft torque [58].

As a result, C_p is used to determine the aerodynamic power, P_{ae} developed by the shaft of a turbine with a rotor radius R, at wind speed v_{eq} and air density ρ [60]:

$$P_{ae} = \frac{1}{2}\rho\pi R^2 v_{eq}{}^3 C_p(\theta_{pitch}, \lambda) \tag{5.2}$$

Furthermore, the aerodynamic torque, $T_{ae,}$ is calculated by:

$$T_{ae} = \frac{P_{ae}}{\omega_{wtr}} = \frac{\pi}{2\lambda}\rho R^3 v_{eq}{}^2 C_p\left(\theta_{pitch}, \lambda\right) \qquad (5.3)$$

In the DIgSILENT simulation modeling, the aerodynamic efficiency coefficient, C_p, can either be a simplified steady state aerodynamic model, C_p^{static} or dynamic aerodynamic efficiency, $C_p^{dynamic}$, with the latter being mostly favoured in DIgSILENT as it estimates the power fluctuations in the stall region [60]. At lower speeds, there is no difference between the two since the amplification factors are similar, but they may differ during high wind speeds [60].

5.5 Mechanical Model

The drive train is considered part of the mechanical model since it influences the power fluctuations of the wind turbine as a result of its interaction with the grid [60]. It converts aerodynamic torque, T_{ae} on the rotor into torque on the low speed shaft, T_{lss}. The gearbox further scales down this T_{lss} into T_{hss} [60] as shown if Figure 5.4.

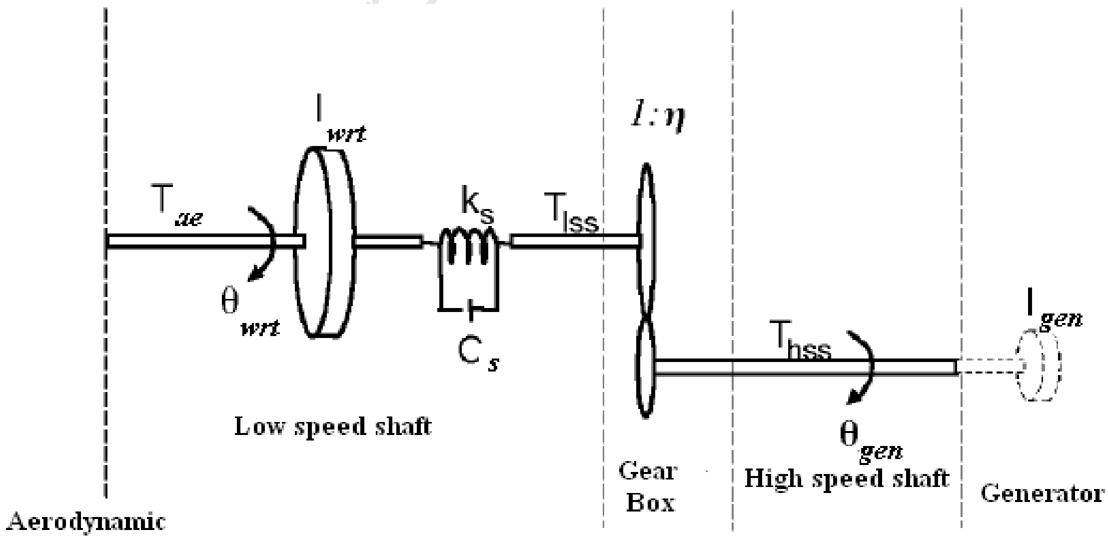


Figure 5.4 Drive train model of a wind generator [60]

The mechanical model used in DigSilent is basically a two mass model consisting of a large mass corresponding to rotor inertia J_{rot} and a small mass corresponding to the inertia of the generator, J_{gen} [60]. In most cases, the low speed shaft is modeled by the stiffness k and a damping coefficient, c whereas the high-speed shaft is assumed to be stiff, with an ideal gear ratio ($1{:}n_{gear}$) [61].

According to [62], the dynamic description of the mechanical model consists of three differential equations,

$$\dot{\theta}_{rot} = \omega_{rot} \qquad [rad/s] \qquad (5.4)$$

$$\dot{\theta} = \omega_{rot} - \frac{\varpi_{gen}}{n_{gear}} \qquad [rad/s] \qquad (5.5)$$

$$\dot{\omega}_{rot} = \frac{(T_{rot} - T_{shsft})}{J_{rot}} \qquad [rad/s] \qquad (5.6)$$

Where:

$\theta_k = \theta_{rot} - \frac{\theta_{gen}}{n_{gear}}$ is the angular difference between the two ends of the flexible shaft and T_{rot} is the rotational torque, T_{shaft} is the shaft torque [61].

The mechanical power of the wind turbine generator, P_t is given as [61]:

$$P_t = \omega_{gen} \frac{T_{shaft}}{n_{gear}} \quad [W] \qquad (5.7)$$

5.6 Electrical Models

The electrical models that are provided in the DIgSILENT simulation tool include the generator, soft starter, capacitor banks, transformers, tower cables and busbars [58]. Most of these components were discussed earlier in chapter 3, and the models of the various wind generators used in this thesis shall be discussed in the following sub-sections.

Wind turbines can either be of a synchronous or asynchronous (induction) nature. Both models are available in DigSilent library but this study was mainly focused on addressing issues and concerns of induction generators that are widely known to have a slight negative impact on the power system as discussed in Chapter 3.

5.6.1 Model of a General Induction machine

The general equivalent model of an induction machine used in the DIgSILENT *PowerFactory* modeling is shown in Figure 5.5 [62].

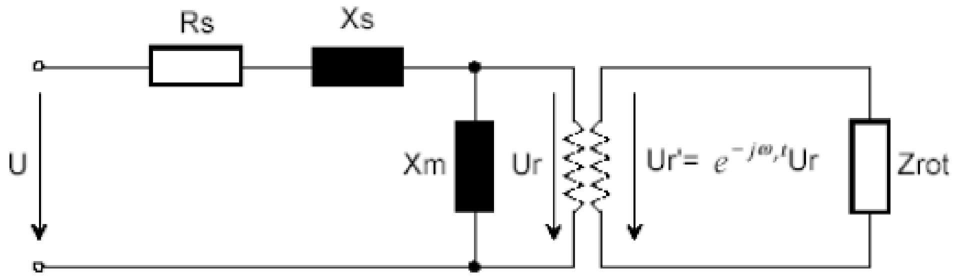


Figure 5.5 General Induction Machine Model [63]

The model mainly consists of the winding resistance, R_s, the stator leakage reactance, X_s, the magnetizing reactance X_m as well as the impedance of the rotor Z_{rot} [62]. This model also takes into account that the rotor impedance, Z_{rot} is dependent on the frequency or slip of the machine thereby allowing the model of the squirrel cage induction machines over a wide slip range [62].
The slip s is defined as the difference between the synchronous speed, n_s and the rotor speed n_r in per unit of the synchronous speed as follows [62]

$$s = \frac{n_s - n_r}{n_s} \tag{5.8}$$

The squirrel cage (SCIG) and doubly-fed induction generators (DFIG) are the two induction machine concepts that have been used in this study. Their models shall be described in the following sections.

5.6.2 Modeling of an induction machine (SCIG)

The operational concept of the SCIG has been discussed in chapter 3. In most system's studies modeling, the Squirrel Cage Induction Generator (SCIG) is normally modeled as a conventional PQ bus, where the real power generated and reactive power demanded are specified [63]. It is however possible to express the reactive power required by the SCIG as a function of its bus voltage according to the following expression [63]:

$$Q \approx U^2 \frac{X_C - X_M}{X_C X_M} + \frac{X}{U^2} P^2 \tag{5.9}$$

Where:

- Q is the reactive power consumed by the generator
- X_c is the capacitive reactance
- X_m is the magnetizing reactance
- X is the sum of the stator and rotor reactance
- *U is the terminal voltage*
- P is the real power of the generator

Figure 5.6 shows the *dq* representation of the commonly used induction generator model. Subscripts *d* and *q* represent the direct and quadrant components respectively [64]

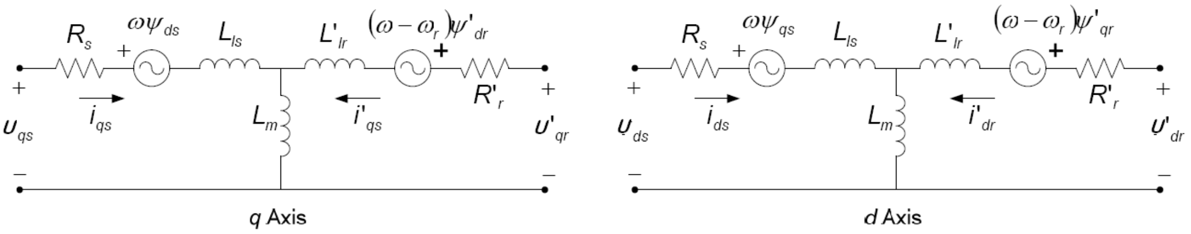


Figure 5.6 A *dq* frame representation of an induction generator model [65]

The dynamic model of a SCIG in the stationary dq0 reference frame is described by the following equations [63]:

Flux linkages per second with saturation effect [64]:

$$\psi_{qs} = \omega_b \int\left(u_{qs} + \frac{r_s}{x_{ls}} \left(\psi_{mq}^{sat} - \psi_{qs} \right) \right) dt \tag{5.10}$$

$$\psi_{ds} = \omega_b \int\left(u_{ds} + \frac{r_s}{x_{ls}} \left(\psi_{md}^{sat} - \psi_{ds} \right) \right) dt \tag{5.11}$$

$$\psi'_{qr} = \omega_b \int\left(\frac{\omega_r}{\omega_b}\psi'_{dr} + \frac{r'_r}{x'_{lr}} \left(\psi_{mq}^{sat} - \psi'_{qr} \right) \right) dt \tag{5.12}$$

$$\psi'_{dr} = \omega_b \int\left(\frac{\omega_r}{\omega_b}\psi'_{qr} + \frac{r'_r}{x'_{lr}} \left(\psi_{md}^{sat} - \psi'_{dr} \right) \right) dt \tag{5.13}$$

The stator dq0 currents are expressed as follows [64]:

$$i_{qs} = \frac{\psi_{qs} - \psi_{mq}^{sat}}{x_{ls}} \tag{5.14}$$

$$i_{ds} = \frac{\psi_{ds} - \psi_{md}^{sat}}{x_{ls}} \tag{5.15}$$

$$i_{0s} = \frac{\psi_{0s}}{x_{ls}} = \frac{\omega_b}{x_{ls}} \int \left(u_{0s} - r_s i_{0s} \right) dt \tag{5.16}$$

The electromagnetic torque and rotor motion characteristics are modeled by the following equations [63]:

$$T_{em} = \frac{3}{2}\frac{P}{2\omega_b} \left(\psi_{ds} i_{qs} - \psi_{qs} i_{ds} \right). \tag{5.17}$$

The equation of motion of the generator is described as follows [63]:

$$\frac{d\omega_m}{dt} = \frac{1}{2H} \left(T_e - F\omega_m - T_m \right) \tag{5.19}$$

$$\frac{d\theta_m}{dt} = \omega_m \tag{5.20}$$

Since it is assumed that the SCIG is an induction generator with zero rotor voltage as a result of short circuiting its rotor, the voltage equations used in DigSilent to model it can be described as follows in d and q components [65]:

$$u_{ds} = -R_s i_{ds} + \omega_s \left[(L_{s\sigma} + L_m) i_{qs} + L_m i_{qr} \right] \tag{5.21}$$

$$u_{qs} = -R_s i_{qs} - \omega_s \left[(L_{s\sigma} + L_m) i_{ds} + L_m i_{dr} \right] \tag{5.22}$$

$$0 = -R_r i_{dr} + s\omega_s \left[(L_{s\sigma} + L_m) i_{qr} + L_m i_{qs} \right] \tag{5.23}$$

$$0 = -R_r i_{qr} - s\omega_s \left[(L_{r\sigma} + L_m) i_{dr} + L_m i_{ds} \right] \tag{5.24}$$

Where:

- u is the voltage
- i is the current
- R is the resistance
- L is the inductance
- ω is the frequency
- s is the slip
- subscript *m*, *s*, *r* is the mutual, stator and rotor
- σ is the leakage
- T_{em} is the electromagnetic torque

The real power, *P*, and reactive power, *Q* equations are given as follows [66]:

$$P = u_{ds} i_{ds} + u_{qs} i_{qs} \tag{5.25}$$

$$Q = u_{qs} i_{ds} - u_{ds} i_{qs} \tag{5.26}$$

When modeling induction generators for stability or power quality analysis, RMS simulations are normally performed and we assume that a third order generator model is used, thereby neglecting the stator transients [57].
The behaviour of wind turbines under grid faults has also been examined to a lesser extent and thus it is recommended that electromagnetic transient simulations be performed in DigSilent [26]. These types of simulations require instantaneous values and for this purpose, some fifth order generator models can be used [57].

The inertia of the induction generator is a built-in component in the models found in DigSilent and is specified in the form of an acceleration time constant in the induction generator type [57].

The mechanical model equations of an induction generator can be given as follows [57]:

$$J\dot{\omega}_r = T_e - T_m \tag{5.25}$$

$$T_n = \frac{P_n}{\omega_n (1 - s_n)} \tag{5.26}$$

$$T_{ag} = \frac{J(1 - s_n)\omega_n^2}{P_n} \tag{5.27}$$

Where:

- J represents the generator inertia
- T_e represents the electrical torque
- T_m represents mechanical torque
- T_{ag} represents the acceleration time constant
- ω_n represents the nominal electrical frequency of the network
- s_n represents the nominal slip
- P_n represents the nominal power of the generator
- T_n represents the nominal torque

5.6.3 Modeling of a Doubly-fed Induction Generator (DFIG)

As mentioned earlier, a DFIG is basically a wound rotor induction machine which has its stator windings directly connected to the grid and its rotor windings connected to the grid through a converter [66]. The composition of the converter, made up of the rotor-side and grid-side components is illustrated in figure 5.7.

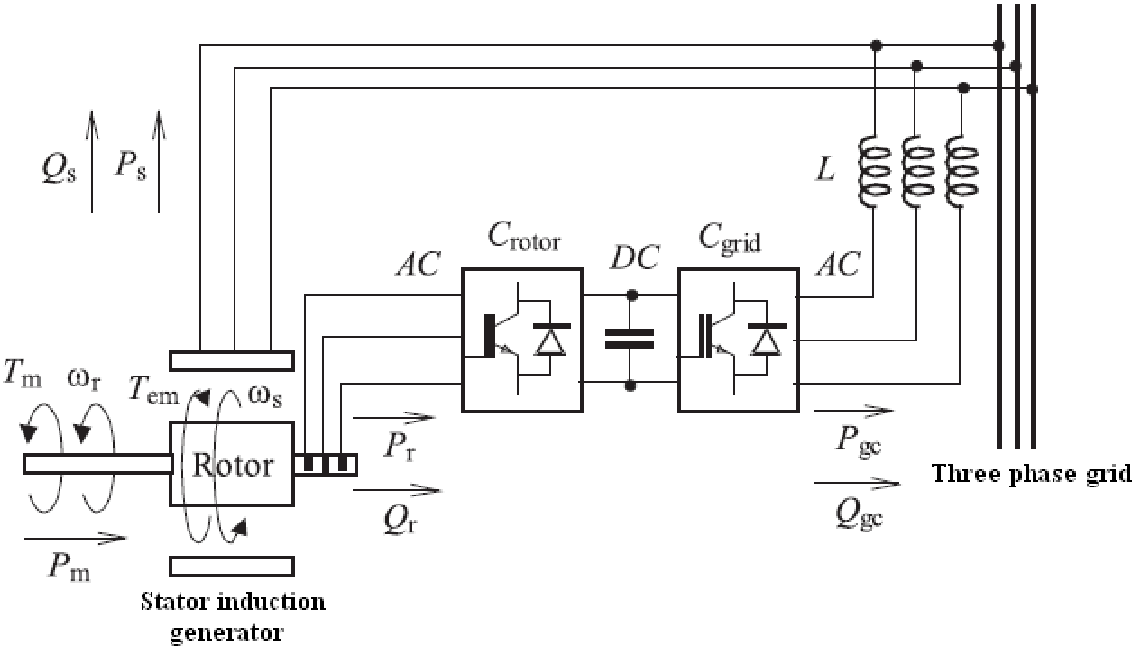


Figure 5.7 Illustration of the power flow through the DFIG and its converter components [66]

Where P_s and Q_s represent the stator real and reactive power respectively, P_{gc} and Q_{gc} represent the real and reactive grid-electrical power respectively, P_m and P_r represent the mechanical and rotor electrical power respectively and T_m is the electro-mechanical torque of the machine.

Since the speed control of a DFIG implies rotor frequency control and control of the active power generated or consumed by the rotor windings, the relationship between the speed and frequency of the stator, f_{stator} and rotor, f_{rotor} of an induction machine is given by [68]

$$s = \frac{f_{stator} - \frac{n.p}{60}}{f_{stator}} \tag{5.28}$$

$$f_{rotor} = s.f_{stator} \tag{5.29}$$

where n is the mechanical speed in rpm , p is the pole pair number and s is the slip[67].

The rotor active power P_{rot} and mechanical power, P_{mech} of a turbine are given by the following equations and this forms the basis of most generator equations [68]:

$$P_{rot} = s.P_{stat} \tag{5.30 a}$$

$$P_{mech} = (1-s).P_{stat} \tag{5.30 b}$$

A DFIG can be modeled with either its static characteristics or its dynamic characteristics [68]. The dynamic modeling characteristics allow for the assessment of the DFIG behaviour during grid disturbances.

5.6.3.1 Steady state simulations model of a DFIG

During steady state modeling, the equivalent model of a DFIG machine can be modeled as shown in Figure 5.8 [66]:

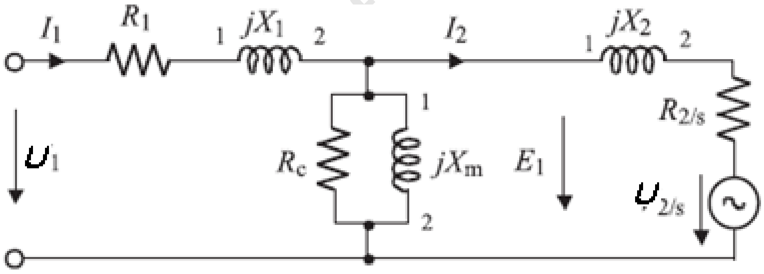


Figure 5.8 Equivalent circuit model of a DFIG [66]

As opposed to the SCIG, the DFIG has voltage injected into its rotor windings through a converter and this helps in controlling the power flows between the machine and the grid [66]. The flow of real and reactive power of the stator, P_{s^w} , Q_s and that on the rotor side P_{r^w} , Q_r together with the resultant torque, T_m that is created can be illustrated in the following equations [66]:

$$P_{s^w} = 3U_1 I_1 \cos(\phi_{V_1} - \phi_{I_1}) \tag{5.31}$$

$$Q_s = 3U_1 I_1 \sin(\phi_{V_1} - \phi_{I_1}) \tag{5.32}$$

$$P_{rw} = 3U_2 I_2 \cos(\phi_{V_2} - \phi_{I_2}) \tag{5.33}$$

$$Q_r = 3U_2 I_2 \sin(\phi_{V_2} - \phi_{I_2}) \tag{5.34}$$

where:

- U_1 and I_1 represents the effective (RMS) value for stator voltage and current
- U_2 and I_2 represents the effective (RMS) value for rotor voltage and current

The rated current of the IGBT frequency converter of most DFIG is used as a cost determining factor and we can conclude that the rated rotor current determines the active and reactive power of the stator but will not impact the speed range of the machine [64].

5.6.3.2 Dynamic simulation model of a DFIG

The following equations are used to model general models of a wound rotor induction machine [64]:

- Stator voltage equations

$$U_{qs} = p\lambda_{qs} + \omega\lambda_{ds} + r_s i_{qs} \tag{5.35}$$

$$U_{ds} = p\lambda_{ds} - \omega\lambda_{qs} + r_s i_{ds} \tag{5.36}$$

- Rotor voltage equations

$$U_{qr} = p\lambda_{qr} + (\omega - \omega_r)\lambda_{dr} + r_r i_{qr} \tag{5.37}$$

$$U_{dr} = p\lambda_{dr} + (\omega - \omega_r)\lambda_{qr} + r_r i_{dr} \tag{5.38}$$

- Power equations

$$P_s = \frac{3}{2}(U_{ds} i_{ds} + U_{qs} i_{qs}) \tag{5.39}$$

$$Q_s = \frac{3}{2}\left(U_{qs} i_{ds} - U_{ds} i_{qs}\right) \tag{5.40}$$

- Torque equations

$$T_e = -\frac{3}{2}\frac{P}{2}\left(\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds}\right) \tag{5.41}$$

- Stator Flux linkage equations

$$\lambda_{qs} = \left(L_{ls} + L_m\right) i_{qs} + L_m i_{qr} \tag{5.42}$$

$$\lambda_{ds} = \left(L_{ls} + L_m\right) i_{ds} + L_m i_{dr} \tag{5.43}$$

- Rotor flux linkage equations

$$\lambda_{qr} = \left(L_{ls} + L_m\right) i_{qr} + L_m i_{qs} \tag{5.44}$$

$$\lambda_{dr} = \left(L_{ls} + L_m\right) i_{dr} + L_m i_{ds} \tag{5.45}$$

Basically, what differs between the DFIG and the general induction generator is the PWM converter connected on the rotor side as shown in figure 5.9.

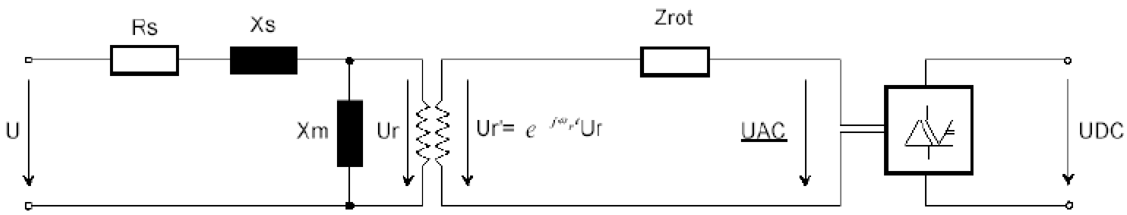


Figure 5.9 DFIG model with a rotor side converter [62]

The PWM converter facilitates the smooth operational control of the generator by modifying the magnitude and phase of the generator's AC voltage on the rotor side. This is done through an AC-DC conversion relationship expressed in the following equations [62]:

$$U_{ACr} = \frac{\sqrt{3}}{2\sqrt{2}}.PWM_r.U_{DC} \tag{5.46}$$

$$U_{ACi} = \frac{\sqrt{3}}{2\sqrt{2}}.PWM_i.U_{DC} \tag{5.47}$$

Where:

- PWM_i and PWM_r are the real and imaginary components of the modulation factor respectively,
- U_{ACr} and U_{ACi} are the real and imaginary components of the AC voltage [57].

The resulting AC and DC currents that pass through the PWM converter are correlated using the following equation [57]:

$$P_{AC} = \mathrm{Re}\left(U_{AC} I_{AC}^{*}\right) = U_{DC} I_{DC} = P_{DC} \tag{5.48}$$

The equation has been derived assuming that the PWM converter will not incur any losses across it [57].

The DigSilent model of the DFIG used in these studies is presented in a single line diagram in figure 5.10.

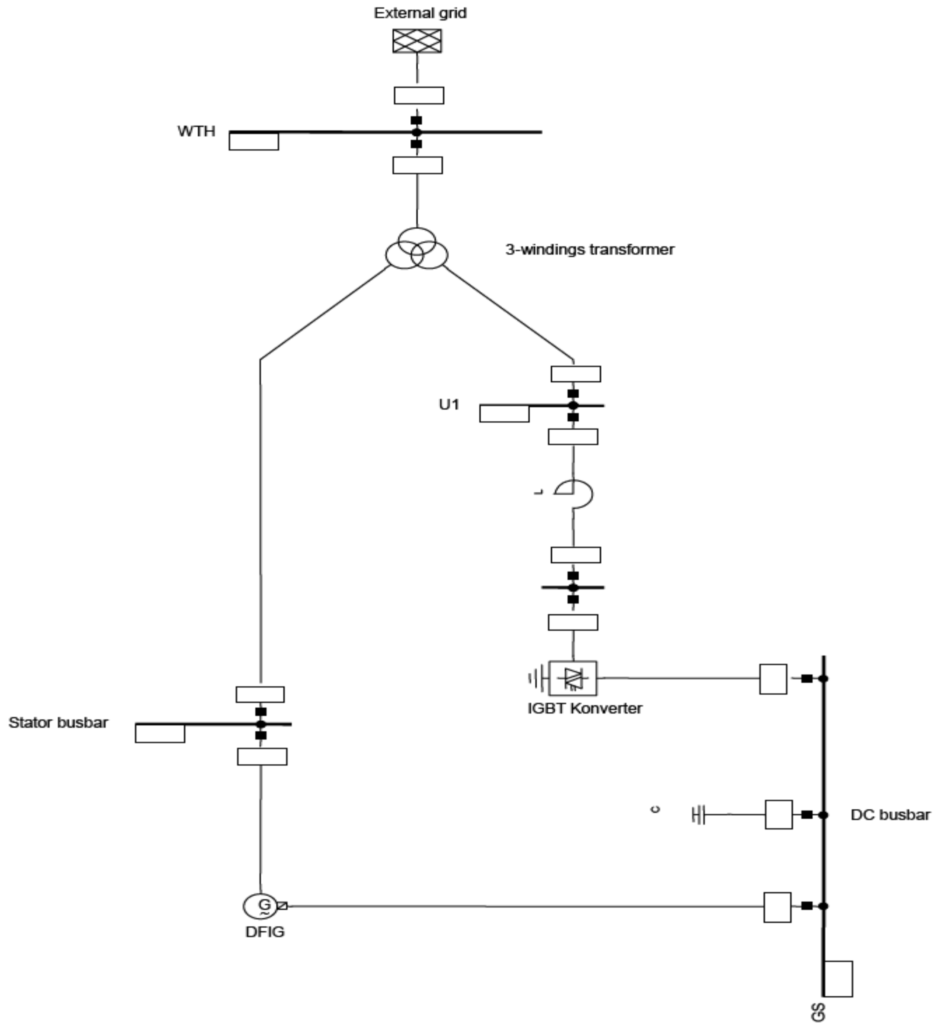


Figure 5.10 Single line diagram of DFIG in DigSilent [63]

This DFIG built-in model consists of the following components [62]:

- The usual induction machine model
- PWM rotor side converter
- DC bus
- IGBT grid-side converter
- Inductor (in series with the grid converter so as to smooth the converter currents)

As previously mentioned, since the PWM controller required an external DSL programming language to model it, only the standard models found in the DigSilent library have been used in this thesis. The parameters of the DFIG used in this study are given in Appendix A2.

5.5.1 The Transformer Model

The model of the transformer depicted in Figure 5.11 has been used for all the two-winding transformers used in this thesis.

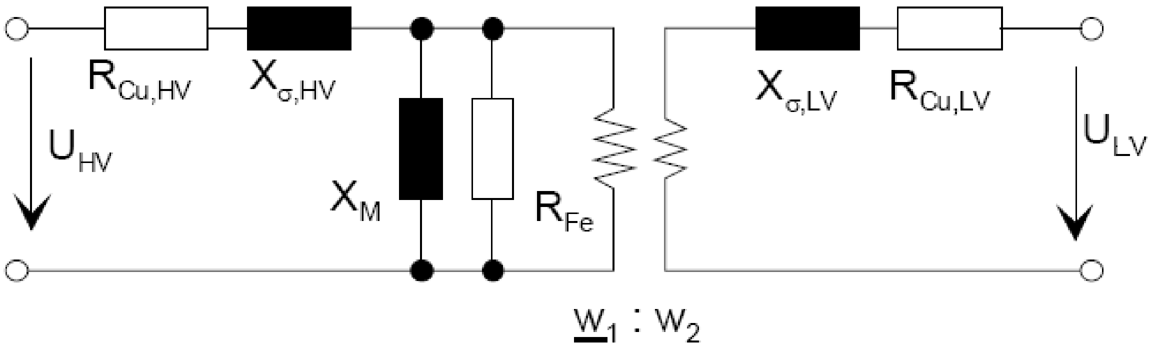


Figure 5.11 Two-Winding transformer Model [68]

Where:

- $R_{Cu,HV}$ and $X_{\sigma,HV}$ represent the winding resistance and leakage reactance respectively of the high voltage
- U_{HV} and U_{LV} represent the nominal voltage of the low voltage and high voltage side respectively
- X_M and R_{Fe} represent the magnetizing reactance and iron loss admittance respectively
- $X_{\sigma,LV}$ and $R_{Cu,LV}$ represent the low voltage leakage reactance and winding resistance respectively [68]
- w_1:w_2 represents ratio of the primary to secondary windings of the transformer

To simplify matters in this thesis, ideal characteristics of the transformer have been assumed in the modeling design and these include losses in the winding and in the core as well as zero leakage flux [69]. However, some specific transformer data was made available by Eskom and this is shown in Appendix A2**.**

5.6.4 Transmission line model

The DigSilent model of the transmission line used in this thesis is taken from the PowerFactory library and has the characteristics shown in figure 5.12.

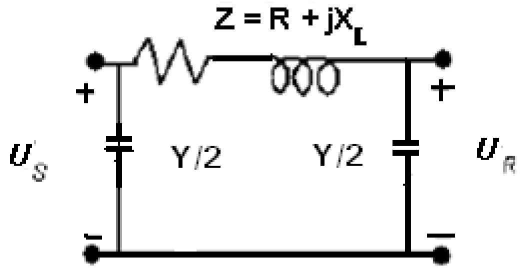


Figure 5.12 The Π circuit model of a transmission line [26]

According to close sources, Eskom has the option of either connecting a single line or double-circuit line running from the wind farm to the point of common connection. However, depending on the power transfer capabilities of these lines, the influence of each option will need to be investigated in this thesis in order to recommend a suitable line configuration.

The characteristics of the model given in PowerFactory were modified to suit the grid parameters and are given in Appendix A3.

6 WIND INTEGRATION POTENTIALS IN SOUTH AFRICA

With the increasing demand for power in South Africa due mainly to economic growth, renewable energy generation has been targeted to alleviate the country's power demand shortfalls. A 4% target for renewable energy generation has been set by the government for 2013 [2]. There is also an increased global demand for environmentally friendly power which leads to the focus on renewable energy.

Grid connection of wind energy will allow owners of private or commercial wind energy systems (independent power producers, IPPs) to deliver excess energy into the grid when they are in surplus or to trade in when there is a shortfall. Standard connection requirements will help simplify the grid-connection process of wind power in South Africa.

According to resource assessment studies that have been performed by Eskom [1], South Africa's wind energy development interests seem to have increased lately owing to the government's drive to meet the renewable energy target. The potential ideas provided by wind energy development projects nationally, stand at about 13 800MW [1]. However, in as much as the actual potential figures may not be precisely known or official at present, any figure in that range (i.e. 10 000 MW) is a fairly considerable amount if you compare it to the current wind energy situation (less than 10MW) in the country.

The above mentioned figures further reinforce the idea that the abundance of the wind as a resource in the country thus indicates a potential high increase in wind penetration levels to follow. With an increasing penetration of wind energy connected to the grid, more interconnection issues are likely to emerge. Therefore there is a need to develop conditions for grid connection suitable for the existing and fast developing wind technologies.

Wind power is most likely to be connected on the distribution parts of the network and there is therefore a need to distinguish between the different types of distribution networks so that we can assess their response to different wind integration scenarios.

6.1 Distribution Network in South Africa

There are typically two main types of distribution networks in South Africa, radial and meshed networks. Radial networks are typically found in most rural and remote places and are characterized by a network leaving the station and passing through the network area with no normal connection to any other supply [70].

Urban areas are often connected through a meshed network system with multiple connections to other points of supply [70]. However, studies carried out in this thesis, focus mainly on radial networks which are closer to the proximity of the wind resources.

As mentioned earlier, wind turbines are also a form of distributed generation connected to the distribution parts of the network. There are a number of definitions in literature that have been used to describe distributed generation [70]. In simpler terms, distributed generation can be used to refer to small scale electricity generation, whereas in other regions with extensive and complex electricity systems, large scale electricity generation can still be considered as distributed generation. Thus there is no exact account to describe distributed generation.

The definition of distributed generation in the Southern African context is give as follows [52] "*Distributed generation is any source of electric power that is interconnected with an electricity supply network at a system voltage level not exceeding 132kV. The generator is not centrally dispatched. It is not a trading participant in a power pool but usually responds to a tariff signal*".

This definition has been derived from characteristics such as the capacity of power delivered, as well as well as voltage levels at the interconnection level [52].

High voltage systems (above 275kV) are usually associated with high fault levels, meaning that they represent the stronger section of the grid, whereas the lower the voltage, the weaker the system. Looking at the South African scenario, mostly in the remote parts of the country, the distribution voltages are 66kV or 11kV. The kV system is the most extensive but, in the remote areas, with a sparse distribution system, it is unlikely to support more than

5 MW of generation [52]. However, according to the definition given in [52], 132kV is still considered to be distribution network voltage.

Since these distribution networks were initially designed to allow the flow of power from transmission to the customer side of the network, connecting distributed wind power on the distribution side may result in the reversal of power flow [35] which may have a significant impact on the power quality of the distribution networks.

The local distribution networks are distinguished by a weak distribution system whose characteristics include a low X/R ratio or short circuit power ratios such that changes in the flow of active and reactive power may affect the steady state voltage levels at the point of common connection leading to voltage level disparities when wind turbines are connected. These characteristics form the basis of our investigations of the power quality issues in this thesis and have been explained in more detail in Chapter 3.

6.2 Wind Situation in South Africa

At the moment, South Africa seems to have reached the end of its surplus generation capacity. The demand seems to be exceeding the capacity (about 40GW) and thus there is an urgent need for other generation options. Currently, Eskom has a total installed capacity of about 42,000MW (net 36,200MW, peak 34, 200MW) mainly from coal based plants (93%), 5% nuclear and the rest from hydroelectric and gas turbines [71]. Eskom has made it public that by 2025, they seek to double the generation capacity to about 80 000MW [7]. Of this capacity, it is expected that about 15% would be contributed from renewable energy [7]. In order to successfully achieve this, other alternative energy sources need to be investigated and used to aid in addressing the capacity bottleneck as a result of increasing load demand.

Wind energy is one such alternative source of generation. Currently, the number of wind energy sources connected to the grid is minimal (less than 10 MW) yet a sustainable increase is anticipated to meet the government target discussed earlier.

With the abundance of the wind resource in the coastal areas, we could except to have quite a significant contribution to this target. Looking at Figure 6.1, it can be seen that the cape coast seems to have a higher concentration of the wind resource.

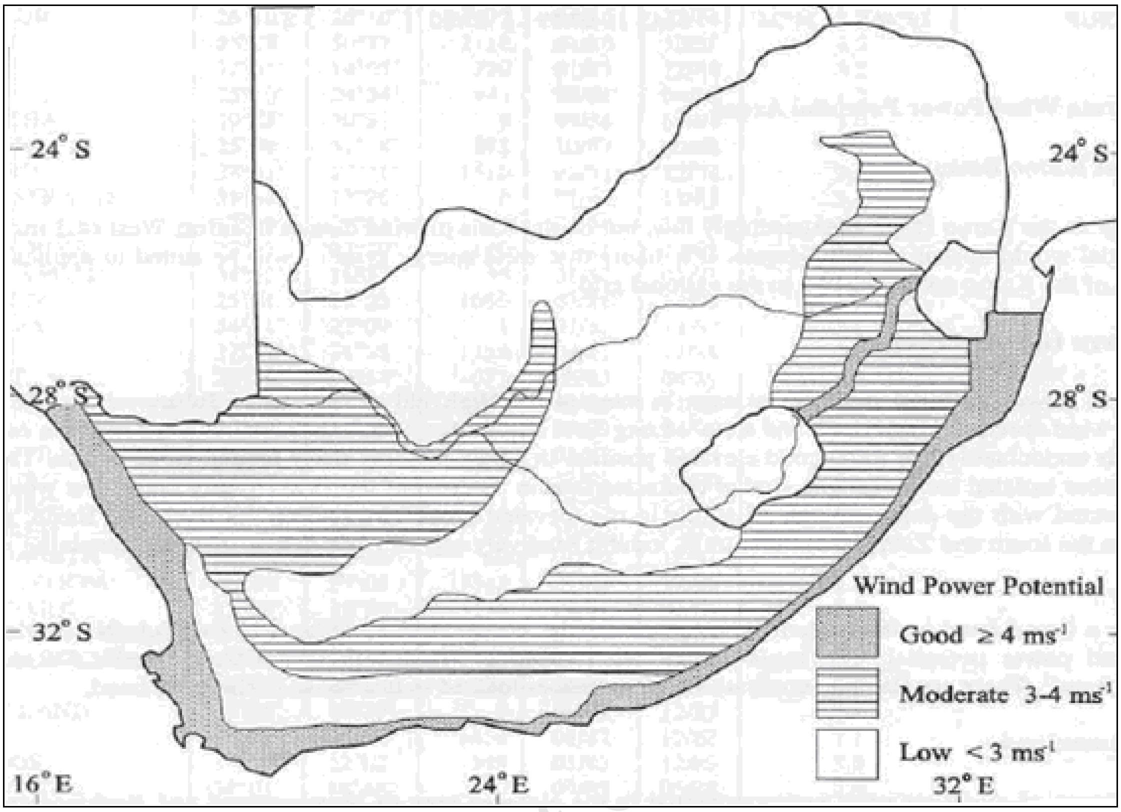


Figure 6.1 Wind Map of South Africa [71]

As seem in Figure 6.1, the local wind prospects seem to be best along the southern and western coastal regions, with estimated average annual wind speeds above 6m/s and 200W/m^2 [71]. According to Eskom's recent figures presented at the Eskom's Grid Results Study Workshop in May 2009, the maximum potential ideas for wind development in the Western Cape are estimated to be about 7 155 MW [1]. Out of this, the wind applications that have already been received from the IPPs requesting to connect to the grid, stand at about 3 692 MW, which is a fairly considerable figure if you consider that the region has a total capacity of approximately 4 000MW [1]. Once again, not all these application would be successful, but these figures show the growing interest in wind energy development and thus calls for a more systematic and pragmatic approach towards the integration of wind power into the grid.

South Africa being a developing country in terms of its economy and resources, has unique characteristics that cause it to have a different power system grid as compared to other developed or first world countries in Europe and America. These different characteristics such as network infrastructure and technology will influence the integration of wind power. Moreover, the difference in climatic conditions may also contribute to differences in technology. The Western Cape, for instance, has an abundance of wind due to the coastal climatic imbalances that are introduced by the relative to land. For example, in areas with relatively high and constant wind speeds, the use of fixed speed wind turbines may be economically feasible as compared to low or variable wind speed areas which may require the use of variable wind speed technologies.

Eskom has carried out a number of feasibility studies of wind energy in South Africa and the first place to be identified was the Klipheuwel wind demonstration facility that was established in 2002 [35]. Following the review of that pilot project, other wind farm developers elsewhere in the region have put forth their proposals to connect to the Eskom network.

Some of the planned wind energy projects in the country have been discussed briefly in the following sections.

6.2.1 Klipheuwel Wind Farm

The Kliphuewel Wind Farm in the Western Cape was the first wind farm that was connected into the grid (at the 11kV Point of Common Coupling (PCC)) in South Africa. This wind farm consists of three wind turbines (a Vestas V66, with 1.75 MW output, a Vestas V47 with 660 kW output and a Jeumont J48 with 750 kW output)) which produce a total output power of about 3.16 MW [72]. The technical information of the three wind turbines installed is given on a data sheet in Appendix A1.

It has been used as a pilot project and demonstration facility to assess the impacts and feasibility of wind energy sources on the South African grid. According to [35], this site was chosen after an environmental impact assessment that was carried out in ten different places. This facility is connected to the grid but no formal or specific guidelines were used during the connection process.

Preliminary assessments carried out at the demonstration facility have shown it to operate at 90% availability and at an average energy utilization factor of about 16% Since its inception, it has generated more than 12GWh of electricity (equivalent to an avoidance of 14 000 t of carbon dioxide emissions) [7]. With regards to technical implications, the impact of the wind farm on the grid or vice versa has been found to be minimal. This is because the wind power penetration is small and connected to a relatively stronger part of the network (11 kV) [72]. Additionally, these preliminary assessments have also shown that wind turbines designed for lower wind speeds are more appropriate for the South African wind conditions [72]. This was established when the V47 (with a DFIG operational mechanism) was found to operate at almost maximum production during relatively low wind speeds [72]. However, the monitoring of the quality of the supply to the grid is still under investigation and needs greater detailed analysis [72].

6.2.2 Darling Wind Farm

The Darling wind farm is the biggest commercial wind project in South Africa which seeks to provide a power capacity of about 13.2MW from seven wind turbines. The overall project was meant to consist of two phases [73]:

- The first phase of the installation capacity was commissioned sometime in May/June 2008, with the first phase of 5.2 MW installations connected to the national grid at 66kV.
- The second phase has not yet been completed but it will consist of 6 x 1.3 MW wind turbines and is expected to be commissioned by 2013.

With regards to preliminary environmental reviews performed, it is estimated that during the project's 20 year cycle, the estimated reduction of pollutants includes about 298 125 tonnes of carbon dioxide as well as a considerable reduction in sulphur dioxide and nitric oxide (over 3 000 tonnes) [7]. South Africa is amongst the top ten countries in the world that emit the most greenhouse gases per capita, owing to its over major reliance of electricity generation from coal (over 90%) [7]. Some of modeling done on climate change has shown that the region is in danger of severe droughts due to excessive carbon dioxide emissions, so this minimizing of green-house gas emissions will go a long way to alleviate the situation South Africa is currently in.

According to a close source, the turbines at the Darling wind farm have been operational since their commissioning last year but stopped running in February this 2009. This was due to some policy issues that needed to be negotiated further but this thesis will not look further into that. Concerning the technical aspects of the project, the monitoring and evaluation is on-going and the progress of the wind turbine functionality has also not yet been included in this thesis as the information has not been made public yet.

6.2.3 Juno Wind Farm (planned 100 MW Cape West Coast Wind Farm)

Eskom has identified an area on the Cape West coast, around Koekenaap (about 350 km away from Cape Town) to install an initial 100MW wind farm which will possibly be increased to about 200MW [74]. Figure 6.2 illustrates the proposed location of the planned wind farm on the Cape West coast, which shall be situated near Vredendaal. The plan is to install 100 wind turbines over an area of about 25km^2 (each wind turbine would have a power rating of between 1.5MW and 2.5MW) [74]. The area meshed shows the area being considered for site location

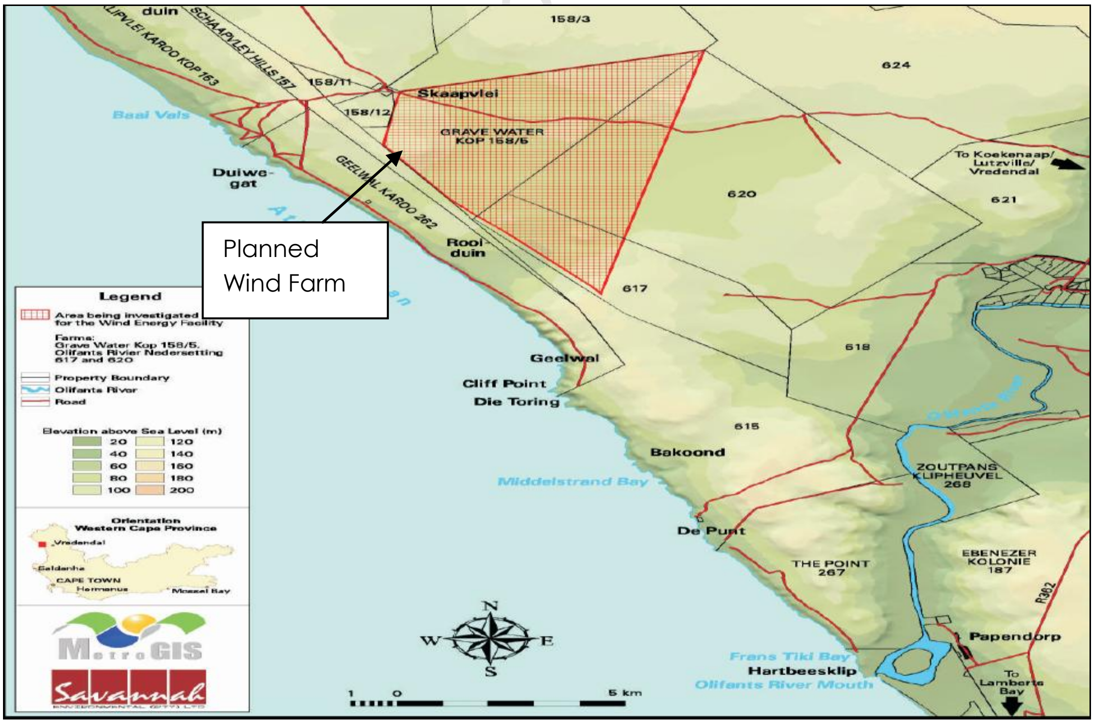


Figure 6.2 Map of the Cape West coast where the wind farm is planned [75]

According to the monitoring and measurements conducted at the site over a prolonged period of three years, it was established that the site was suitable, with a capacity factor of 26 %, much higher than that at Klipheuwel wind farm and also closer to other international capacity figures [75].

Since details of the type of wind turbines to be used at the proposed west coast wind farm project have not been made official, there is no technical data available for use in this study. Some assumptions have therefore been made based on the unofficial information put out by Eskom with regards to the most likely wind turbine technology to be used. These assumptions are based on the success of the performance of the DFIG turbine at the Klipheuwel demonstration facility, coupled with the global trend of wind turbines that are currently being recommended or are in use [3]. However, a number of power system simulation studies shall be conducted in this thesis to validate this assumption.

The proposed 100MW West coast Wind Farm has been used as a basis for this thesis.

7 ANALYSIS OF THE IMPACTS OF WIND TURBINES ON THE NETWORK DURING NORMAL OPERATION

The purpose of this chapter is to analyse the steady state behaviour of the grid connected wind turbines and their influence on the network to which they are connected. The steady state load flow studies are performed so as to analyse the following characteristics on the network:

- Steady state voltage levels
- Line capacity (line loading)
- Short circuit levels
- Impact of grid strength
- Impact of conductor type
- Harmonics

This chapter presents studies on the investigation of the steady state voltage level issues that could possibly occur at the point of common connection. In as much as these issues could be common to any other electric power sources, this investigation will be carried out for a particular case study of the Juno Wind Farm in order to address the voltage level effects of the wind farm on the nominal voltage of the grid.

The simulations performed in this chapter are aimed at investigating the following characteristics:

- Impact of wind turbine-type on the voltage level at the point of common connection
- Impact of the grid strength on the voltage levels at the point of common connection
- Impact of increasing penetration levels on the voltage levels at the point of common connection
- Impact of the turbine choice on reactive power control (reactive power compensation)
- Power fluctuations due to varying wind speeds

The most notable simulation studies were done in order to illustrate the impact of changes in power produced by wind turbines (assumed to be as a result of wind speed changes) on the voltage levels at the point of connection of the wind farm to the grid. At this point of connection, some customers are also linked and they may also feel the voltage level effects resulting from the A wind turbines. Both the DFIG and SCIG were used in this study, with DigSilent PowerFactory software tool being used to carry out simulations. As previously mentioned, due to the limited capability of the available software, dynamic studies, voltage variations at the PCC where not dealt with in detail. However, since voltage variations are a result of the flow of the varying power generated by the wind farm into the grid, a number of assumptions were made in the modeling of the network in order to address this phenomenon. These will be discussed in the following sections.

7.1 Description of the Network Model Investigated

The full layout of the Cape West Coast network was not available for use in this thesis as it was considered confidential by the Eskom authorities. Therefore, using the information supplied by Eskom (see Appendix A2), a simplified network model of the Juno Wind Farm has been depicted in figure 7.1.

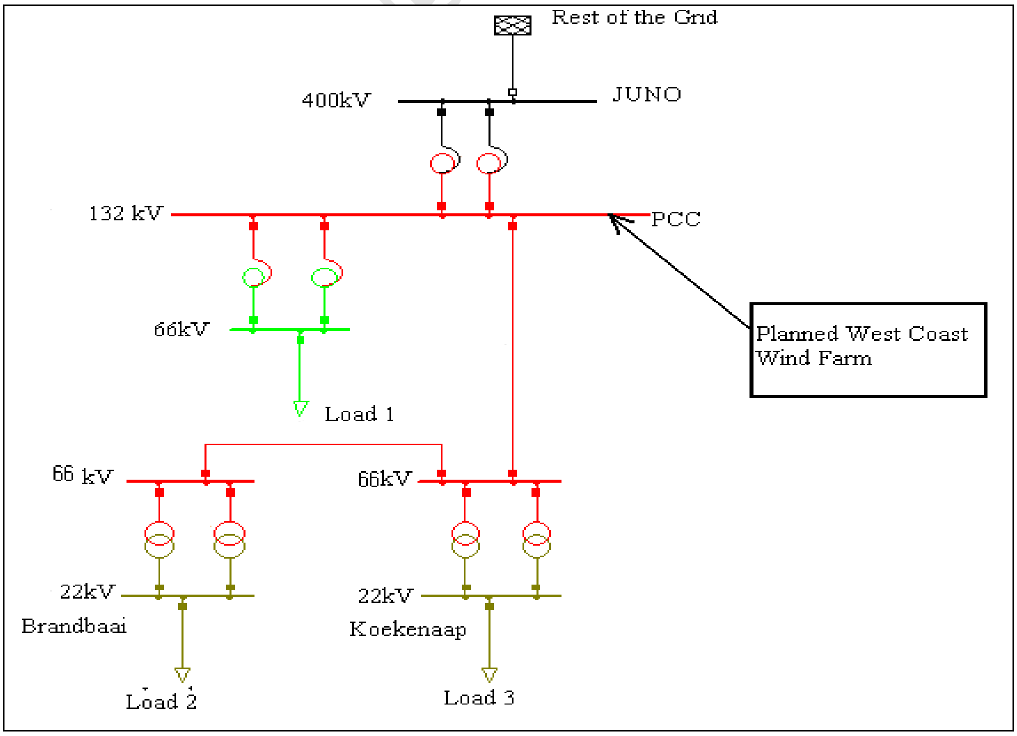


Figure 7.1 Schematic drawing of the Cape West Coast Wind Farm HV Network

In coming up with the power network shown in figure 7.1, some of the following assumptions where made:

- The external grid was assumed to represent the rest of the Eskom grid to which the 400kV network of Juno is connected
- The 132kV busbar was the proposed point of connection of the wind farm
- The loads were modeled as constant loads
- The fault levels used were from past surveys carried out by Eskom (early 2000's)
- Only the most relevant network sections were considered for this study

The point of common connection (PCC) as indicated in figure 7.1 shows the proposed point where the wind farm would be connected to the network, i.e. at the 132 kV busbar. The DFIG and SCIG wind turbines were used in this voltage analysis study. Their models have been described in Appendix A2. Each single wind turbine was assumed to have a rating of 2MVA and an operating power factor of 0.8, which is common amongst the globally used wind turbines of that rating. To model the overall wind farm, it was assumed that all the wind turbines in the park were similar and hence contributes the same amount of power into the grid. Therefore, using the function in DigSilent which allows wind turbines to be aggregated in a parallel arrangement, the various wind farm aggregation scenarios and options were investigated.

For most of the simulations performed in this section, the following network shown in figure 7.2 is a more detailed single line diagram of figure 7.1 as it shows the proposed connection options of the Juno wind farm.

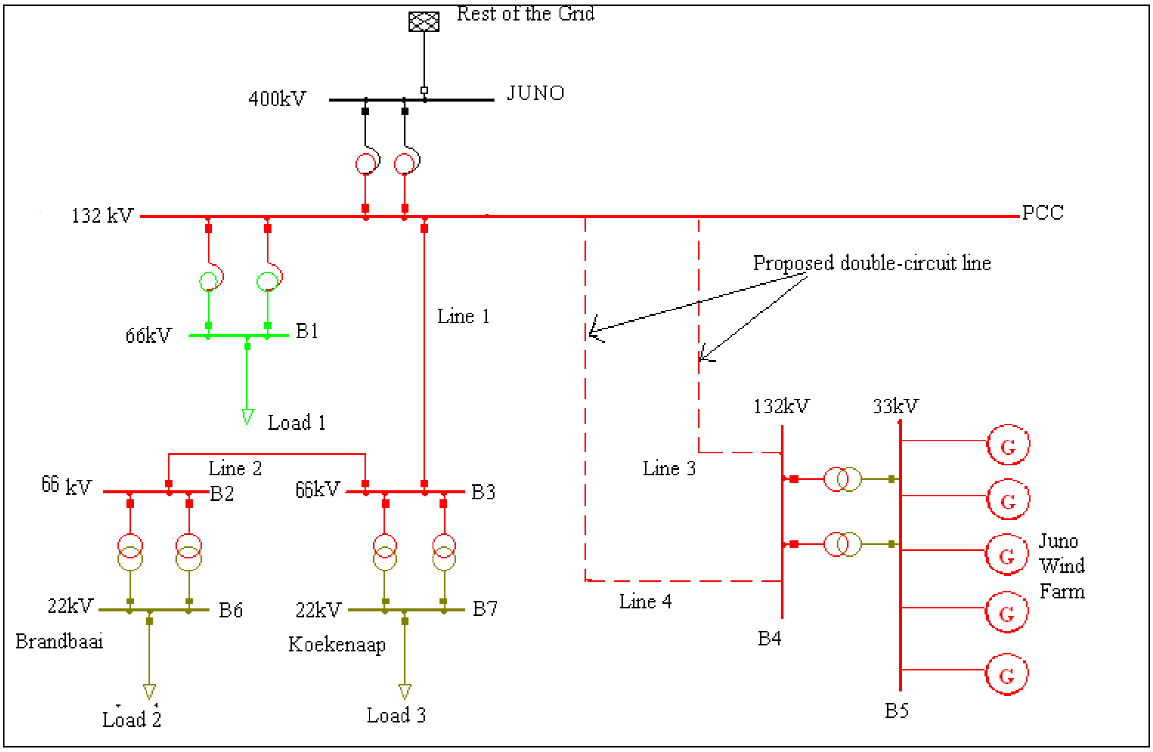


Figure 7.2 A more detailed single line diagram of the proposed connection options for Juno Wind Farm

As can be seen in Figure 7.2, the external grid (or infinite bus) connected to the 400kV busbar acts as the rest of the Eskom grid. The 400kV bus is stepped down to 132kV by 2x80MVA autotransformers. The total load in the area is about 60MVA which is made up of constantly varying loads with a power factor lagging between 0.87-0.94. This comprises the mine load (about 30MVA) and the community loads (also about 30MVA) plus smaller secondary loads. All the loads are lumped together and modelled as a single 60MW with a power factor of between 0.87-0.94. This is the recorded power factor variation range of that area.

The proposed wind farm should be connected at the 33kv/132kV substation, which joins the grid via a double line circuit of 40km and 132kV rating. The five generators connected on the bottom left side of figure 6.2 are an illustration representing how the Juno wind farm is connected to the grid. (Note: the representation does not necessarily mean that only five wind turbines are connected to the grid). Eskom proposed to connect 50 by 2MW wind turbines onto the grid. However, this value may be more or less than the proposed figure, so different penetration levels have been considered in order to come up with the optimum penetration level that will not compromise power quality and the operation of the grid.

In order to assess the impact on the grid-integration of the proposed Juno Wind Farm, a number of scenarios were considered during this investigation and these include:

- Pre-connection conditions (before the proposed wind farm was connected)
- Post connection conditions (DFIG and SCIG connected)

7.2 Analysis of the Existing Network (No Wind Farm Connected)

The pre-connection investigations were carried out in order to assess the existing operation of the modelled grid. These will assist in quantifying the changes that could result from the wind farm being connected to the grid. As discussed earlier, figure 7.1 shows a simple grid model of the Juno area network before the proposed wind farm was connected. Network data obtained from Eskom was used during the modeling of the network (see Appendix A2). A number of assumptions where also taken into account and these were presented in the earlier sections. After performing a normal load flow analysis, various results were yielded and tabulated in Table 7.1 to 7.4.

The normal load-flow simulations were performed in order to analyse the pre-connection active and reactive power exchanges across the network.

Table 7.1 The load flows on the network

	P(MW)	**Q(Mvar)**
Grid	57.09	26.78
Load 1	26.75	10.57
Load 2	21.64	9.86
Load 3	7.92	2.88

From Table 7.1, it can be seen that the infinite bus is assumed to be the primary supplier of the various loads on the network. Using the laws of energy conservation, we would expect all the power supplied by the infinite bus to be delivered to the load, but due to losses across the transformers and lines during the transmission of power, there are bound to obtain discrepancies. These losses are briefly discussed in section 6.2.1.3. The overall load is approximately ±60MVA as mentioned earlier.

The steady-state voltage levels at the busbars on the network were simulated and presented in Table 7.2. These results were simulated under no-wind-farm conditions so as to get a rough estimate of the current voltage levels existing on the network.

Table 7.2 The voltage levels at the busbars

Busbar	**V (kV)**	**V (p.u.)**
Juno 400 kV	400 kV	1.00
PCC	129.64	0.98
B1	64.55	0.98
B2	126.02	0.95
B3	128.24	0.97
B6	20.92	0.95
B7	21.27	0.97

The results presented in Table 7.2 show that all the voltage levels at the busbars are generally within the acceptable limits of ±5%, of the corresponding nominal voltages. Assuming that no voltage regulation mechanisms are implemented at the busbars, a further increase in the size of the loads at busbar B2 and B6 by a sizeable percentage (about 25%) may result in the corresponding voltage levels going below the permissible limits. Therefore these busbars also need to be carefully monitored when the Juno wind farm is connected and may require additional voltage regulation mechanisms. Further up the grid, we notice that the voltage levels are closer to the nominal values and since they are at the higher voltage levels, it may possibly signify that these are the stronger parts of the network.

Table 7.3 Percentage loading of the transmission lines

	P (MW)	**Q (Mvar)**	**Loading (%)**	**Losses (MW)**
Line 1	30.01	13.89	14.73	0.19
Line 2	21.89	10.48	10.94	0.25

The power losses are very minimal (about 0.6% of the total power transferred). However, in most cases, these power losses are also dependent on the conductor size, length and type that is used. As expected, the longer the length of the conductor, the higher the losses that should be expected since I^2R losses are increased (since the resistivity of a conductor is proportional to its length). The standard conductor type preferred in most Eskom transmission and distribution projects is the Hare conductor [7]. It is mostly used over long distances.

The fault levels at the network busbars before and after the proposed new wind farm was connected were calculated using the DIgSILENT PowerFactory simulation tool. The IEC method of calculating fault levels was considered with the following characteristic assumptions [26]:

- A fault impedance of 0 ohms
- A maximum voltage of 5 % before the fault which is standard for an MV feeder
- With a short-circuit operational time of 0,1 sec (typical fault operational times in the Eskom network)
- Fault clearing time of 0,2sec, which is typical on the Eskom network

These input values are added into the calculations model as shown in figure 7.3. It must however be mentioned that the fault level results given in this thesis represent the initial short circuit current which were observed when a three phase fault was applied to the network [26].

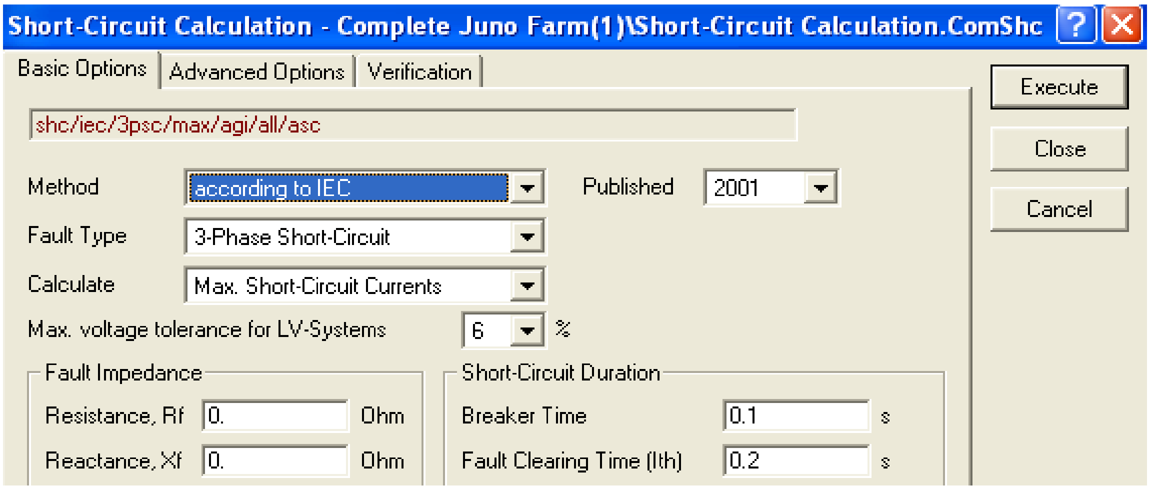


Figure 7.3 Input of basic data for fault level calculations in DigSilent

As mentioned previously, the short-circuit power levels give an indication of the importance of determining the strength of the grid. These are relatively higher, closer to the PCC and therefore we would expect these parts to experience the least power quality issues. The fault level calculations on the network were simulated and presented in Table 7.4.

Table 7.4 Short circuit power levels

Busbar	**3 phase Fault level [MVA]**
Juno 400 kV	3 600
PCC	1 380
B1	930
B2	470
B3	850
B6	410
B7	390

Since short circuit power levels can be used to distinguish the relative strengths of the different parts of the grid, it can be seen that the HV side of the network has a stronger grid configuration. Seeing as the proposed point of common connection is on the 132 kV busbar, a relatively stronger part of the grid, we should expect minimum power quality issues from the wind power plants connected to it. However, should the wind power plant output go beyond the proposed penetration level, it is most likely that some power quality issues may be experienced. This aspect of wind power integration shall be investigated in later sections of this thesis.

7.3 Impact of Connecting SCIG on the Network

In this particular case, the wind farm was connected into the grid at the 132 kV busbar as shown in Figure 7.2. For simplification purposes, the turbines were aggregated at a common busbar (33 kV) which feeds the power from the wind farm to the grid through 2 x 80 MVA transformers. The dotted lines (Line 3 and Line 4) illustrate the proposed double circuit line that is intended to be connected to feed the power from the wind farm to the point of common connection on the network. .

7.3.1 Impact of SCIG on the Network Power and Voltage

A 100 MW wind farm was connected to the grid via 50 x 2 MW SCIGs and the following results were obtained.

Table 7.5 Load flow results with SCIG

	P(MW)	**Q(Mvar)**
Grid	-38.68	141.86
Load 1	26.75	10.57
Load 2	21.64	9.86
Load 3	7.92	2.88
Wind Farm	100	-80

Table 7.5 shows that the wind farm is sending 100MW of power into the grid and drawing about 80Mvar from the network. This figure seems to be higher than the normal reactive power drawn by induction generators and this could be as a result of the design parameters that were used in this thesis. One would expect the real figure to be lower than the above. The infinite bus seems to be the only source of reactive power on the network. The amount of power supplied to the loads is also indicated in the table.

Table 7.6 The voltage levels at the busbars

Busbar	V (kV)	V (p.u.)
Juno 400 kV	400	1
PCC	123.10	0.93
B1	61.27	0.92
B2	119.25	0.93
B3	121.61	0.92
B4	118.76	0.90
B6	19.78	0.90
B7	20.16	0.92

Looking at the Table 7.6 above, we notice that there is a drop in voltage levels in the corresponding busbars with the introduction to the grid of the 100MW wind farm composed of SCIG. However, of main interest in this investigation is the voltage level at the PCC which dropped from 0.98p.u. (without SCIG in Table 7.2) to 0.93p.u. This is outside the permissible limits (0.95.pu. – 1.05p.u) and thus calls for this discrepancy to be addressed through voltage regulation interventions. This is attributed to the increased reactive power consumption from the network by the SCIG wind farm since it corresponds to the voltage drop on the point of connection as explained in section 4.3.

Normally, in such a situation, SCIGs are usually equipped with capacitor banks that will act as reactive power compensators so as to restore the voltage levels to their corresponding permissible limits. In this particular analysis, the amount of reactive power compensation required was determined initially through a non-systematic approach of trial and error form. This would be investigated in the following sections. Since capacitor banks are costly, it is recommended to select most economical solution by selecting the minimum capacitor bank size which would meet the fully restore the voltage levels at the point of connection of the wind farm to the rest of the grid. This in turn should also naturally improve the voltage levels at the subsequent busbars on the network.

7.3.2 Impact of SCIG on Reactive Power Compensation

Capacitor banks (of almost 0.5 Mvar per 2 MW turbine) were connected at the wind farm to improve the reactive power requirements of the network since SCIG were being connected to the grid. As expected, one can see in Table 7.7 that the reactive power supplied by the infinite bus has dropped significantly (by about 27Mvar) since the capacitor banks are also providing reactive power to the grid.

Table 7.7 Loadflow results for SCIG with capacitor banks included

	P(MW)	**Q(Mvar)**
Grid	-39.73	113.50
Load 1	26.75	10.57
Load 2	21.64	9.86
Load 3	7.92	2.88
Wind Farm	100	-60

From Table 7.8, it can be seen that with the addition of capacitor banks on the generator busbars, the voltage levels seem to have improved significantly as observed from the change in figures. As previously mentioned, since the PCC is our area of interest, we notice an increase in voltage level from 0.92p.u to 0.95p.u which is the acceptable limit of a voltage level profile. In this particular case, this increase was as a result of connecting a 25 MVar capacitor bank to the 100MW SCIG wind farm. The 25 Mvar reactive power compensation size (500 kVAr per 2 MW wind turbine) was achieved through trial and error from monitoring the voltage levels at the PCC with the addition of the capacitor banks. Therefore using the rule of thumb, it can be assumed that 25% compensation would be recommended for reactive power compensation.

However, most modern SCIGs are equipped with capacitive compensation and therefore may only require low or reduced external capacitor banks to cater for reactive power compensation.

Table 7.8 Voltage level results for SCIG with capacitor banks included (25Mvar)

Busbar	V (kV)	V (p.u.)
Juno 400 kV	400	1
PCC	123.10	0.95
B1	61.27	0.94
B2	119.25	0.92
B3	121.61	0.94
B4	118.76	0.92
B5	27.33	0.87
B6	19.78	0.91
B7	20.16	0.93

As indicated in the earlier chapters, as much as capacitor banks (static compensation) can improve the voltage profile of a network, over-compensation may lead to a voltage rise above the permissible limits at the point of common connection and could be propagated to other busbar nodes on the network. In such a situation, it would be highly recommended to introduce the converter based dynamic compensators which can be used to control the amount of reactive power injected or absorbed in a system. This is achieved by power electronic controllers which operate systematically through continous switching mechanisms that provide required reactive power support when needed and in the required quantities [46]. A Static Var Compensator (SVC) can be used. However, this has not been investigated in this part of the thesis.

7.3.3 Fault Level Contributions by SCIG

The fault levels at the network busbars after the 100 MW wind farm consisting of 50 x 2 MW SCIGs were connected were also calculated using the IEC model in the DIgSILENT PowerFactory simulation tool and the results are given in Table 7.9.

By connecting any form of generators on the network, it most likely that the fault levels will increase in areas surrounding the generator PCC and this may have an impact on the protection equipment on the network. Switchgears (consisting of breakers and CTs) are designed to operate under certain fault levels, so increasing these levels may compromise their operation mechanisms.

The short circuit power level contribution becomes important to the utility planner as it determines how much wind power penetration levels can be achieved with the current equipment installed [31].

Table 7.9 Short Circuit power level (or fault level) contributions from SCIG

Busbar	**3 phase Fault level [kA]**
Juno 400 kV	3 950
PCC	1 770
B1	1 100
B2	510
B3	990
B6	440
B7	420

The worst case fault condition on a network occurs when there is a three phase fault. This is of particular interest in this thesis. As indicated in Table 7.9, the three phase fault level at the PCC increased from 1 380 MVA to 1 770 MVA after the connection of the SCIG wind farm. This represents a 28 % contribution to the fault level at the point of common connection (PCC). Moreover, the fault level contribution at the other subsequent busbars was less than 10%.

However, in a scenario where the wind farm was connected to B2 (a relatively weaker part of the grid), the fault levels at that busbar increased significantly to 870 MVA, indicating a fault level contribution of about 85%. This would most likely affect the thermal limits of the protection devices in the network.

Therefore connecting of a wind farm to a relatively weaker part of the grid will limit the amount of wind turbines that can be connected. As previously suggested, the rating of protection equipment on the network should be such that an increase in fault levels does not make the system trip incorrectly. This is an indication that the designers of breakers or relevant protective devices should conform to the fault level of the network.

7.4 Impact of Connecting the DFIG to the Network

Similar studies performed on the SCIG were conducted on the DFIG so as to help in the comparison of the different technologies that would be most suitable for the proposed wind farm. A 100MW wind farm (2 x 50 MW DFIGs) was connected at a similar connection voltage level as the SCIG and various simulations presented in following sections were performed.

7.4.1 Impact of DFIG on the Busbar Voltage Levels

DFIGs are known to provide reactive power into the grid owing to the electronic converter controls that they posses. One would expect the voltage levels on the busbars to be improved as a result of reactive power injection. The following Table 7.11 has been used to illustrate this phenomenon.

Table 7.10 Voltage level results with DFIG

Busbar	**V (kV)**	**V (p.u.)**
Juno 400 kV	400	1
PCC	134.78	1.02
B1	67.13	1.02
B2	*131.31*	*0.99*
B3	133.44	1.01
B4	139.39	1.06
B5	36.35	1.10
B6	21.80	0.99
B7	22.14	1.01

An increase in the voltage levels is observed at the PCC and other subsequent busbars on the network. However, the voltage levels are still kept within the permissible limits of 105% of the nominal voltage. However, over-voltages on busbar B4 and B5 are observed and this it outside the permissible limits. In such a scenario, a series reactor may be required to lower the over-voltages. However, busbars B4 and B5 form part of the proposed wind farm and even though simulations do show over-voltages on these busbars, the design characteristics of the wind farm would be required to conform to the voltage level requirements of the network. Our interest in this investigation is the impacts of the wind farm on the network therefore we are mainly monitoring the effects at the point of common connection and other subsequent busbars.

7.4.2 Impact of DFIG on reactive power compensation

Table 7.11 The load flows on the network

	P(MW)	**Q(Mvar)**
Grid	-39.79	-35.14
Load 1	26.75	10.57
Load 2	21.64	9.86
Load 3	7.92	2.88
Wind Farm	100	76

From Table 7.10 above, we notice that the DFIG is actually contributing 76 Mvar to the grid as compared to the SCIG which drew MVArs from the network. More so, the amount of reactive power supplied by the infinite bus has reduced to about 35 MVAr due to the reduced demands of reactive power in the grid. This is due to the DFIG contributing to the reactive power control of the network through its power electronic converters.

7.4.3 Fault Level Contribution of DFIG

The three phase fault level contributions of the DFIG based wind-farm are shown in Table 7.12.

Table 7.12 Short Circuit power level (or fault level) contributions from DFIG

Busbar	**3 phase Fault level [MVA]**
Juno 400 kV	3 800
PCC	1 620
B1	1 000
B2	450
B3	900

B6	380
B7	370

Seeing as we are mainly interested in the fault level contributions at the PCC, we notice an increase from 1 380 MVA to 1 620 MVA. This signifies a fault level contribution by the DFIG wind of about 17% to the overall fault level at the point of common connection. However, though our interests lie with the PCC, the subsequent busbars will also be affected and therefore need to be monitored. The fault level contributions at the other busbars on the network are less than 8%.

Once again, in a scenario where the DFIG wind farm is connected to the grid via busbar B2 (a relatively weaker part of the grid), the fault level contribution is about 53%. . Since fault level contributions by a generator may have an influence on the operation of the existing installed equipment (mostly protection equipment ratings for current transformers, circuit breakers and isolators), we notice that the SCIG contributes more short-circuit current (or fault levels) as compared to the DFIG.

Should the connected wind farm increase the fault levels, there may be a need to reconfigure the protection system and also refurbish it with new equipment that would cope with the new ratings. In most cases, you would expect the protective equipment rating to be designed to cope with such an increase in fault levels, unless the fault levels are excessively increased. However, should there be a fault level issue on the network as a result of incorporating a wind farm, the equipment may need to be refurbished. Increasing the impedance of the transformer could be another mitigation procedure to try and reduce the fault levels.

7.5 Comparison of Impact of DFIG and SCIG on the Grid

7.5.1 Impact of Wind Turbines Voltage Profiles

It is common knowledge that the injected power from wind turbines is meant to improve the voltage profile of a network at the PCC. In most cases, it may eventually lead to over-voltages or to a lesser extent, under-voltage, especially if SCIG with no reactive power compensation are used (since they draw reactive power from the network and thus lower the system voltage at the PCC). The DFIG and SCIG have been investigated under different penetration levels so as to determine and compare their influence on the voltage profiles.

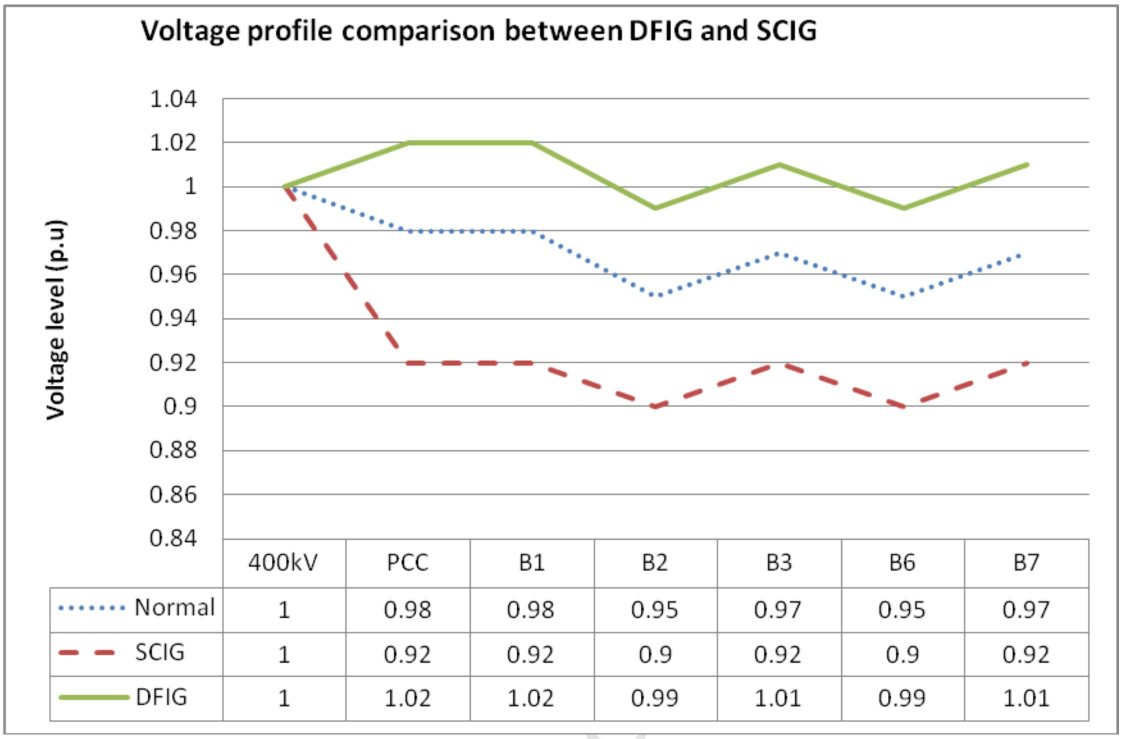
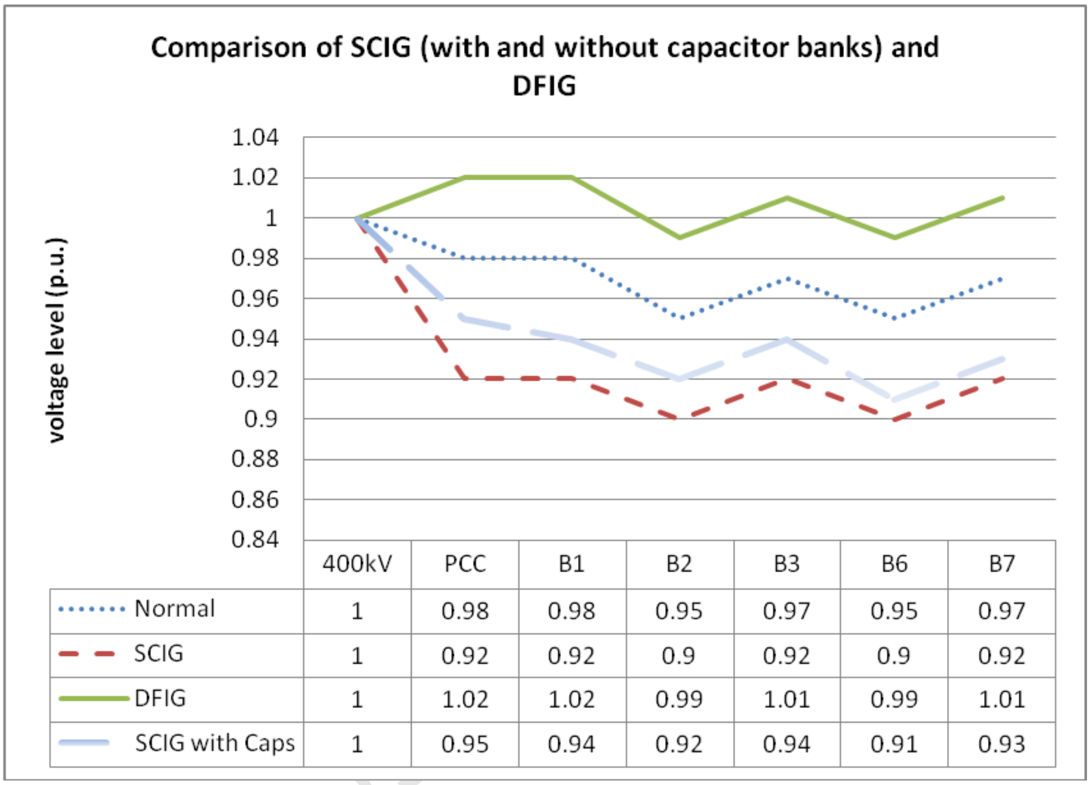


Figure 7.4 Impact of wind turbine technology on the voltage profile

The voltage profiles at the PCC and subsequent busbars on the network have been presented in figure 7.4 to show the influence of the turbine techonolgy on the voltage profile. The normal condition is assumed to be when no wind farm is connected and the correspoing SCIG and DFIG conditions refers to when a 100MW wind farm of each techonology is connected to the grid. There is a marked improvement in wind profile with the connection of DFIG, as compared to a drop in voltage levels associated with the connection of a SCIG as a result of the reactive power requirements on the network of the two different technologies explained earlier in this section. The voltage profile of the DFIG is within the acceptable limits of operation (between 0.95 and 1.05p.u.). However, that of the SCIG is below the permissible limits.

Since we are mainly interested in monitoring the PCC in this study, in order to improve the voltage level to within acceptable limits, a 25Mvar passive capacitor bank was connected to the grid (equivalent of 500kVAr per 2MW wind turbine) to bring voltage levels to about 0.9 p.u. There is a marked improvement in the general lood profile of the nodes even though they are still below the limits. However, it is likely that there are already voltage regulation mechanisms in place in the existing network but we are only interested in maintaining the voltages of the proposed PCC. Figure 7.5 compares the profile of the SCIG (with and without compensation) and the DFIG. The DFIG seems to have a better voltage profile even as compared to the reactive power compensated SCIG.



	400kV	PCC	B1	B2	B3	B6	B7
Normal	1	0.98	0.98	0.95	0.97	0.95	0.97
SCIG	1	0.92	0.92	0.9	0.92	0.9	0.92
DFIG	1	1.02	1.02	0.99	1.01	0.99	1.01
SCIG with Caps	1	0.95	0.94	0.92	0.94	0.91	0.93

Figure 7.5 Comparison of the SCIG (with and wothout reactive power compensation) and DFIG

7.5.2 Impact of Increasing Wind Farm Penetration Levels

In this case, the wind farm is connected through a proposed double-circuit line as shown earlier in figure 7.2. The penetration levels of the wind farm are increased from 0 to 100M for both DFIG and SCIG, (and beyond 100 MW for interpretation purposes) whilst monitoring the voltage levels at the point of common connection. The same assumptions explained in section 7.1 and 7.2 are followed. The following results were obtained after running a load flow simulation in DigSilent.

Table 7.13 Impacts of wind turbines on the voltage levels at PCC

Penetration level [MW]	Voltage level at PCC [p.u] (using SCIG)	Voltage level at PCC [p.u] (using DFIG)
0	0.98	0.98
20	0.98	0.99
40	0.97	1.00
80	0.95	1.01
100	0.93	1.02
150	0.86	1.03

From the above results, we notice that the voltage levels decrease with the addition of more SCIG onto the network. This could be attributed to the fact that the SCIG draws reactive power from the grid which may cause voltage to decrease at the PCC. Using SCIGs for the 100MW wind will result in voltage levels falling outside the permissible limits (0.95p.u – 1.05p.u.), meaning the 0.93p.u (123.1 kV) voltage level is below the minimum permissible voltage of 1.05 p.u. In such a scenario, reactive power compensation may be necessary in the form of capacity banks to ensure that the voltage levels are kept within the acceptable limits. In this particular case, the amount of reactive power compensation required was determined through a trial and error method. This analysis was discussed in previous sections.

In the case of the DFIG, when 100MW of DFIG wind turbines were installed onto to the network, the voltage levels actually increased, as opposed to when the SCIG where connected. This behaviour is attributed to the controls of the DFIG which facilitate reactive power compensation for the grid connected generator. One advantage of using a DFIG over SCIG is that its power electronic converters regulate the generation or absorption of reactive power, thereby eliminating the need to install extra capacitor banks. These controls provide reactive power that helps improve the voltage level of the grid. The voltage level at 100 MW DFIG wind farm connection is about 1.02 p.u (134.78 kV) which is still within the permissible maximum limit. A further increase in wind capacity to 150MW still meant the voltage levels were kept within the acceptable limits. However, care must be taken not to increase the wind farm capacity to beyond 200MW as this may lead to voltage levels at the

PCC rising above the permissible limits. In such as case, series reactors may be needed to try and avoid over-compensation.

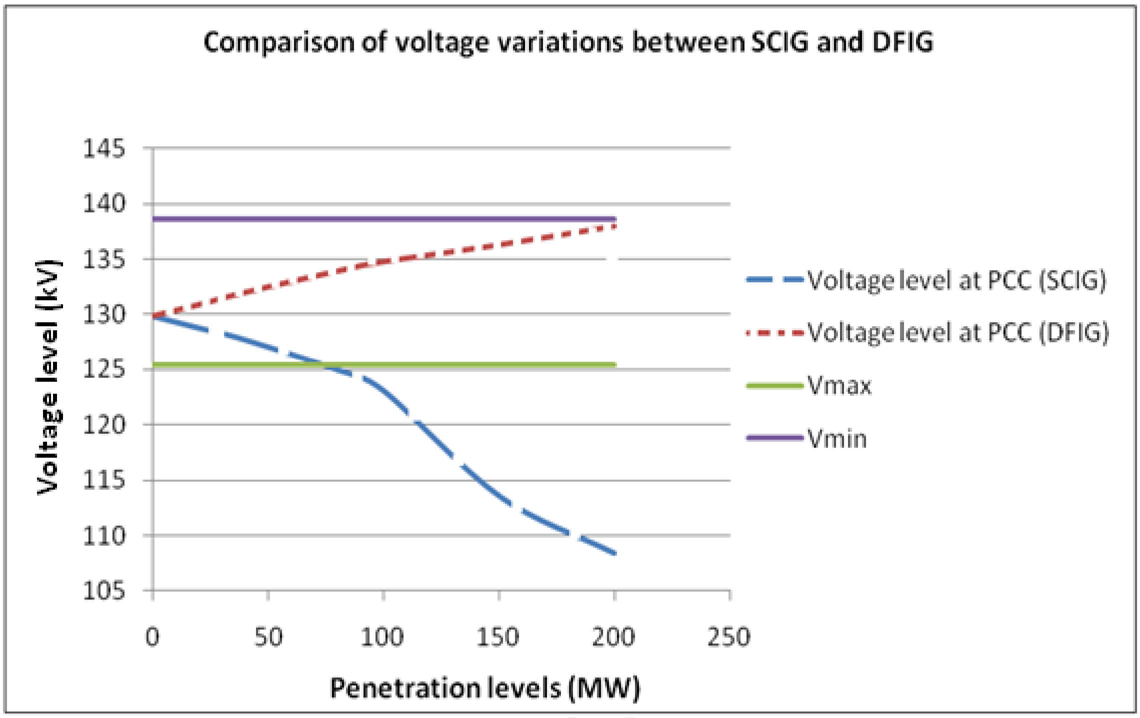


Figure 7.6 Impact of penertration levels of SCIG and DFIG on the voltage levels at the PCC

From figure 7.6, we notice the fall in voltage levels as one increases the penetration levels of wind power provided by the SCIG. In this study, we can assume that only about 80MW of SCIG can be connected to the grid without causing the voltage levels to be outside the permissible limits. Beyond that, customers also connected to the PCC would start experiencing some voltage level problems. In contrast to that, the DFIG seems to be helping improve the voltage level at the PCC.

7.5.3 Impacts of Reactive Power Compensation

Going beyond the 200MW wind capacity results in voltages beyond the permissible limits which may be a hazard to other customers connected to the same bus-bar. This may be a problem and shunt reactors may need to be connected, as mentioned earlier, to keep within voltage limits. This investigation was carried out to compare the voltage levels at the PCC and other subsequent busbars before and after a shunt reactor was added onto the network.

Figure 7.7 shows the influence of the shunt reactor on the voltage rise on a network.

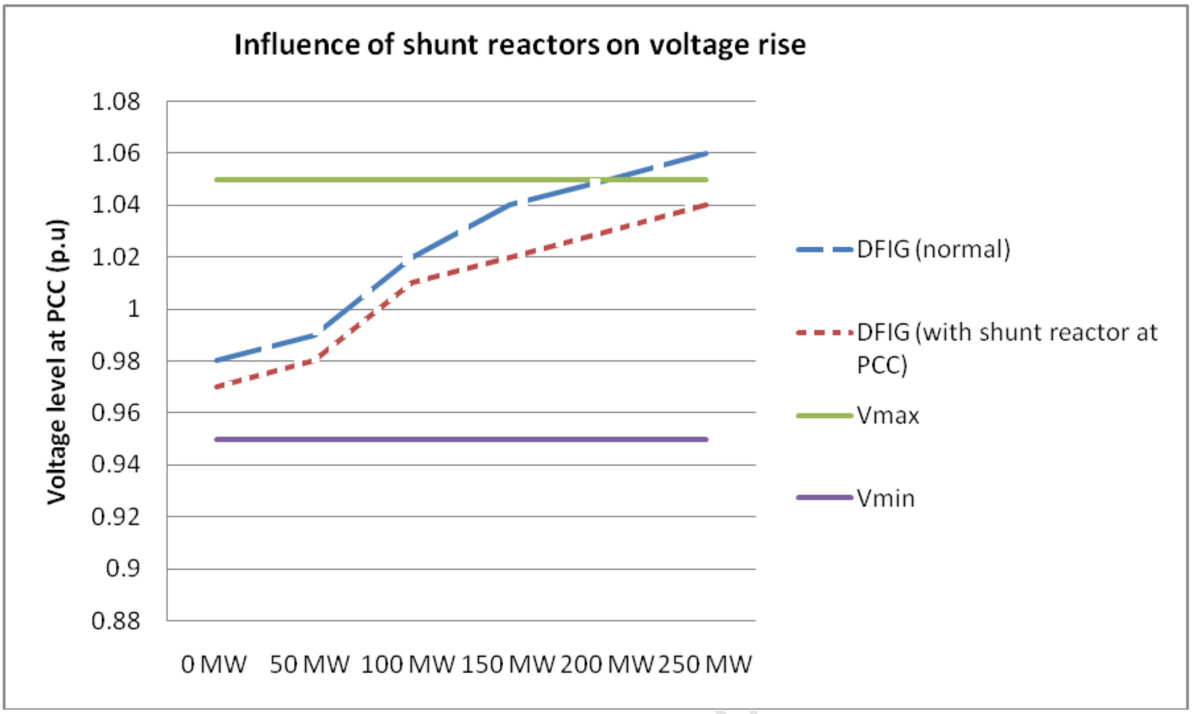


Figure 7.7 Impact of shunt reactor on voltage rise

From figure 7.7 above, one notices that having shunt reactors on your network will help deal with voltage rise issues. Above 200 MW of DFIG wind farm, the voltage levels go above the permissible limits even though under practical circumstances this voltage would be controlled by the power electronics connected to the DFIG. However, the introduction of shunt reactors makes it possible to connect up to 250 MW of DFIGs without going beyond the allowable limits. A 25 MVAr static shunt reactor was installed at the point of common connection and this reduced the voltage levels from 1.06 p.u to 1.04p.u. However, it must be mentioned that connecting shunt reactors may increase losses on the network and may also be a costly procedure and thus it should be used as a last resort.

In theory, it is possible to connect a wind farm of this size to this particular network, but practically there are constraints such as over loading of the lines and the transformers that technically make it less feasible. As experienced already, the percentage loading of the adjacent 2 x 80 MVA transformers that transmit power from the wind farm to the grid shot up to about 124%, which is technically not permitted. There may therefore be a need to add an extra transformer so as to avoid overloading of the proposed 2 x 80 MVA transformers. . This however will not be considered in this study.

Fixed capacitor banks were used for the 100MW SCIG wind farm, and figure 7.8 shows some of the results that were achieved. In this case, a shunt capacitor bank with a capacity of about 600kVAr was used to provide reactive compensation for every 2 MW sized wind turbine. This was achieved by assuming that one third of reactive power compensation would be needed (the economically efficient size that would achieve allowable compensation levels). This was done by trying out different capacitor sizes till we achieved minimum allowable compensation to bring the voltage levels to within the acceptable limits. (In ideal cases, a 2 MW SCIG with a power factor of 0.8 would draw about 1.2MVAr but that was regarded as too much compensation so economic values were chosen).

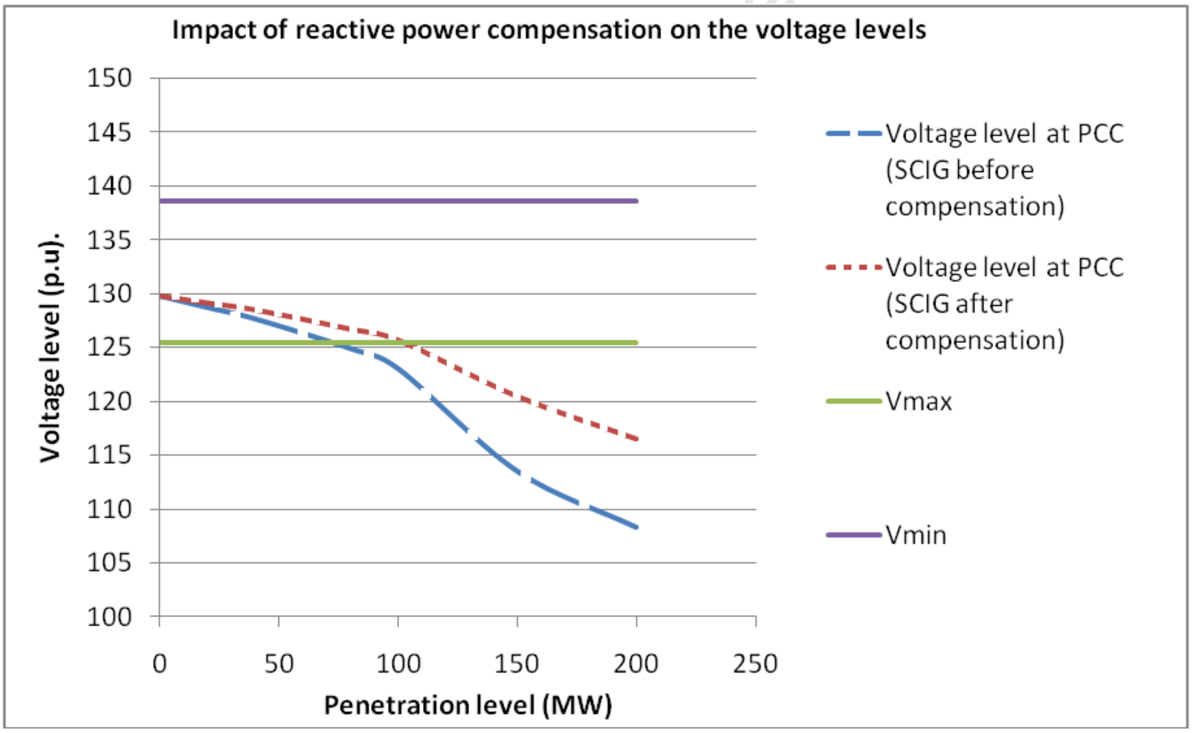


Figure 7.8 Impact of reactive power compensation on the 100MW SCIG wind farm

As seen in figure 7.8, connecting 100MW resulted in voltage levels of 123.10 kV which is below the allowable limits. However, the addition of fixed capacitor banks (about 30MVar for a 100MW wind farm) improved the voltage levels to about 125.81 kV (about 0.95p.u), which is within the allowable limits. With adequate compensation, the wind power capacity can still be increased to beyond 100 MW without noticeable voltage level changes.

7.5.4 Impact of Wind Turbines on Power Losses

A comparison of the power losses on the network resulting from the connection of wind turbines was conducted in DigSilent. Of main interest in this analysis are Line 3 and 4 which are the proposed lines to be used to connect the wind farm to the rest of the Eskom network, at the PCC.

With regards to losses, the connection of a SCIG wind farm results in more real power losses on the network as compared to connecting a DFIG. This could be attributed to the ability of the DFIG to supply reactive power to the grid and thus reduce losses on the network. This has been presented in Table 7.14.

Table 7.14 Comparsion of line losses with DFIG and SCIG

Line Losses (MW)				
	Normal	SCIG	SCIG (with caps)	DFIG
Line 1	0.19	0.2	0.2	0.18
Line 2	0.25	0.27	0.26	0.25
Line 3	0.07	1.38	1.04	0.64
Line 4	0.07	1.38	1.04	0.64

The lower losses resulting from the use of DFIG technology makes it more economically viable owing to the increased costs resulting from line losses in the network. This situation would make more business sense especially if one considers increasing penetration levels in relations to line losses. Therefore a clearer view on how losses are influenced by increasing wind farm penetration levels is presented in figure 7.9.

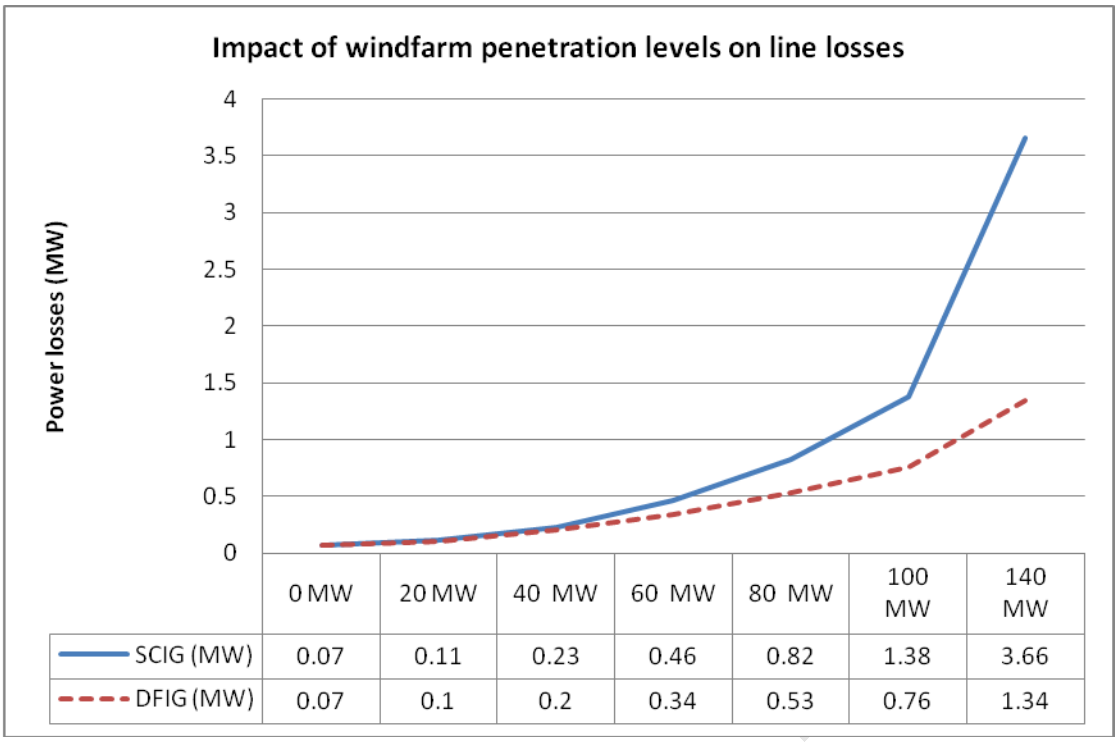


Figure 7.9 Impact of peentraton levels on line losses

As indicated by figure 7.9 above, the distinction in transmission line losses between the SCIG and DFIG becomes increasingly significant as you increase the penetration levels (the horizontal axis shows increasing penetration levels from 0MW →140 MW) owing to the increase amount of power flowing in the network. For instance at about 100MW penetration levels, the losses due to the connection of SCIG generators are double those of DFIG and this discrepancy continues to increase exponentially above 100 MW.

7.5.5 Impact of Wind Turbines Connected to Weak Grid Networks

When looking into the location of wind farms, land availability and ease of accessibility to the existing grid infrastructure are also important [3]. Location of the wind farm closer to a substation is also economically favourable as it reduces the integration costs associated with the wind farm. However, wind availability plays a major contribution to determining the site of a wind farm. Therefore a compromise would need to be made in order to have an economical and technically viable wind farm.

For example, most high wind areas are found on the coast and mostly in remote locations (e.g. the Cape west coast), which are typically characterized by long transmission lines which are common to weak grid system with generally low fault levels. It would therefore be worthwhile to investigate how these weak grid systems will impact the wind farms or how the wind farm will impact the weak grid systems

It has been mentioned in most wind energy publications that the power quality issues related to wind turbines are significantly experienced in weak grid systems. In this case the choice of technology used despite its location on the grid may have an impact on the voltage quality during steady state operations as well as during voltage disturbances, the severity depending on the strength of the grid.

The proposed point of common connection of the wind turbine is at the 132 kV busbar represented as PCC in figure 7.2. To observe how the different fault levels will impact the voltage quality of the network, two other 132 kV busbar nodes, B2 and B3 have been used as connection options for comparison purposes. The results are presented in figure 7.15.

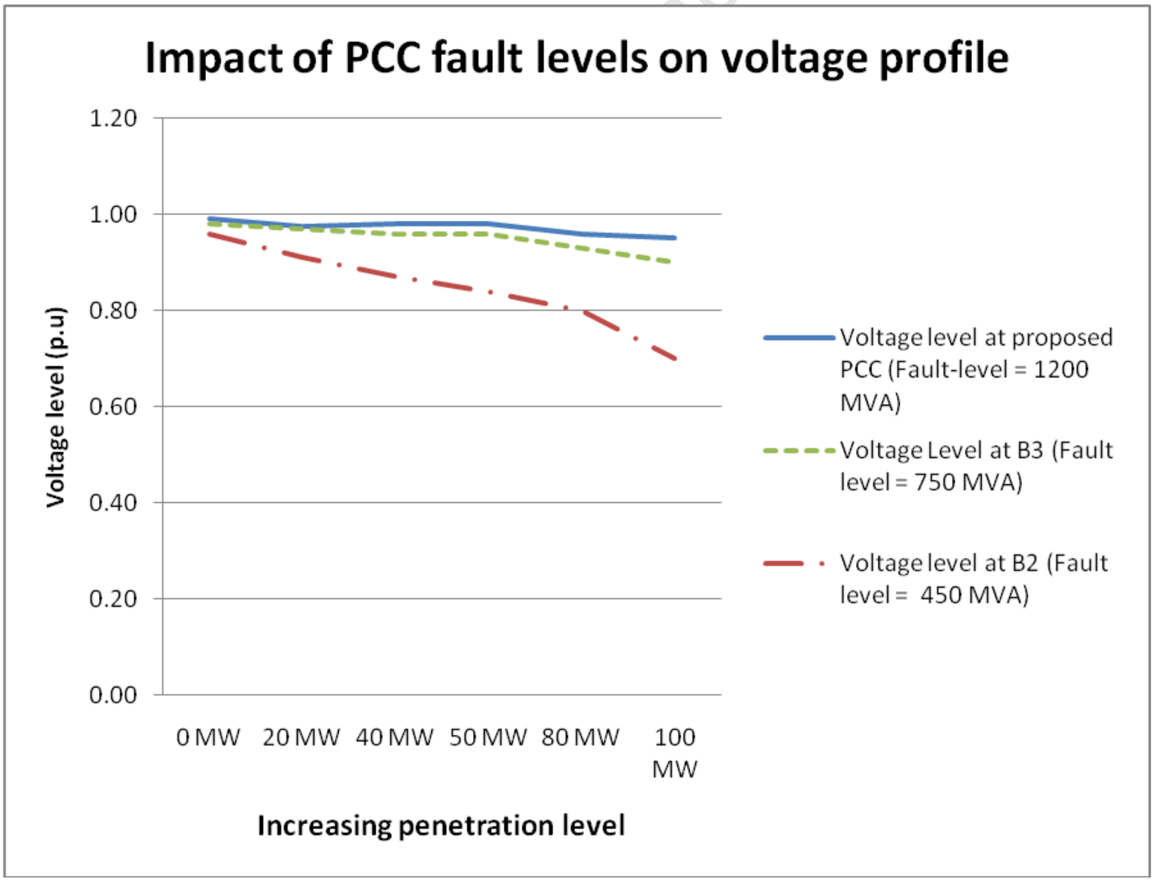


Figure 7.10 Impact of grid-strength on voltage levels at the point of common connection

Firstly, looking at figure 7.10, we notice the general decrease in the voltage profile as the penetration level increases owing to the SCIG being used in this particular analysis. This is due to their reactive power consumption which leads to a lowering of the voltage profile at the point of common connection. However, of particulat interest in this figure, is the reduction in the voltage profile as the point of common connection changes from a high fault level point to a relatively low fault level point, which is a charactieristic of a weak grid point.

These results further show that 100 MW wind power can be comfortably connected to the proposed point of common connection without any significant voltage level problems since it is a relatively stronger part of the grid (1200 MVA fault level). However, only 50 MW of wind power can be connected at B3 (at 750 MVA fault level) and likewise, a smaller amount of about 10 MW wind power can be connected at point B2 without exceeding the permissible voltage limits (See further Table A2 in the Appendix). These results infer that the weaker network point limits the the amount of wind power that can be integrated onto the network. It is in this part of the grid that voltage controllers can be implemented to continously monitor and control the voltage levels to within the specified limits [76].

A doubly-fed induction generator wind farm was conneceted to compare it with the performance of a SCIG on a weaker grid system. The results have been presented in figure 7.16

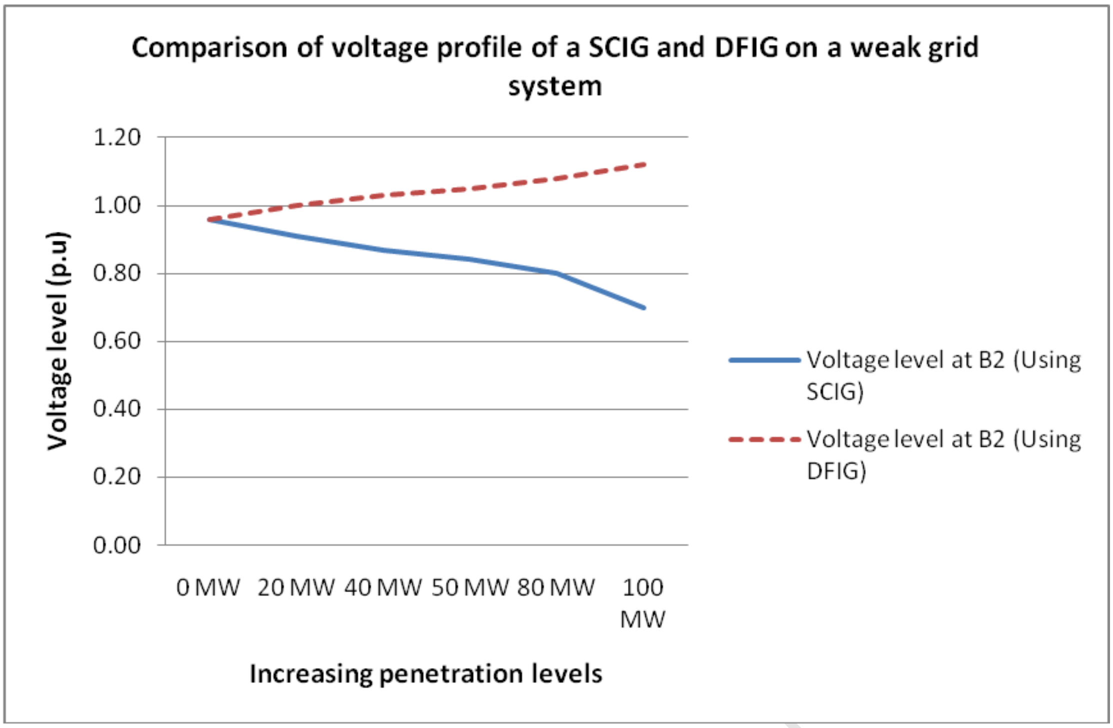


Figure 7.11 Impact of turbine type on voltage profiles on a weak grid connection point

The general impact of the SCIG and DFIG on the voltage profile at the connection point is shown in figure 7.11. As discussed earlier, the DFIG seems to improve the voltage profile, as compared to the SCIG, due to the reactive power compensation provided by its power electronic controls.

The most important point worth mentioning in these results is that the DFIG wind farm facilitates the connection of about 50 MW of wind power without upsetting the voltage levels outside the allowable limits. This is significantly higher than the 10MW that can be provided by the SCIG to keep the voltage level within the limits. This aspect further consolidates the reason behind the connection of the more adaptible DFIG wind turbines in weak grids. It must also be noted that at least 100MW of DFIG can be integrated into the weaker grid connection point if a 25MVAr reactor is connected, since the line and transformer loading (19% and 55% loading respectively for a 100MVA wind farm) would still be within the percentage operational limts . However, it must be noted that the lines are usually loaded heavier than the 19% indicated above. Therefore in this case, should the loading increases, adding shunts reactors may have an adverse effect on the network as this would increase the power losses on the network. This was however not investigated in this thesis. Reactor should be electronically controlled so they they can only be switched on only when required to maintain voltage levels on the network.

7.6 Impact of Wind Farm Transmission Line Parameters

The length and type of conductor used to transmit power from the wind farm to the grid will have an impact on the voltage drop and losses contributed by the wind farm. Various conductor types where modeled to connect the 100 MW DFIG wind farm to the grid. These are the commonly used conductors by Eskom [7]. Simulations were performed to investigate their influence on the line losses and voltage profile at the point of common connection. The following results given in Table 7.15 were acquired:

Table 7.15 Comparison of the different conductor types

Conductor Type	Juno Line_Type	Hare	Bear	Kingbird	Cu
Line losses (MW)	0.76	1.14	0.85	0.71	3.85
Voltage PCC (p.u)	1.02	1.02	1.02	1.02	1.02
%Line loading	24.51	41.85	46.2	41.49	124.05

The conductor type influences some of the parameters such as line losses and line loading as presented in Table 7.15. Normally, the voltage drop would also be a factor, but in this particular case, this did not influence the voltage levels at the PCC. However, the Copper conductor (Cu) contributed the most line losses on the network, over 5 times the losses resulting from the use of the Juno Line_Type conductor. Moreover, the Copper loading was over-loaded to 124% when 100 MW of wind farm was connected making it the least favoured option. Meanwhile, the Juno Line_Type conductor had the most suitable percentage loading of 24.5%.

Therefore, a number of factor such power losses, voltage drops and loading capacity would contribute towards choosing a perfect conductor to connect a wind farm to the rest of the grid, especially when using a SCIG which has higher line losses and voltage drop problems as shown in section 7.5.4.

7.7 Impact of Loss of Line on the Network

This study shows the impact of losing a transmission line during the operation of the network. This could be as a result of a line fault or line maintenance on the network. Should such an event occur on the network, it is most likely that the remaining line would be overloaded (including the transformers) thereby increasing the voltage limits as well. This has been examined in DigSilent and presented in the following figures:

Table 7.16 Impact of line loss on the power transfer capability

	P_trans (MW)	**P_trans (MW)**	**P_losses (MW)**	**%Volt_drop**	**% Loading**
Both Line on	48.5	32	0.77	0.03	24%
Line 3_out	96	58	2.69	0.07	49%

From analysing Table 7.16, it can be noticed that the power transfer capacity is almost doubled to about 96 MW when you lose one of the double circuit lines connecting the wind farm to the point of common connection. This is to be expected as all the power from the wind farm would have to be fed through that single transmission line. However, there is a noticeable increase in the voltage drop across the line which increases by more than double from 0.03% to about 0.07%. This must be noted since voltage drops are a major concern in weaker grid networks.

The doubling of the line loading to almost 50% may appear to be fairly within reasonable limits, but in reality, this may not be so since we have made a number of assumptions in the investigation. Eskom uses an N-1 operational sequence which implies that when one line fails, there should be contingencies within system that should enable it to operate normally without experiencing any abnormalities. This investigation showed that the line loss will not have much of an impact on the transfer capabilities of power from the wind farm since the line parameters used are real. However, this may not be the case should the wind farm have been connected to a weaker part of the grid where the transfer capabilities are very low owing to higher line reactance.

8 ANALYSIS OF THE HARMONIC IMPACT OF WIND TURBINES ON THE GRID

It is important to understand the harmonic behaviour of wind turbines so that we may analyse the effect they will have on the grids to which they are connected. This chapter seeks to investigate the harmonic distortions on the network resulting from the integration of variable speed wind turbines (DFIG). In order to facilitate this analysis, the following exercises where performed:

- Impact of penetration levels on the total harmonic distortion (THD) and individual harmonic distortion (HD) level
- Impact of the grid strength on the THD level
- Impact of harmonic current spectrum on the THD levels
- Mitigation of harmonics using filters
- Impact of the filter location on the THD levels

In this thesis we have chosen the PCC to be at the distribution bus since the only source of harmonics in this network was assumed to be from the wind farm. These harmonics flow into the network and interact with the network impedance, causing voltage harmonics on the network which affect the power quality of the overall network. This eventually results in increased line losses on the network.

8.1 Modeling of the Harmonic Network

A similar model to the proposed Cape west coast wind farm network model captured in DIgSILENT has been used in the analysis of harmonic distortions (see Figure 8.1).

8.1.1 Description of the Network

The existing network has the same characteristics and parameters as the previously modeled one in chapter 7. The only difference is that only the DFIG generators would be considered in this harmonic distortion investigation since they are the source of harmonics.

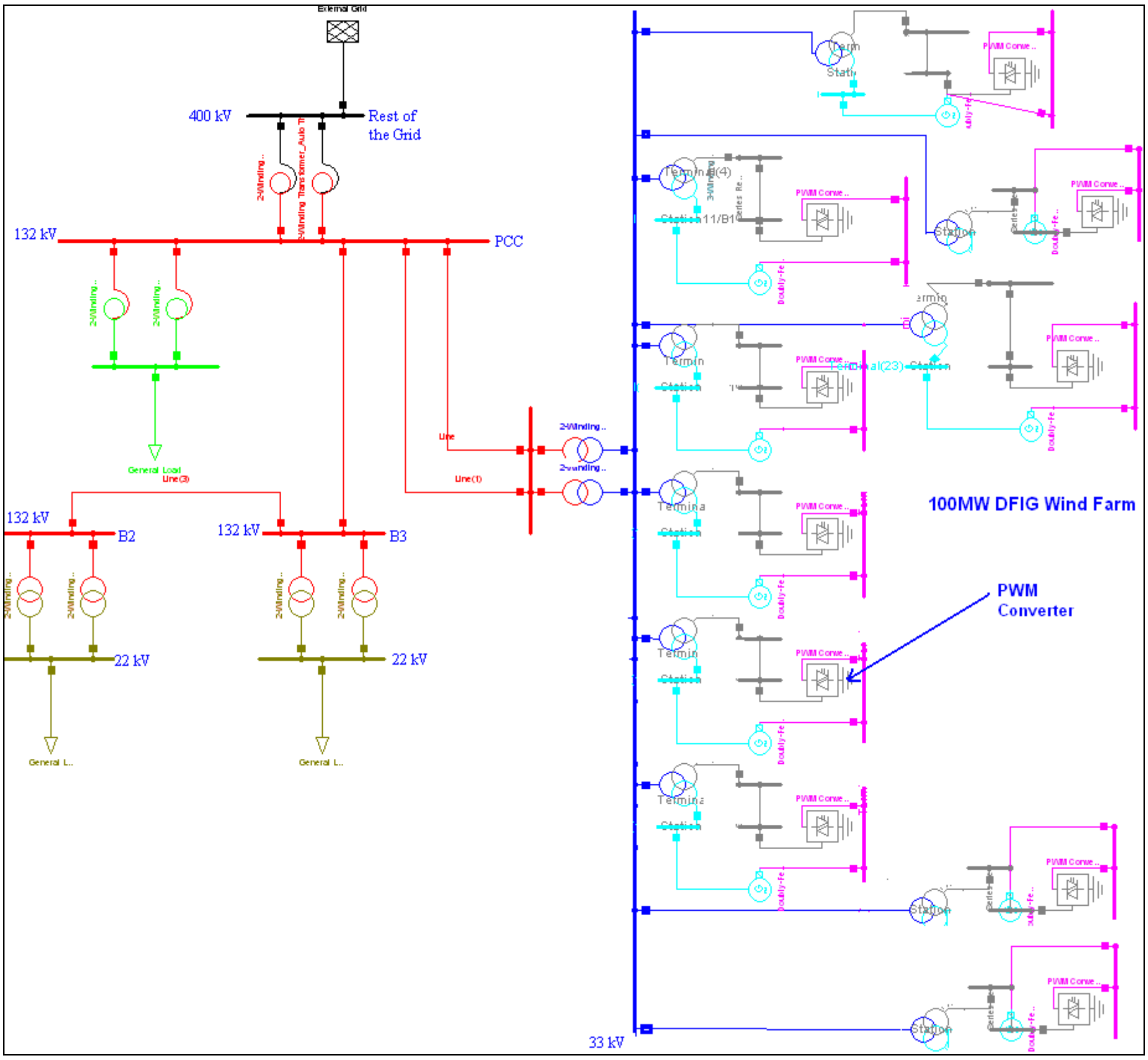


Figure 8.1 DFIG connected to the grid

The 100 MW of wind power was fed into the grid using DFIG which consists of a PWM converter as shown in figure 8.1. The PWM converter attached to the DFIG acts as a source of current harmonics, which are assumed to be kept at lower harmonic orders. Although most current PWM converters usually emit higher order harmonics which are often easy to filter, there are still a few remaining DFIG based PWM converters with low order harmonics available on the market. This particular analysis has considered the lower order harmonics (h= 5, 7, 11 and 17) which are associated with the older types of PWM converters [50]. This will present a worst case scenario since harmonics with lower order spectrums are presumed to be problematic as they have a likelihood of distorting the waveforms and are also difficult to filter.

8.1.2 Harmonic Load-flow Calculations

Harmonic load-flows were performed in the DigSilent PowerFactory. In performing these harmonic investigations, the following assumptions were made:

- Determination of the contribution of the overall harmonic distortion at the point of common connection by the wind farm can be a complex analysis as it can depend on other background contributions from the load and the network supply [77]. Therefore, for the sake of this investigation, the wind turbines (DFIG) were the only sources of harmonic currents on the networks and this helped in quantifying their harmonic contributions to the grid
- The PWM converter was modeled as a harmonic current source
- 0% THD and HD contributions were assumed at the PCC before the wind farm was connected
- Since specifications of harmonic spectrums from wind turbine manufacturers were deemed confidential, generic harmonic spectrums found in DIgSILENT were assumed

In order to perform a harmonic calculation in DIgSILENT, the harmonic load-flows were run at a nominal frequency value (50Hz) and thereafter, the operating frequencies were varied from the 5th order till the 17th order so as to see the harmonic performance of the converters at different frequency order harmonics. Whilst performing the different harmonic load-flow calculations, the THD and HD levels were monitored at the point of common connection busbar (PCC).

8.1.3 Modeling of the Harmonic Source (Harmonic Spectrums)

According to DigSilent technical reference manual [26], harmonic load-flows allow the calculation of harmonic voltages or current based on the pre-defined harmonic sources and grid characteristics [26]. Also, the software allows for the user-defined harmonic current sources to be located at any bus-bar on the grid [26]. In our investigations, we have defined the PMW as our harmonic source and considering a worst case scenario, its harmonic current spectrum has also been assumed to resemble that of the ideal (generic) model given in DIgSILENT. The assumption is that if the PMW is modeled as a harmonic current source and an ideal model ($I_h = \frac{I_1}{h}$) is used for the harmonic current spectrum, then the 5th ,7$^{th, 11th,}$ 13th and 17th harmonic currents would be presented in Table 8.2 as follows [26]:

Table 8.1 Ideal harmonic spectrum [26]

Harmonic order	Magnitude (I_h/I_1) (%)	Spectrum angle (θ_1-θ_2) (^{o})
5th	20.0	0
7th	14.28571	0
11th	9.090909	0
13th	2.702703	0
17th	2.439024	0

The ideal spectrum shows the harmonic current injections worked out using the formulae in Appendix A2. This ideal model is generally used when the actual values obtained from the measurements and published data are not available [49]. For the simplicity of this study, the harmonic currents are assumed to be balanced.

The ideal spectrum shall allow us to compare the total harmonic distortion at the point of common connection at different penetration levels as well as grid strengths. In a worst case scenario where the THD levels exceeded the permissible limits, a filter had to be designed to mitigate the distortions. The harmonic order of the source was operated several times at lower frequencies (h = 5, 7…..13) as these harmonics presumably have the likelihood of distorting the voltage (or current) waveforms.

Various wind turbines may emit variable harmonic spectra and their shapes (magnitudes) are dependant on the characteristics and control of the wind turbine converters used [49]. In this case we decided to work with the ideal spectrum which is provided in the DigSilent manual and these have a zero spectral angle across the different frequency harmonics [26].

8.2 Impact of Short Circuit Level on THD

The harmonic load-flow was performed for a 100MW DFIG wind farm connected at the proposed point of common connection. In order to analyse the impact of the strength of the grid on the overall %THD, the short circuit power levels at the PCC were varied so as to examine the changes in the percentage THD values. Of interest is the fact that the monitoring was done at the point of common connection (PCC) and the following results tabulated in Table 8.2 were yielded:

Table 8.2 Impact of grid-strength (short circuit power levels) on the % THD

Short-Circuit Power Level at PCC (MVA)	**%THD**	**Ratio of SCC to Wind Generator Capacity**
1600	3.79	~16
1200	5.21	~12
800	7.33	~8
600	10.50	~6

Results show that the THD decreases with an increase in short circuit power levels and therefore, in order to allow for minimal harmonic disturbances on the network, it is recommended that the wind power plants be connected to a stronger part of the grid. The short circuit level at the PCC for the planned Cape West Coast wind farm is expected to be high (in the region of ±1500MVA) Therefore according to the results from the investigation, it is expected that the impact of the harmonics for a 100MW wind farm will be minimal, as seen by the lower value of 3.79% THD. This is safely within the allowable limits.

It can be noticed that the THD level increases as the grid strength becomes relatively weaker, almost doubling up as one reduces the short-circuit power level by half as seen in Table 8.2. From the give results, we can conclusively say that by reducing the short circuit power level by half, the value of the %THD increases by a factor of almost 2.

8.3 Impact of Penetration Levels on Harmonic Distortions

Assuming the connection point was either at busbar B2 or B3, the 100MW wind farm will have a different harmonic contribution owing to the strength of the grid. When 100MW wind farm was connected at B2, the connection option with the least grid-strength amongst the different 132 kV connection options, the %THD results at that busbar were above the permissible limits of 8% (see Table 8.3)

Table 8.3 Comparison of %THD levels at different points of wind farm connection

	% THD level	
Penetration level	Proposed PCC (Fault level – 1500 MVA)	PCC at B2 (Fault level – 700 MVA)
20	1.45	3.3
40	2.34	4.91
100	3.79	7.07
200	5.12	8.97

In Table 8.3, one can notice that the total harmonic distortions when connecting the wind farm at B2 would be twice as much as when the wind farm is connected at the proposed PCC. However, though there are higher THD levels at B2, they are still within the acceptable limits of 8%. In reality, since a number of assumptions were made during this investigation, the actual %THD values when 100 MW DFIG wind farm is connected may be more than the results presented in Table 8.3 and therefore it would be important to keep the THD levels as low as possible.

Results presented in Table 8.4 show that it is very possible to connect 200 MW of DFIG wind power at the proposed point of common connection without adversely affecting the harmonic distortions at that point. The increase is not so pronounced considering that the doubling of the wind farm capacity to 200 MW only increases the THD levels by about 1.1%. It is possible that the connection point could still accommodate more wind power and still maintain an allowable percentage THD value. This was explained earlier and could be due to the relatively stronger part of the grid to which the wind farm is connected. However, this may impact on other voltage quality issues. This implies that the stronger grid can accommodate more wind capacity without a significant increase in harmonic distortion as compared to a weaker grid.

However, the maximum amount of wind power that can be connected at busbar B2 and is still within the allowable THD levels at about 100MW. Should it go beyond this penetration level, there is a high probability that the %THD could fall outside the permissible limits as shown by the %THD of 8.97 when 200MW of wind farm is connected. In such a case, one may need to install filters to mitigate the distortions.

8.4 Mitigation of Harmonic Distortions

Since the %THD levels were exceeded when connecting the 200MW wind farm at busbar B2 as shown in Table 8.3, a filter was required to mitigate these distortions. Following the design equations of the single tuned filter given in section 4.4, the following values given in Table 8.4 were calculated:

Table 8.4 The calculated parameter values of the filter

Parameter	Calculated value
θ_1	*0.84*
θ_2	*0.95*
P	*200 MW*
Qc	*20*
Q	*18*
n	*4.7*

The harmonic distortion was analysed before and after a filter was connected to the wind farm connection point, B2. With the connection of the filter on the wind farm's busbar connection, there was a marked improvement in the THD levels observed on the network busbars. There was a general decrease in THD level at busbar B2 and other corresponding busbars on the network. However, it must be mentioned that the most reduction occurred at the nodes closer to where the filter was connected.

The reduction in THD levels at busbar B2 is of particular interest since it is a point which had a THD level exceeding the permissible limits when an arbitrary 200MW DFIG wind farm was connected to the system. Arbitrary in the sense that under real conditions, it may not be technically feasible to connect 200 MW on a wind farm at that particular point, but in order to facilitate our investigation of harmonic filters, we needed to exceed the THD levels of 8%. The following results were attained from the analysis:

Table 8.5 Impact of filters on %THD levels

Bus type	%THD (before filter connection)	%THD (after filter connection)
132kV – Busbar B2	8.97	2.32

The %THD level dropped significantly by almost 75% of its value to about 2.32 %THD. This value is within the acceptable harmonic distortion limit and is further elaborated by figure 8.2 which shows the difference in output voltage at the connection point before and after the filter was connected to the wind farm connection point.

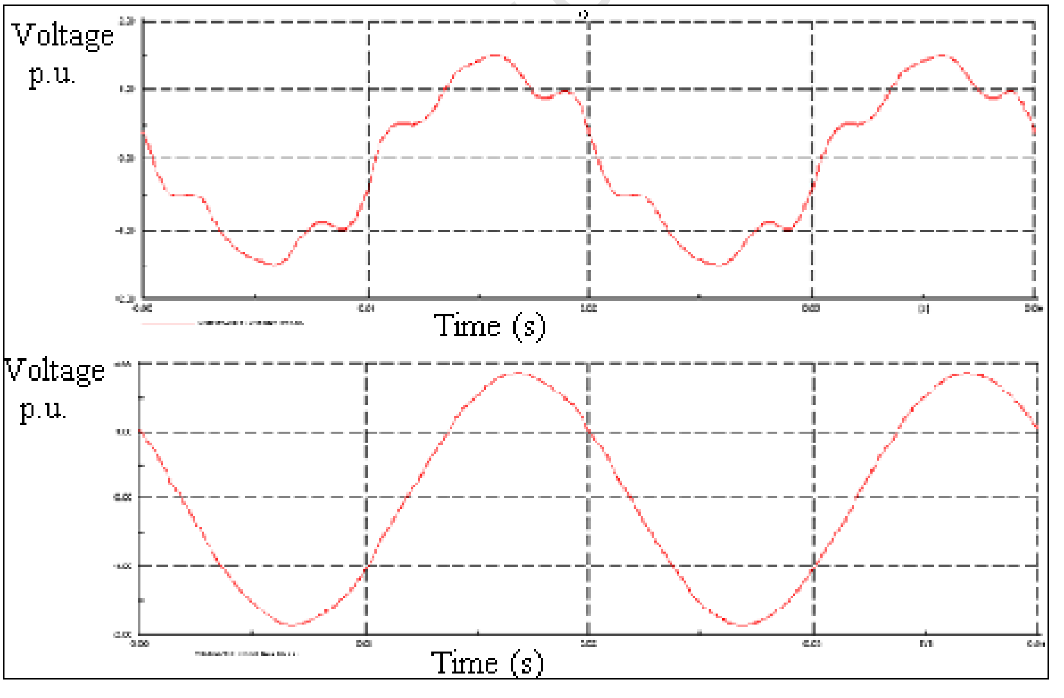


Figure 8.2 Voltage waveform before after a single-tuned filter was connected

Figure 8.2 shows two voltage waveforms taken at the point of connection of the wind farm to busbar B2. The top graph shows a distorted waveform as a result of increasing the penetration levels to 200MW and the bottom graph shows the corresponding voltage level when the filter was connected at the connection point. The distortions shown on the top graph are smoothened out by the single-tuned filter. In reality, the resultant voltage curve is not as smooth as the one illustrated in Figure 8.2 as smoothening it out may be a costly exercise and require a highly efficient filter.

However, care must be taken during the design of the filter as the value of the reactive power contributed by the filter may result in the voltage levels rising beyond the acceptable limits. The reactive power should thus be carefully adjusted so as to keep the voltage levels at the PCC within the permissible limits. Also, excessive capacitive compensation on the network may further cause harmonic resonance on the network due to its interaction with the grid impedance. This phenomena has however not been considered in this thesis.

9 ANALYSIS OF THE IMPACTS OF WIND TURBINES DURING GRID DISTURBANCES

The stability and reliability of the network with regards to the integration of large wind farms has become the focus of most large wind integration projects. It is worth mentioning that generator stability studies were outside initial scope of this thesis since only power quality issues are of main interest. However, the author has decided to include a few stability studies to validate the technical issues associated with grid connected wind turbines. The studies performed in this chapter are therefore not as rigorous and detailed as they should have been and are meant to help give an insight into future work that could be done on relevant stability studies.

This chapter seeks to describe the interaction between the wind turbine generators and the grid during network disturbances, and their effects on the power quality. Disturbances could be as a result of transients or faults on the grid, and this investigation would mainly compare the behaviour of the squirrel cage induction generators (SCIG) and doubly-fed induction generators (DFIG) during a network fault.

9.1 Description of the Network Model

The network model used in this investigation is similar to the one used in the previous investigation of this thesis (see Figure 7.2 and 8.1). Both the SCIG and DFIG have been modeled using similar characteristic as in the previous chapters. The wind power capacity from each wind farm technology was varied between 0 and 100MW in order to assess the behaviour of the wind farm and that of the network connection point during the disturbance.

Assuming a worst case scenario, a three phase fault was applied between the wind farm and the point of common connection (either Line3 or Line4), allowing a fault clearing time of about 100ms which is a typical fault clearing time for the breaker to operate and the fault to be cleared. Note that in this case, to simplify the fault analysis, the short circuit was simply removed from the network without opening any breakers in order to clear the fault. However, in real life, a line fault is normally cleared by opening the line breakers, and in many cases, the line breakers will re-close automatically after the protection operation. Should there be a delay in clearing the fault, the generators may lose their stability as shown in Figure 9.2.

Note that the SCIG and DFIG wind farms are not operated or simulated concurrently.

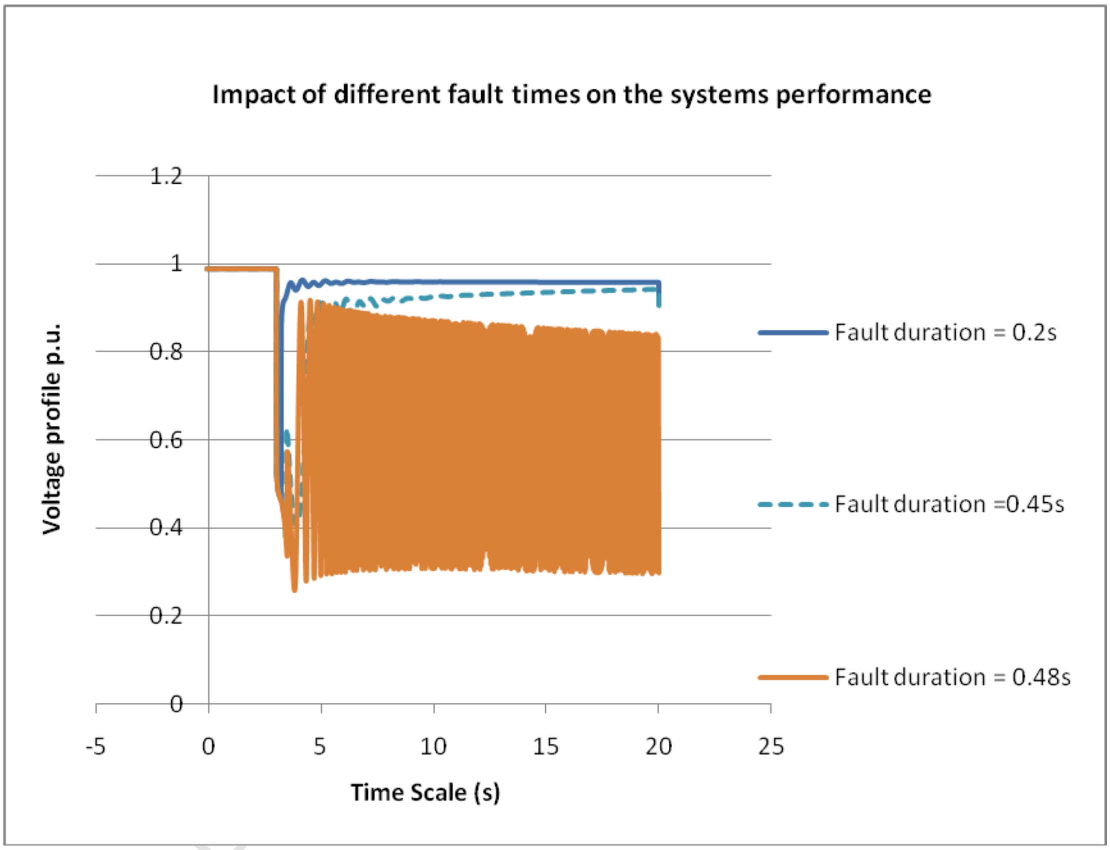


Figure 9.1 Impact of fault-clearing time on the SCIG

Figure 9.2 shows that the longer it takes to clear a system fault (in this case a line fault on either Line 3 or 4), the more vulnerable the SCIG are to losing their stability. The fault clearing times where varied between 0.2 seconds and 0.5 seconds. Results show that the generators lose their stability when a fault takes longer than 0.45 seconds for this particular analysis. Therefore the wind turbines may have to shut down so as to avoid further damage to the machine. This mode of operation would be expected since the SCIG are not expected to support the grid during a grid disturbance.

However, modern day variable wind turbines (mostly DFIG) are required to be capable of riding through a fault or dip (Low voltage ride through capability, LVRT) or fault ride through capability, FRT)) in a network so as to help support the network during a disturbance. This means that the generators may stay connected on the network during a fault, provided they have sufficient reactive power to support the grid during a voltage dip. The fault ride through requirement of the DFIG was however not investigated in this thesis as the relevant turbine parameters were not made available by the manufacturers.

9.2 Comparison of SCIG and DFIG during a Grid Disturbance

A comparison of the performance of a DFIG and a SCIG during a fault on either line 3 or 4 was investigated. This was done by connecting about 20 MW wind turbines (DFIG or SCIG) onto the network and introducing a fault on the network for duration of about 0.100ms and then clearing it afterwards, whilst monitoring the voltage profile of the generator connection point. The following results were achieved.

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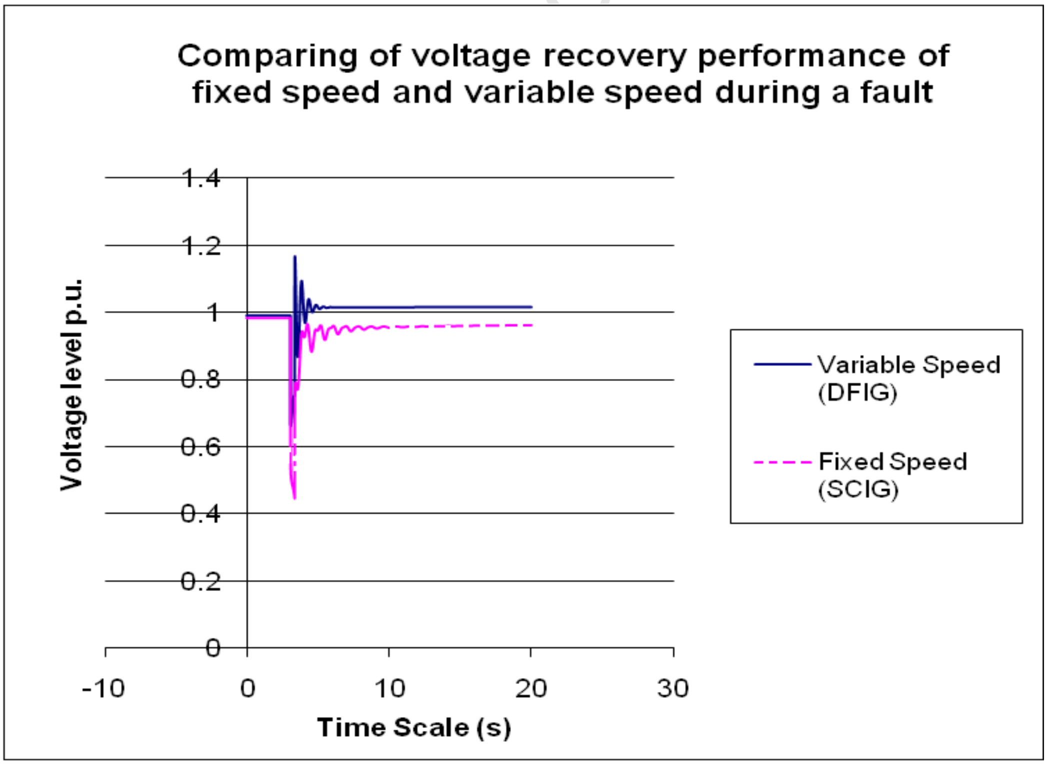

Figure 9.2 Impact of turbine choice on the behaviour of a generator during a grid disturbance

When the bahaviour of the two turbines are compared during a grid disturbance as in figure 9.2, the doubly-fed induction generator (DFIG) seems to have a better voltage recovery than the squirrel cage induction generator (SCIG). When a line fault occurs on the network, the voltage across the generator busbar drops from its pre-fault value of about 1p.u to about 0,7 p.u and eventually recovers to a voltage level slightly higher than its pre-fault value once the fault is cleared. This is as a result of the power electronic controls of its converter that allows a DFIG to compensate for the reactive power absorbed by the system during a fault. After the fault, the voltage level overshoots the pre-fault value and then dies away quickly in an oscillatory fashion.

When SCIG wind turbines were connected however, the voltage dip went as low as 0.45p.u. of its nominal value, before the generator was stabilized which occurred after 6,5 seconds (10s - 3,5s). It then fell to a voltage level of about 0.95% of its nominal value.

There are two things worth noting in these results. Firstly, the voltage dip seems to be more for a SCIG (0.45p.u) than it was for a DFIG (0.75p.u). This is due to the reduction in active power transmitted across the lines which causes the voltage at the generator connection point to be reduced. Once the fault is cleared, the active power supplied by the turbines through the transmission lines will increase and jump

Secondly, the voltage recovery time for a DFIG (1.5s) is shorter than that of a SCIG (6.5s). This is mostly as a result of the power electronic converters incorporated into a DFIG which enhance its performance during a grid disturbance and thus making it the preferred turbine choice. The voltage levels of the SCIG machine remain within the acceptable levels but may deteriorate should there be an increase in penetration levels.

It must be noted however that only 20MW of wind capacity was used during this analysis as the software could not incorporate more DFIGs on the network due to limitations in the modeling complexity of the controls and other components of the DFIG. So, to allow for a fair comparison, 20MW of both DFIG and SCIG had to be compared. These results do not therefore give an exact analysis of the proposed 100 MW Cape West coast wind farm; they only serve to highlight a trend that we should expect should we choose either of these technologies.

9.3 Impact of Grid Strength on Voltage Recovery

As discussed earlier, the strength of the grid seems to have an impact on the impact of wind turbines connected to the grid. Weak grids are often characterized by long transmission lines which are far from the loads and these have typically low fault levels (or grid impedance ratios, normally expressed as X/R ratios). The reactance of the transmission line was verified around the typical ranges from 0.05 to 0.436 ohms/km, whilst keeping the resistive impedance of the line very constant and minimal at 0.095ohms/km so as to reduce I^2R losses.

To provide clarity on the impact of wind turbines on the network, 20 MW of SCIG was connected in this analysis and a 3-phase fault with duration of 100ms applied at 3.5 seconds (arbitrarily). The following results shown in Figure 9.3 were obtained.

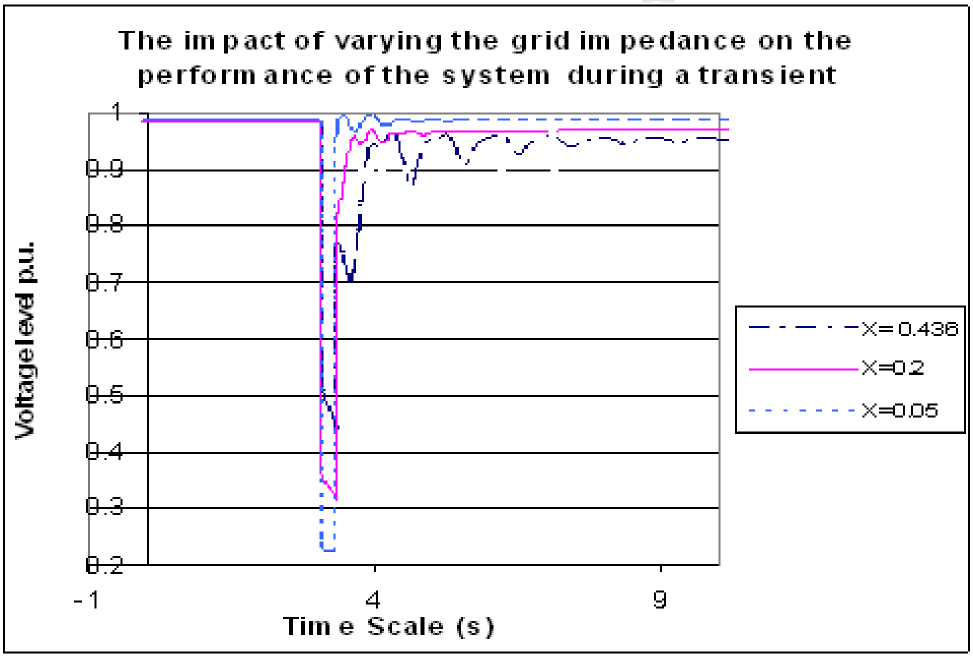

Figure 9.3 Impact of grid strength on voltage recovery of a SCIG

The results in Figure 9.3 show that as one reduces the reactance of the transmission line, the systems voltage recovery of the generator at the point of common connection gradually improves. Since the reactance of the transmission line increases with disctance, ideally one would like to get a lower reactance values so as to have a lower voltage drop across the line. When x = 0.436ohms/km, the voltage profile takes over 6 seconds to recover to its steady volatge level. More so, the voltage profile after the fault has been cleared showed some marked oscillations which eventually died away and returns to a voltage level of about 0.95p.u, with a 5% decrease from the nominal voltage at the connection point of the turbines.

As you gradually reduce the line reactance to about 0.05ohms/km, the duration of the voltage recovery and the oscillations are reduced, such that the generators reach a stable voltage of about 0.99p.u in a shorter period of time, about one second. Also, the magnitude and duration of the oscillations of the voltage profile of the machine after the fault is cleared become more prominent when the reactance is increased, which is a characteristic of relatively weaker grid systems. This could be attributed to the first swing characteristic of a machine which is prolonged in a weaker grid system which has higher reactances resutling from the long transmission lines which further contribute to the overall network reactance.

The strength of the grid can be described by the expression [3], $P = \frac{E_1 E_2}{X} Sin\alpha$, where E_1 is the voltage at source side, E_2 is the voltage at the load side, α is the power angle and X is the reactance of the line. The lower values of the reactance will allow maximum power transfer capabilities from the wind farm to the rest of the grid [86]. Thus the lower line reactance means that part of the grid is relatively stronger since it corresponds to higher fault levels and thus reduces minimal power quality or stability impacts emanating from grid disturbances. This is of particular interest since it guides the wind farm developers on where to locate their turbines on the network. Should should they be located at the weaker points on the grid, they can then take some counter measures to mitigate the impacts of weak grid on the turbines.

9.4 Impact of Reactive Power Compensation on Voltage Recovery

Possible solutions would include the installation of dynamic reactive compensators (e.g. an SVC unit) or a voltage source controller (VSC) on the generators (see Appendix A3) for continuous voltage control. This would improve the voltage stability and allow for the possibility of a wind capacity increase [76]. In this investigation, a standard IEEE voltage controller model (vco_IEEET2) found in DigSilent library was installed on each generator in order to improve the voltage recovery of the generators connected to a weak grid system.

The following modified results presented in figure 9.4 were attained:

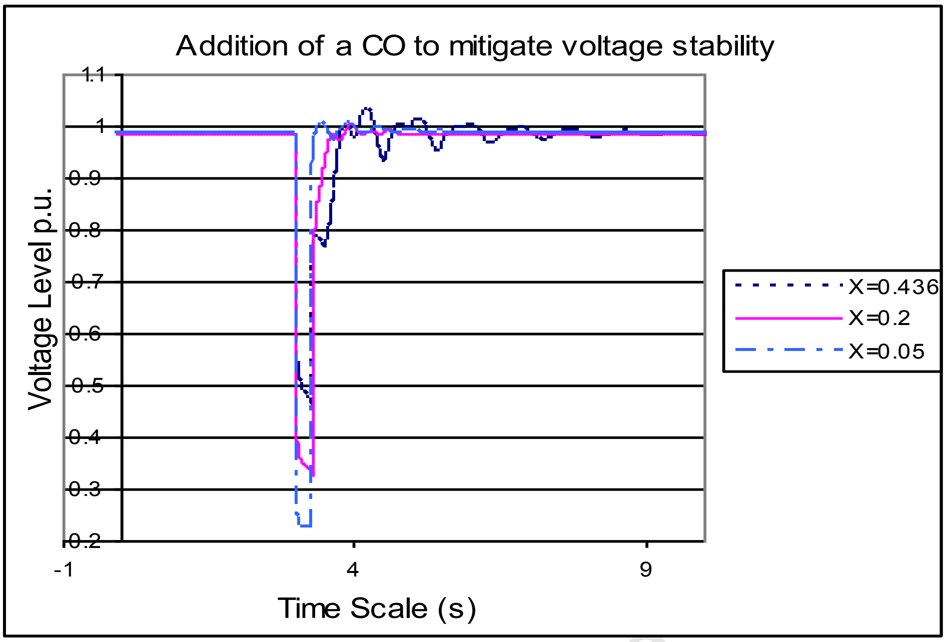

Figure 9.4 Addition of voltage controllers to improve the stability of the SCIG

Figure 9.4 shows a steady improvement in the duration at which the nominal voltage was recoverd after the fault was cleared. As compared to the more than 10 seconds it took for the voltage of the generator connection point to recover for a weaker grid system (resulting from higher reactance of 0.436p.u.), the addition of the voltage controller model to the generator improved the recovery time slightly by 2 seconds. Even though this may not seem like much, it is quite a significant duration in power systems analysis as seen in section 9.1 where the fault duration does have an impact on the stability of the generators.

The voltage level to which the generators recovered after the disturbance was cleared, was about 0.99p.u of its pre-fault value as compared to about 0.95p.u. when there was no voltage controller connected. Therefore in this case, it may not have been necessary in terms of nominal voltage recovery to add a VCO since 0.95p.u. was still within the acceptable voltage level limits, but for sake of this investigation, it was meant to show the impact of VCO on the network., which is typically to return the voltage level of the generator to its pre-fault value.

10 GRID INTERGRATION REQUIREMENTS FOR WIND ENERGY IN SOUTH AFRICA

This chapter seeks to provide an insight into some of the requirements that are to be recommended as guidelines for the integration of wind power into the South Africa network. Most of these recommendations are based on the review of grid codes and wind integration requirements from other countries but some of the findings from the investigations were carried out in this thesis.

The simulation study was limited only to a small section of the Eskom network which may not reflect the requirements of the overall grid. These recommended requirements do not specify any specific permissible values as they are aimed at giving an idea about which technical issues should be considered (low and high priority) in the wind integration grid code.

10.1 Technical Requirements

10.1.1 Wind Power Penetration Limits

As previously mentioned, the penetration levels may refer to the total amount of wind power installed in relation to the peak load in that region [8]. However, in other areas, the capacity is specified with regard to the capacity of the transformers and transmission lines or cables that are used as well as the thermal limits of the system [31].

Based on investigations carried out in this thesis, the author recommends that the penetration level of wind that can be connected to the grid at a particular substation or point should be based on the following characteristics:

10.1.1.1 Transformer Loading (Transformer Rating)

The author has resolved that as long as 100% loading on the transformer is not exceeded, the penetration levels can still be improved, as shown by the studies in the investigations. However, seeing that some of the parameters used in the simulations were not refecting the actual characteristics on the real network, a figure lower than that may need to be recommended (e.g. between 80 - 90%). This will also depend on the other loads that are being fed from this transformer.

10.1.1.2 Line Loading (Thermal Rating)

Even though the % loading of the line tends to increase as the penetrations are raised, the increments are generally lower and not so pronounced. The standard conductors used by Eskom in their transmission and distribution line would be applicable. Though the thermal limits of the line should be determined, they are not as high a priority compared to the other characteristics that determine the penetration levels.

10.1.1.3 Voltage Levels

Based on the findings from the studies carried out, the penetration levels seem to have a marked effect on the voltage levels at the point of common connection. The voltage levels at the point of common connection should be kept within the permissible limits and in this case, the author has considered ±5% of the nominal voltage as the allowable limits. The amount wind power that can therefore be connected on the network would be limited by the voltage levels at the connection point.

10.1.1.4 Short circuit Power Level (or Fault Levels)

The relative strength of the grid has also shown to be essential in determining the amount of wind power that can be connected to the network. The discrepancy can be shown by the higher penetration levels in stronger parts of the grid as compared to lower penetration levels on the weaker networks.

Also, based on the findings from the studies, the increase in fault levels as a result of increased penetration levels of wind power was found to be minimal and thus would not put a high priority on the formulation of grid codes for wind power. However, with a higher potential of wind power anticipated in the future, this requirement may need to be addressed to ensure that fault level contributions resulting from the wind injection will not compromise the operation of the circuit breakers, switch-gears and other equipment on the network (i.e. the fault levels should not exceed the ratings of the equipment as they will cause it to malfunction, thus compromising their protection capability on the grid), as previously established.

All these characteristics must be considered in order to attain the required penetration level for wind power on the network.

10.1.2 Voltage Levels for Wind Connection

Since the higher wind concentration areas are on the coast, the voltage levels for the closest places to the wind farms are most likely to be the 66 kV and 132 kV [85]. It seems that most of the potential wind power installation would be closer to the medium voltage distribution networks, with a few on the higher voltage substations.

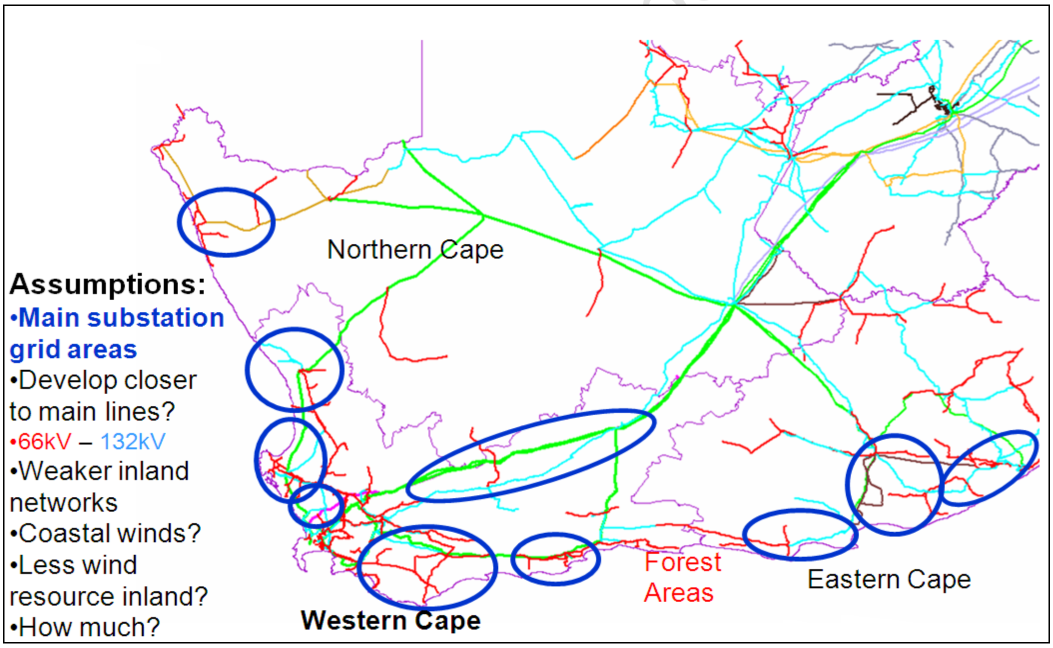

Figure 10.1Voltage levels at the high wind penetration level points [1]

10.1.3 Reactive Power Control Requirements

The studies have shown that the reactive power compensation capability of the wind turbines is essential in ensuring that the voltage levels are kept within acceptable limits. This can be used as a determining factor in the choice of wind turbines to be used. Modern wind technologies such as DFIGs and full converter driven wind turbines would be recommended since they provide reactive power control to the network as opposed to SCIG.

Based on the findings from the studies performed in this thesis, reactive power control on the network is very significant and should be considered in the future development of the grid codes.

10.1.4 Fault Ride Through Capability

As mentioned previously, the fault ride through requirements are a characteristic of modern grid codes for wind integration, largely in the leading wind energy industries with higher penetration levels (Germany, Denmark, Spain, USA etc.). Having analysed the history and literature on the development of grid codes [11], [23], the fault ride through capability is critically considered in areas where the wind penetration is very high. It contributes significantly to the overall control of the stability of the network, especially in the interconnection system in countries like Germany, Ireland, Denmark and other European countries.

For South Africa, this requirement is not a priority due to the fact that the influx of wind power is minimal (currently less than 0.01% of the overall grid capacity). Wind turbines would be expected to trip should there be a fault on the network as there are too few to provide grid support. However, this requirement may need to be enforced when the concentration levels reach about 1% (about 400MW) even though this would still be a lower figure.

However using the rule of thumb, since the Western region has the most potential for wind energy resources (up to about 3 000MW potential), this can be seen as over 50% of the total capacity of the region (±4 000 MW) and would require the ride-through capability to be enforced.

The author does not consider the fault ride through capability a high priority in developing the current grid code and therefore recommends that it be addressed when penetration levels reach about 400 MW or above.

10.2 Power Quality Requirements

Based on the findings from the literature, the current wind turbine technologies being manufactured have power electronic converters that are able to mitigate the impact of wind turbines on the power quality of the grid. However, studies have shown that the higher penetration levels as well as the strength of the grid may influence the power quality impacts.

The following sections discuss the power quality requirements which the author considers to be significant for the future development of the wind integration grid code.

- Voltage Limits (Voltage Variations)
- Harmonic Requirements
- Flicker Requirements

The author proposes that the grid codes be reviewed when the wind power penetration levels in South Africa reach 1% so include all the possible issues that could result from the increased penetration levels.

11 CONCLUSIONS AND RECOMMENDATIONS

The following conclusions have been drawn from the investigations:

11.1 Technical Considerations

- **Grid Codes** - The current South African grid code does not cater for wind power integration. Though wind energy is still in its infancy in the country, there is huge potential of increased wind power penetration levels in future and therefore grid codes may need to be addressed so that they can also cater for wind power plants.
- **Fault level contribution** – It has been concluded that the fault current level that will flow as a result of connection of the wind farm is very minimal and would be insignificant in the overall fault current flowing through the network. However, with an anticipated future increase in penetration levels of wind power resulting from the grid's capability to contain over 5 GW of wind power, wind farms are most likely to be spread across the grid, regardless of the grid strength and therefore this may have a significant influence on the fault levels and thus the protection coordination of the system components. The fault level determines the grid strength and has an influence on the power quality issues as they become more prominent in relatively weaker grid systems. However, the proposed Juno wind farm is connected at a stronger part of the grid and therefore would not be influenced much by the power quality problems
- **Wind turbine choice** – As expected, the DFIG has shown to be the better technology than the SCIG in terms of technical compliancy with the requirements as well as operational capability. Its ability to perform reactive power compensation without the external capacitor bank requirements make it favourable to be used in the proposed Cape coast wind farm. The modelling and performance aspects of this type of generators are not readily available in commercial software tools as this data is deemed confidential by the manufacturers.

11.2 Power Quality

Considering the results presented in this thesis, there were very minimal power quality problems that were identified during the investigation of the influence of the proposed 100MW Cape West Coast Wind Farm on the Eskom network.

- Voltage variations
  - Minimum voltage variation impacts were observed during the analysis. This as expected was as a result of the stronger grid point to which the wind farm would be connected
- Harmonics
  - There was very limited harmonic distortion observed on the network. The 100MW DFIG wind farm would comfortably make an insignificant harmonic contribution into the grid to which it is connected.
  - Similar work done on this subject has also shown that the current developments in wind turbine technology have resulted in power electronic converters that actually aid in mitigating harmonic distortions on the grid, instead of introducing them. These harmonic distortions are not really a cause for concern at this stage with the current converter driven technologies being manufactured.
  - Should there be harmonic currents contributed by the PMW converters of the DFIGs, these would be significantly reduced by using a harmonic filter.
  - A very general and simplified single-tuned filter design has been used in mitigation of the harmonic distortions resulting from the 200MW of DFIG. However, a far more detailed design of different filters could have been presented to validate the impact of filters on harmonic distortion reductions and make the results more authentic.

- The strength of the grid has an influence on the power quality issues as they become more prominent in relatively weaker grid systems. However, the proposed Juno Wind Farm is connected at a stronger part of the grid and therefore would not be influenced much by the power quality problems

- Reactive power control in a wind turbine is essential as this has a direct impact on the voltage quality of the network. The DFIG seems to perform better in this respect and therefore would be highly favourable in high wind penetration projects.

Based on the overall findings from the investigations, the proposed 100MW wind farm could feasibly be connected to the grid without adversely affecting the operation of the grid.

11.3 Recommendations for Future Work

Based on the understanding of the model development and during the analysis of simulation results attained during the investigation, the following recommendations for future work have been suggested:

- A separate guideline that specifies the technical requirements needed to connect wind power in South Africa needs to be reviewed and formalized so that future wind farm penetrations do not adversely affect the grid operational dynamics.
- Detailed dynamic studies have not been fully investigated in this thesis and therefore actual wind speed models are not included. In order to accurately investigate the interaction between the wind turbines and the grid, new and improved models including all the features of wind turbines may need to be modeled. It is recommended that an actual wind model be implemented in the grid so as to assess the real time impact of wind speed on the power fluctuations on the network. To do this, the DSL language needs to be studied further as well as the scripting of the actual control parameters.
- To fully investigate the impact of the wind farm on the South African network, it would be important to negotiate to get the DIgSILENT single-line diagrams of specific regions from Eskom, notably the Western Cape which has high wind penetration. This data will assist in giving a more effective and detailed analysis of the impact the wind energy will have in the local conditions
- Modern wind turbine technologies, mainly the variable speed turbines which are converter driven, will become the commonly used turbines in future owing to the power electronic advancement. These have been designed to mitigate power quality

issues and therefore may not be a need to address these power quality concerns when developing future wind farms.

- Some of the models used in this thesis were generic and a number of assumptions were made during the modeling since the actual modelling and performance aspects of these components are not readily available in commercial software tools. An improvement in the model accuracy is recommended for future work. For instance, in modeling the wind turbines, the tower shadow effects, wind models, controls and the aerodynamic models in DIgSILENT library were used instead of the actual specifications from the manufacturers.

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APPENDIX A1

A1.1 List of author's publications

Some of the results from my research project have been presented and included in the following conferences proceedings and publications:

1. Standards and Technical Guidelines for the Interconnection of Renewable Energy Sources into the Grid - IEEE PES PowerAfrica Conference, Johannesburg (2007)

2. Issues Related to Integration of Renewable Energy into the Grid – South African Universities Power Engineering Conference (SAUPEC), Durban (2008)

3. Power Quality of Grid Connected Wind Farms - International Association of Science and Technology for Development (IASTED) Conference on Power and Energy Systems (PES), Botswana (2008)

4. Power Quality of Grid Connected Wind Turbines – Harmonic Investigation: South African Universities Power Engineering Conference (SAUPEC), Stellenbosch (2009)

APPENDIX A2 – JUNO WIND FARM MODEL DATA RECEIVED FROM ESKOM (RIAAN SMIT)

A2.1 Report Summary – Meeting with Eskom Representative to Evaluate the Grid Model (Mr Riaan Smit)

Proposed questions for discussion with Riaan Smith

- Current projections of wind energy capacity. What are the different scenarios that you can come up with? Make recommendations in terms of expected changes in the regulations. Your recommendations should have a basis.
- Is there a fundamental guideline in South Africa? If so, what does it constitute of?
- What connection regulations were following in connecting Klipheuwel Wind Farm was? From that fundamental regulation, what can be discarded and based on what?
- What are the power quality issues that have been experienced at the Klipheuwel Wind farm? From the different types of wing turbine technologies?
- With the 100MW wind farm, what is the most likely average rating of the wind farm in that area, given that the wind speed is varying and what is the capacity factor at that site?
- What would be the % penetration level of the proposed Juno Wind Farm as compared to the local load?

  .

Outcome from the discussions

With regards to how the Klipheuwel Wind Farm was connected, a basic procedure was followed. Fig 1 shows the basic connection of the wind turbines at Klipheuwel wind farm to the grid. The interconnection is at the 11kV busbar.

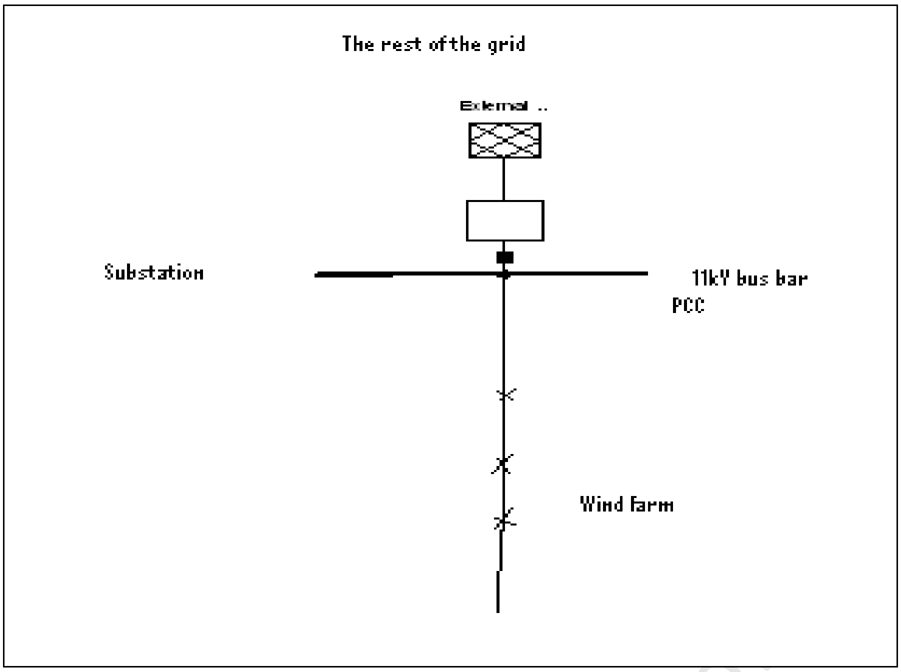


Figure A1: Basic diagram showing the interconnection of the wind turbines at Klipheuwel

The issues that they took into consideration were as follows:

- **Fault level contribution** by the wind turbines at the point of common connection. The wind farm contributed very minimal fault levels to the grid as compared to the external grid. This is expected considering that the % penetration of these wind turbines as compared to the total capacity is very minimal (less than ±0.01% if you consider that the wind farm has a total capacity of 3.2MW as compared to the grid capacity of about ±36 000MW)
- **Thermal effect** of the conductor to determine the size and type of conductor to use. The thermal rating designs on the conductors were done to see verify the suitable conductor type and size that would be able to cope with the ratings of the wind farm (3.2MW).
- Since the wind turbines where interconnected to the grid through a motor starting effect, some of the reactive power absorbed by the turbines had to be determined (which may affect the fault level through drawing of VARs)
- **Flicker measurements** were done on the network and at the point of connection using flicker-meters before and after the wind turbines were connected and results showed a very insignificant deviation from the two graph (i.e. there was no difference between the flicker measurements of flicker before and after the wind turbines were connected).

- **Harmonic measurements** were performed and the findings showed that there was also no significant difference between before and after readings
- **Tests were done to determine the impact of this wind farm on the voltage levels of the network** and these were also found to be very minimal. Again as expected, the voltage levels are mainly controlled by the grid and therefore the very minimal contribution of capacity by the wind farm does not have any conspicuous effects on the voltage levels of the grid.

- According to the current discussions that the author has had with Eskom, the regulations that would be used to connect the proposed Juno Wind Farm to the grid are not yet finalized.

While wind turbines are most commonly classified by their rated power at a certain rated wind speed, annual energy output is actually a more important measure for evaluating a wind turbine's value at a given site [7]. Expected energy output per year can be reliably calculated when the wind turbine's *capacity factor* at a given average annual wind speed is known [19]. The capacity factor is simply the wind turbine's actual energy output for the year divided by the energy output if the machine operated at its rated power output for the entire year [19]. A reasonable capacity factor would be 0.25 to 0.30. A very good capacity factor would be 0.40 [19].

- The capacity factor of the Cape west coast area where the wind farm is going to be cited is about 25% on average. This means that we would expect about 25% of the energy output from the wind turbines energy operating at its rated power output.

  - With regards to the common mix of expected mix of the wind energy technologies, Eskom has no plans of having a mix as they want to have a specific type of manufacturer and technology so as to allow for easy maintenance and lower costs associated with bulk purchasing. Also the fact that 100MW capacity is very minimal as compared to the total grid capacity may lead very minimum impacts on stability therefore a mix may not be relevant.

Here is the list of data I had requested:

- Line parameters – R and B values

- Transformer data – got the MVA ratings of the transformers that are currently on that part system
- Feeder and busbar data
- Turbine models and data – NONE

The DigSilent models/files were not obtainable as the information is regarded as confidential. However, the summarized schematic of the network around that area, the West Coast grid in Koekenaap is similar to the one given below.

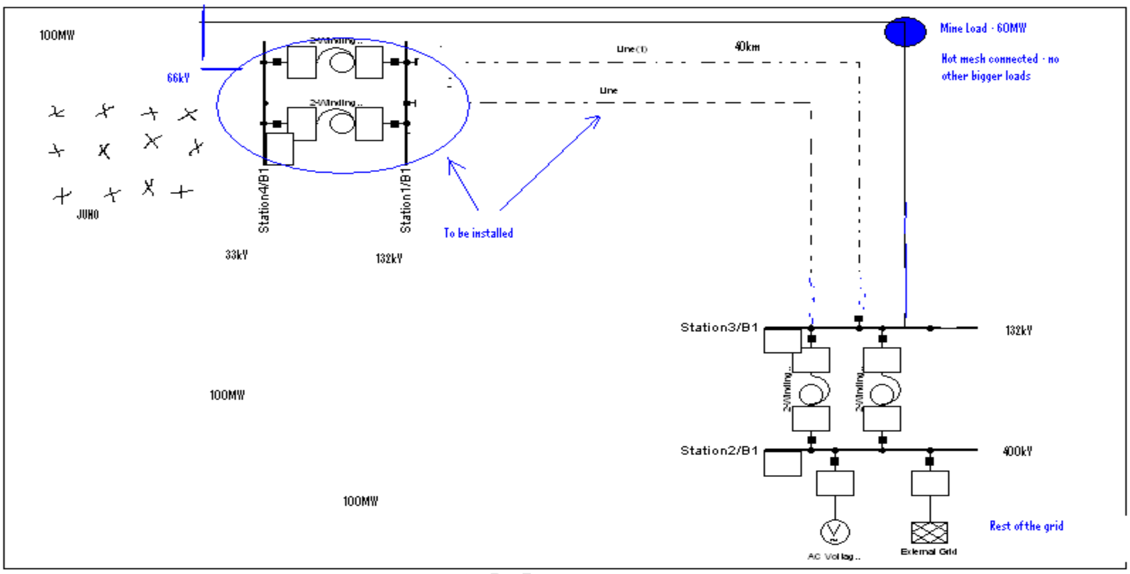


Figure A2: The proposed Juno Wind Farm in the West coast and its connection to the grid

At the bottom left of the Figure A1, we see the rest of the grid being connected to the 400kV busbar which in turn is stepped down to 132kV by 2*120MVA transformers. That busbar is the one that feeds the external loads, which in this case the biggest load is the mine (to verify name) which is the biggest load. Total load on that busbar is about 60MW. The dotted line shows of the possible connection options of the wind farm to the 132kV busbar which is about 40km away. With this option, the point of connection of the wind farm is on the 33kV substation that will need to be erected. Eventually this may look as follows:

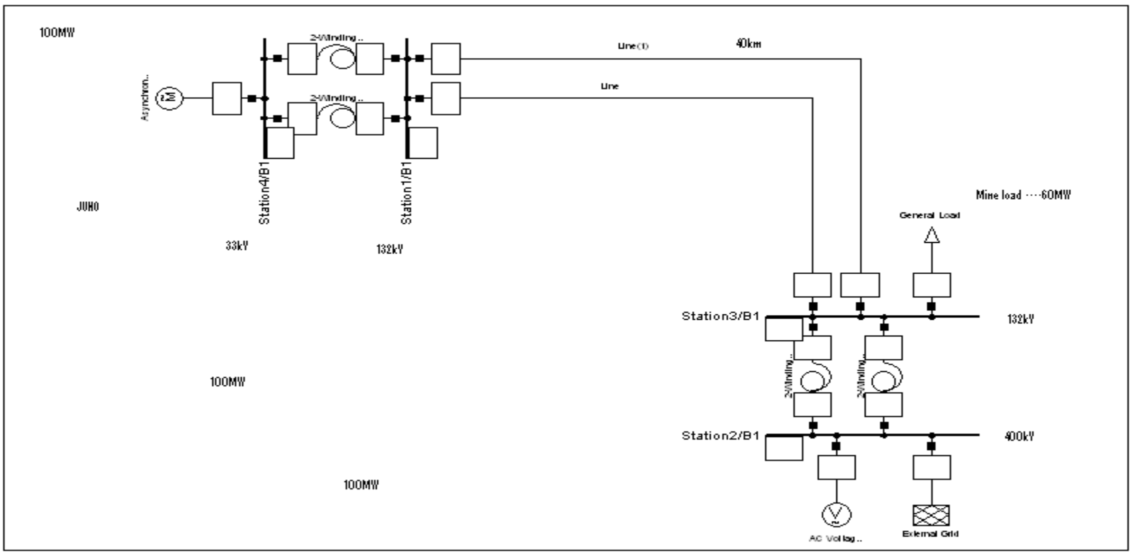


Figure A3: Rough schematic of the connected wind farm in the West Coast.

From this preliminary modeling, the following schematic model was recommended by Eskom:

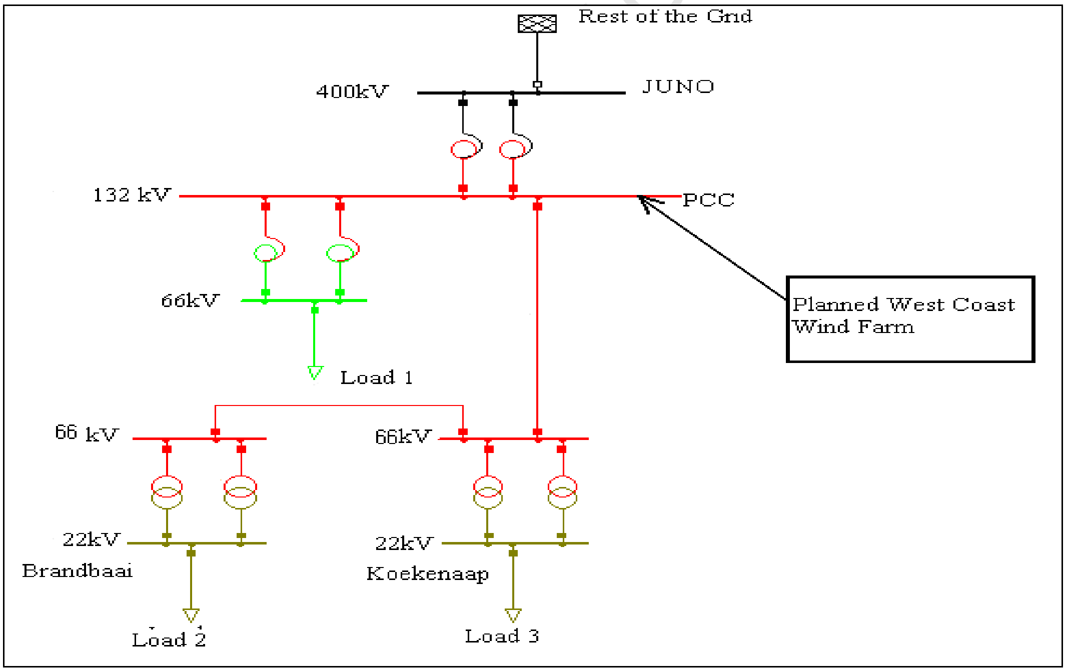


Figure A4: Proposed schematic for wind farm model (established from existing network)

A. Actual modeling parameters used:

Use 400kV as your source bus:

Expected 3-phase fault level: 9kA -80.2 degrees (currently maybe in order of 5-6kA)

Expected SLG: 4.5kA -75 degrees

R1 = 0.0030 ohm

X1 0.0174

R0=0.0220

X0=0.0692

B. Transformers

- Then use 2x120 MVA 400/132kV transformers with impedance of 12.2% each.
- Assume zero seq. impedance as about 90% as for Pos seq.
- Assume tap data of +-8 taps from mid tap position at tap 9b.
    - Allow for tap step size of 0.94% per step.
- You may also test 500MVA trfrs for different scenarios, and then use transformers impedance of about 14.69% and 14.345% respectively. Allow for 5% buck and 15% boost at 16 steps of 1.25% per step.

C. Proposed transmission lines between Wind Farm and PCC at 132kV

- Use 1 or 2 or 3 132kV transmission lines for different scenarios
- The transmission line type that was recommended by Eskom to be used for simulations was the Kingbird conductor with following impedance as per line design. These line types and values were change for different scenarios during the modeling so as to find the suitable conductor parameters
    - :R1=0.09503 ohm/km
    - X1=0.35143
    - B1=0.30437 microS/km
    - R0=0.30434 ohm/km
    - X0=1.04952
    - B0=0.64398 microS/km
    - Length = 40km, may change once substation site etc, finalized.
- Other transmission lines used in this thesis include
    - Hare
    - Bare
    - Copper

D. Proposed Transformers to be connected (Wind Farm Side)

- Use 1/2/3 80MVA 132/33kV transformers for scenarios ranging up to 200MW:
- Prefer transformer impedance of 11.2% and assume zero sequence impedance of 90% of positive sequence value.
- Use tap data of 16 steps of 1.25% per step, with 5% buck and 15% boost.
- No other local loads on the 33kV busbar.

E. Earthing

- Use a NECRT to earth 33kV side.
- These values needs to be checked properly, but the following were used at the moment:

  R0=81.298 ohm

  X0=35.6973

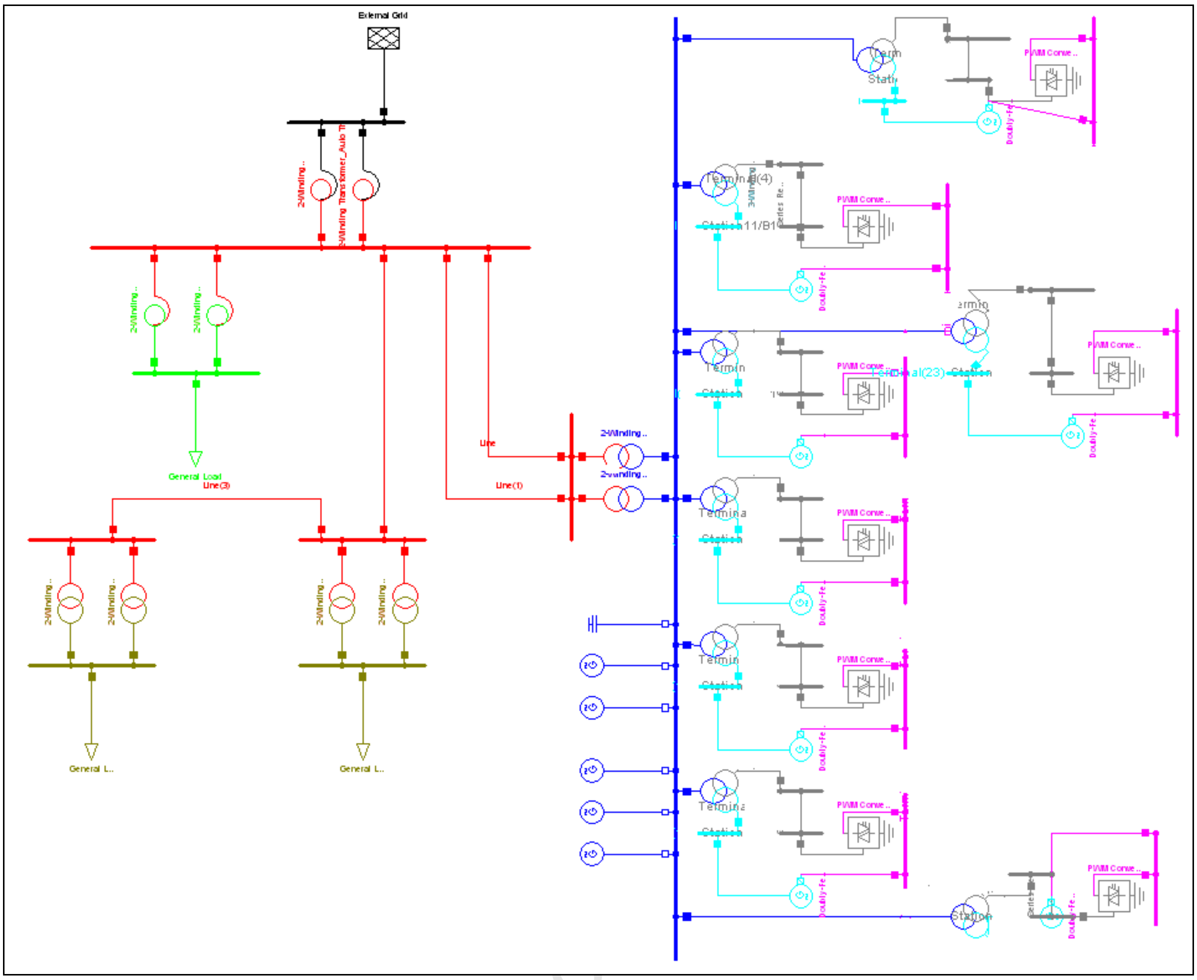
F. Loads

- Use various load scenarios from auxiliary load of say 5kW per turbine to full generation of say 2MW per turbine.
  - L1 –
  - L2 –
  - L3 –

G. Wind Farm design

- Wind Farm design not available, therefore no idea of type of WTG to be installed or detail on 33kV cabling.
- Such cabling to vary in size from say 95 to 400 sq mm Aluminium, depending on feeder length, layout, optimization etc.

A typical 2MW DFIG wind turbine generator was recommended by Eskom for the proposed wind farm, hence most of the studies entailed in this thesis involved the DFIG.

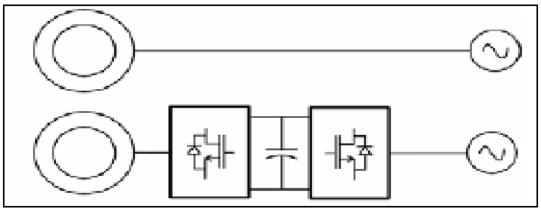


West Coast Wind Farm HV Network (with DFIGs connected for Harmonic Analysis

DFIG: GEN 2 MW		
Active Power		2 MW
Reactive Power		-1.6MVar
Power Factor		0.8
Efficiency		98%
Rated Voltage		33 kV
No of Pole Pairs		2
RMS/EMT-SIMULATION	Input Mode	Electrical Parameter
	Inertia	0.402s
	Ilr/In	4.6 p.u.
	Locked Rotor Torque	0.117 p.u.
	Torque at Stalling Point	2.122 p.u.
	Magnetising Reactance	2.31 p.u.
	Rotor Resistance	0.0506 p.u
	Rotor Reactance	0.12p.u
	Stator Reactance	0.03p.u.
	Stator Resistance	0. 0071p.u.

SCIG: GEN 2 MW		
Active Power		2 MW
Reactive Power		-1.6MVar
Power Factor		0.8
Efficiency		98%
Rated Voltage		33 kV
No of Pole Pairs		2
RMS/EMT-SIMULATION	Input Mode	Electrical Parameter
	Inertia	0.400
	Ilr/In	4.6 p.u.
	Locked Rotor Torque	0.117 p.u.
	Torque at Stalling Point	2.122 p.u.
	Magnetising Reactance	2.48 p.u.
	Rotor Resistance	0.012 p.u
	Rotor Reactance	0.12p.u
	Stator Reactance	0.098p.u.
	Stator Resistance	0. 013p.u.

PWM Controller Settings	
Rated Power	**3 MVA**
Rated AC voltage	**0.704**
Control mode	V_{dc}-Q
Reactive power Setpoint	
DC Voltage Setpoint	1.15 p.u
Reactive power Setpoint	-0.1 MVar
Reactive power limits	-1MVAR to 3 MVar



Generator with and without a voltage source converter [22]

Transmission Line Parameters

Juno Line_Type	
Length	80 km
Rated AC voltage	132
Resistance	0.09503 Ohn/km
Reactance	0.3514 Ohm/km
Susceptance	0.3043uS/km

APPENDIX A3 – KLIPHEUWEL WIND FARM DATA

Table A1: Data for wind turbines connected at Klipheuwel Wind Farm

	Klipheuwel Wind Turbine Data		
Owner: ***Eskom Resources & Strategy***		**Purpose:** ***Research & Demonstration***	
Location: *Klipheuwel, 15 km north of Durbanville, close to Slent Rd crossing with Stellenbosch-Malmesbury Rd*			
Unit **Rated Power**	**Vestas V66** **1.75 MW**	**Vestas V47** **660 kW**	**Jeumont J48** **750 kW**
Rotor			
Diameter	66 m	47 m	48 m
Blade Number x Length	3 x 32 m	3 x 23 m	3 x 23 m
Swept area	3 421 m^2	1 735 m^2	1 810 m^2
Speed revolution	21.3 rpm	28.5 rpm	Variable
Operational interval	10.5 - 24.5 rpm	28.5 - 30 rpm	7-26 rpm
Tip speed	130.6 - <u>265</u> - 305 km/h	<u>252.5</u> - 265.8 km/h	63 - 235 km/h
Rotor orientation	Horizontal, face wind	Horizontal, face wind	Horizontal, face wind
Power regulation	Pitch/OptiSpeed™	Pitch/OptiSlip®	Stall Aerodynamic uncoupling
Air brake	Feathered	Feathered	Aerodynamic Tip-brake
Disc brake	Hydraulic controlled	Hydraulic controlled	Hydraulic controlled
Tower	*John Thompson - Bellville*	*Vestas Imported*	*Jeumont Imported*
Hub height (approx)	**<u>60</u>** (Other 67, 78 m)	**<u>40</u>** (Other 45, 50, 55 m)	46 m
Foundation (approx)	~ 500 ton	~ 240 ton	~ 450 ton
Operational data			
Cut-in wind speed	4 m/s (14.4 km/h) Self start	4 m/s *(self start at ave wind speed of ~4.5 m/s)*	3 m/s (10.8 km/h)
Nominal wind speed	16 m/s (57.6 km/h)	15 m/s (54 km/h)	13.5 m/s (48.6 km/h)
Stop wind speed	25 m/s (90 km/h)	25 m/s (90 km/h)	25 m/s (90 km/h)
Maximum 5 s gust	Class 1: 70 m/s (252 km/h)	Class 1: 70 m/s	Class 2: 55 m/s (198 km/h)
Generator			
Type	Asynchronous Induction Generator (radial flux cylindrical) with OptiSpeed™	Asynchronous Induction Generator (radial flux cylindrical) with OptiSlip®	Synchronous generator with permanent magnets, (axial flux discoidal) with IGBT electronic converter with vectorial control system
Nominal output	1750 kW	660 kW	750 kW
Operational data	50 Hz; 690 V	50 Hz; 690 V	50 Hz; 690 V (Grid)
Synchronous speed		1,515 - 1,650 rpm	900 V (Gen)
Gearbox			
Type	1 planet step	Planet/parallel axles	None (Direct - gearless)
	2-step parallel axle gears		
Control			
Type	Microprocessor - based monitoring of all turbine fuctions with the option of remote monitoring.	Microprocessor - based control of all turbine functions with the option of remote monitoring.	Microprocessor
	Output regulation and optimisation via OptiSpeed™ and OptiTip® pitch regulation.	OptiSlip® output regulation and OptiTip® pitch regulation of the blades.	IGBT electronic converter (with DC-bus)
Weight			
Tower <u>(hub height)</u>	<u>60 m</u> / 100 t (3 sections) *Various sizes available*	<u>40 m</u> / 32 t (2 sections) *Various sizes available*	<u>46 m</u> / 40 t (2 sections) *Various sizes available*
Nacelle	57 t	20.4 t	30 t
Rotor	23 t	7.2 t	9 t
Total	180 t	60 t	80 t
Additional info	***Khoebaha Sousoa***	***Krotoa***	***Khamisoa***
Sousa adopted Jan van Riebeeck as a son on 29 Sept 1660.	Father of the nation at the time of transformation (Last emporer of Hottentot lands)	Transformation Goddess Daughter of Wind Goddess	The Wind Goddess
Approximate cost	R18 million	R8 million	R12 million
Date Commissioned	**13-Dec-02**	**17-Aug-02**	**20-Feb-03**
Contractor / Tender	Vestas / Partners International Technologies		Intens Lesedi
Civil work by:	WBHO (also road)		Summit Projects
Installation by:	Vestas & Vanguard		Jeumont & Summit Projects
Crane from:	Johnson Cranes: 550 t	Target Cranes: 175 t	Ashley: 1000 t
www.sabregen.co.za	www.windpower.org	www.vestas.com	www.espace-eolien.fr
Source: Manufacturer data on Websites		Updated:	12 March 2003

APPENDIX A4

A4.1 Calculation of penetration levels

- Wind energy penetration – This considers the percentage of demand covered by the wind energy in a region, normally on an annual basis and is given by the following expression [5],

  Wind energy penetration (%) = Total amount of wind energy produced annually (MWh)/Gross annual energy demand(MWh)

  ………………………………………………………..(2.1) [5]

- Wind power capacity penetration levels which consider the total amount of installed wind power capacity in a certain region in relation to its peak load and is given by the following expression [5]:

$$\text{Wind power capacity penetration (\%)} = \frac{\text{Installed wind power capacity (MW)}}{\text{Peak load (MW)}}$$

A4. 2 Reactive Power in a Generator

The reactive power of a generator is determined by the terminal voltage and the generator internal voltages [7]. During the fault, the fault current is determined by the external reactance between the generator and the fault and the subtransient generator reactance. Thus, the product of the fault current and the terminal voltage give the reactive power generated at the terminals of the generator. The reactive power generated decreases as the fault continues as a result of the effective generator impedance changing from its subtransient value to its transient value. On clearing of the fault, the reactive power goes instantaneously to zero due to the reactive power requirements associated with the rotor angle and the generator internal angle, $Q = \frac{E \times V}{x} cos\theta - \frac{V^2}{x}$ [7]. In a similar fashion to that when the fault occurred, the reactive power decays as the reactance changes from the subtransient to transient.

APPENDIX A5

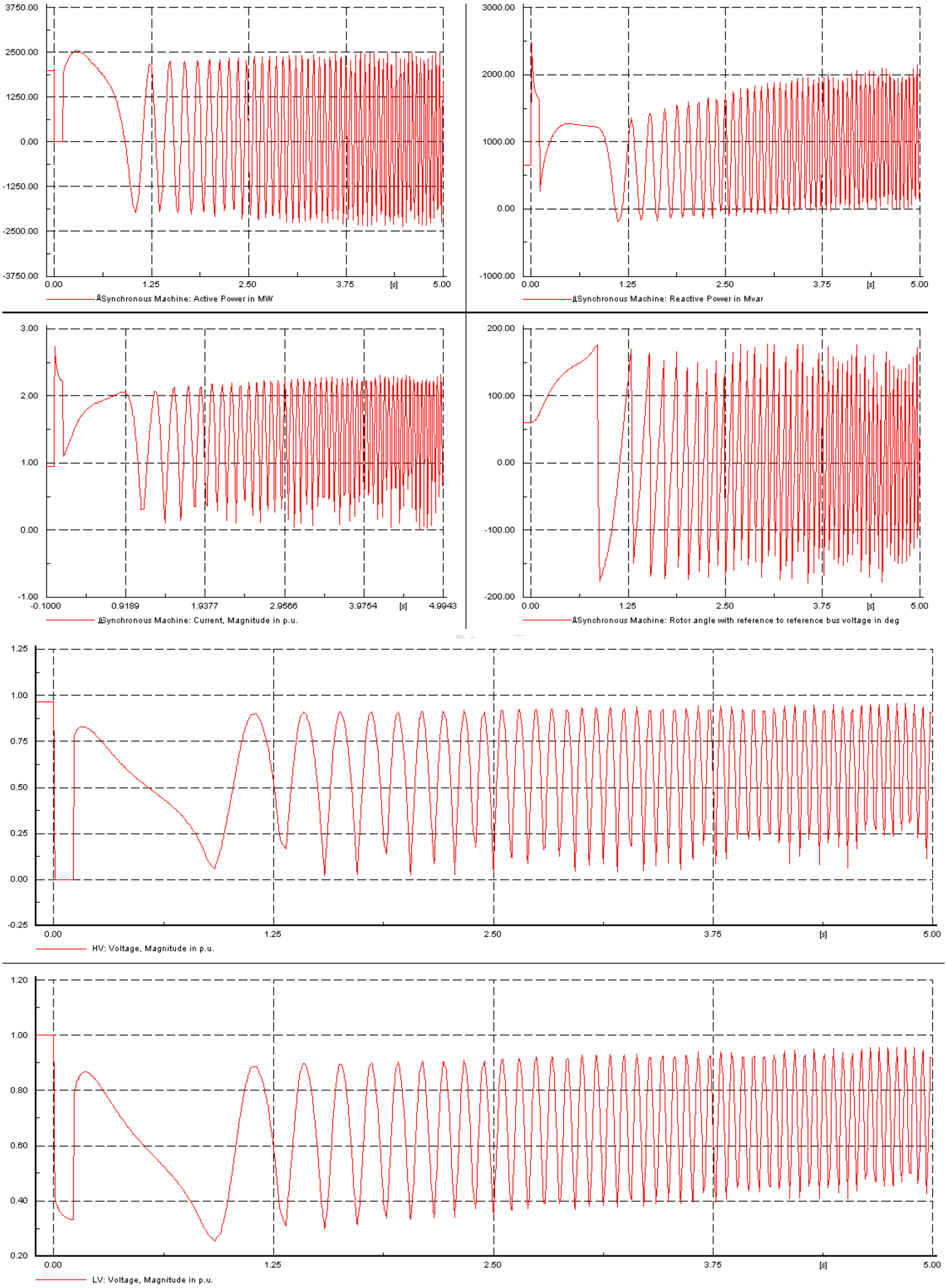


Figure A6 Plots for an unstable squirrel cage induction generator

Table A1 Impact of penetration levels on voltage level at PCC

Penetration level [MW]	Voltage level at PCC [kV] – (using SCIG)	Voltage level at PCC [kV] – (using DFIG)
0	129.84	129.84
20	128.77	130.88
40	127.71	131.98
80	124.96	133.93
100	123.1	134.78
150	113.58	136.31

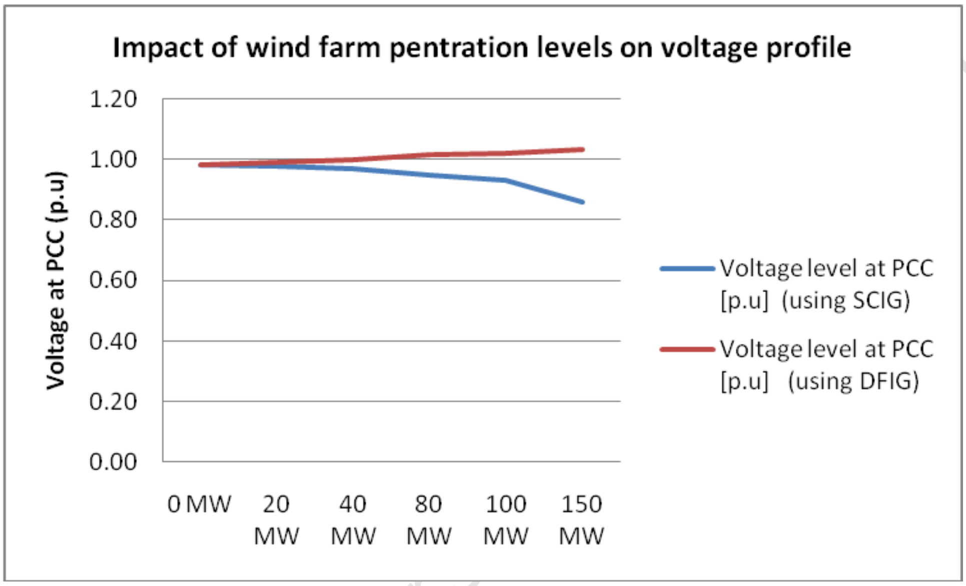


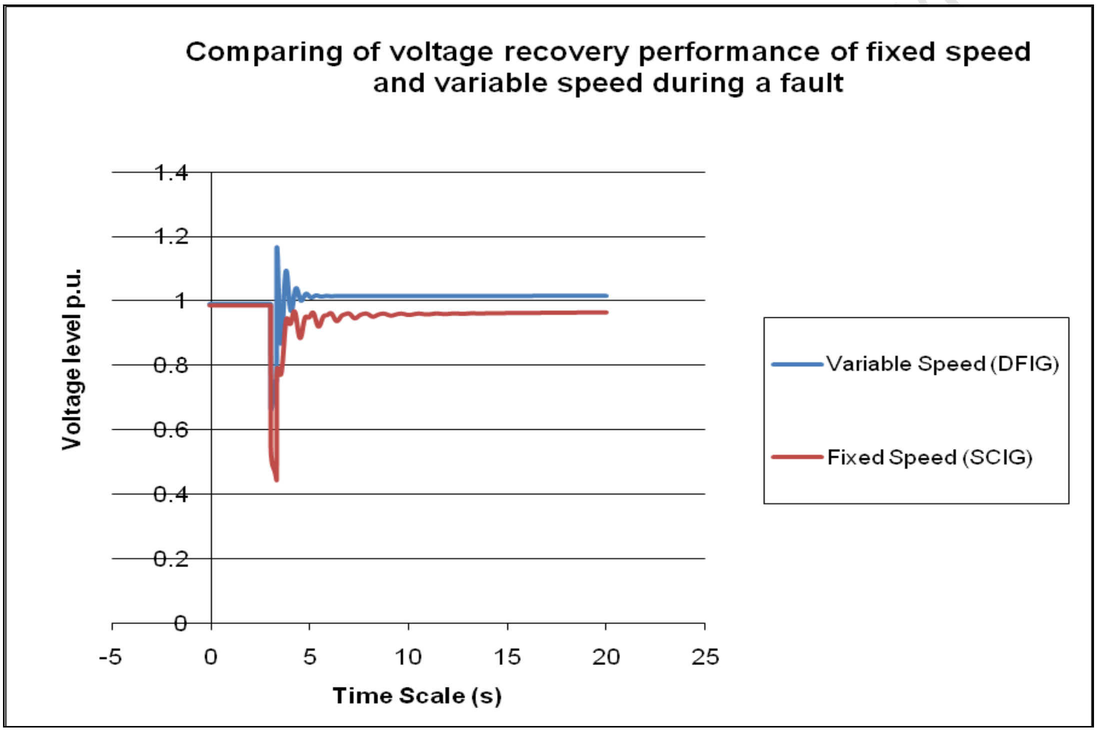
Figure A7

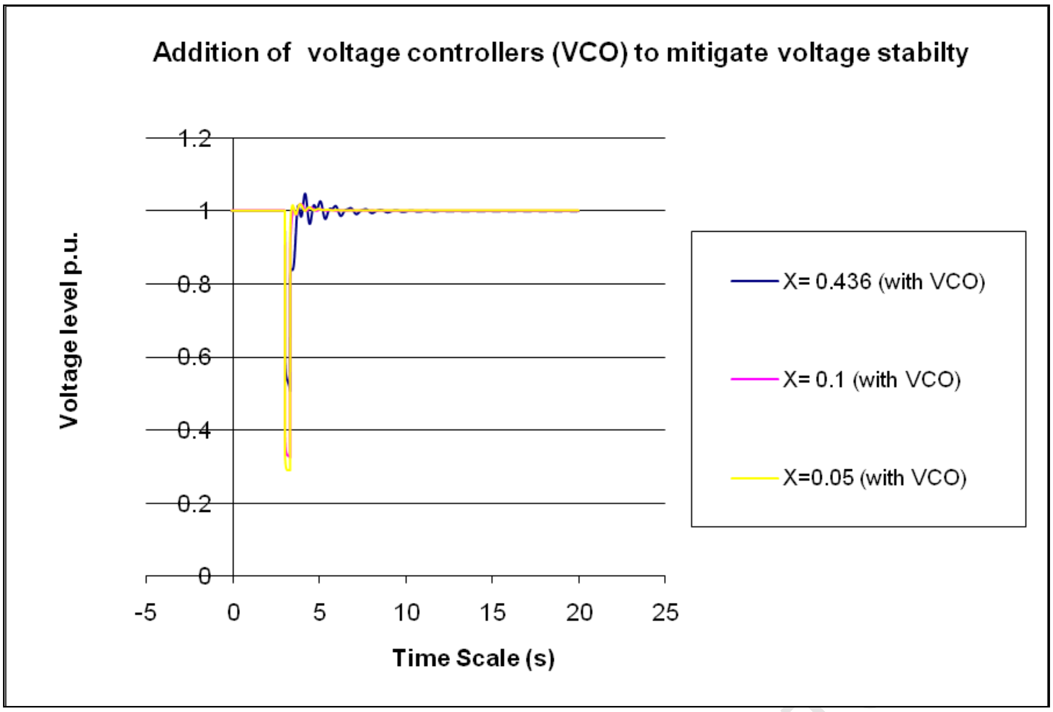
Table A7

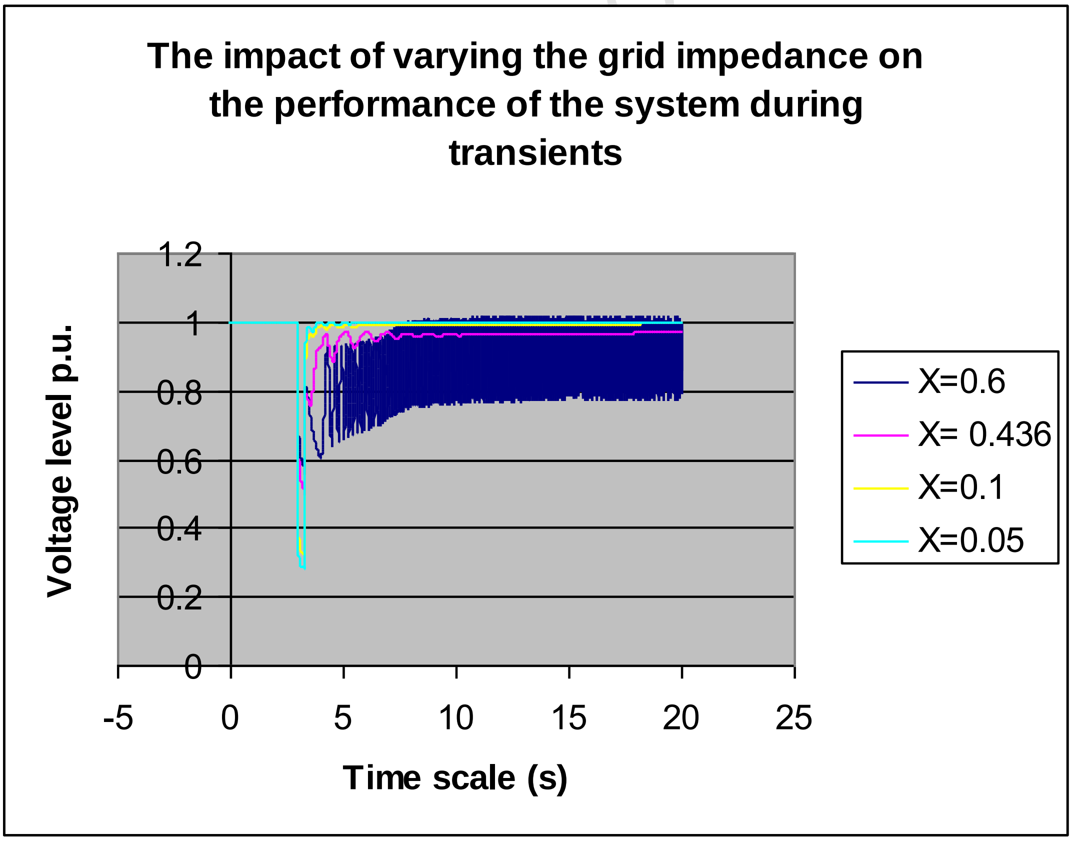
Using a SCIG (with capacitive compensation)			
Penetration level [MW]	Voltage level at proposed PCC (Fault-level = 1200 MVA)	Voltage level at B2 (Fault level = 450 MVA)	Voltage Level at B3 (Fault level = 750 MVA)
0 MW	0.99	0.96	0.98
20 MW	0.98	0.91	0.97
40 MW	0.98	0.87	0.96
50 MW	0.98	0.84	0.96
80 MW	0.96	0.80	0.93
100 MW	0.95	0.70	0.90

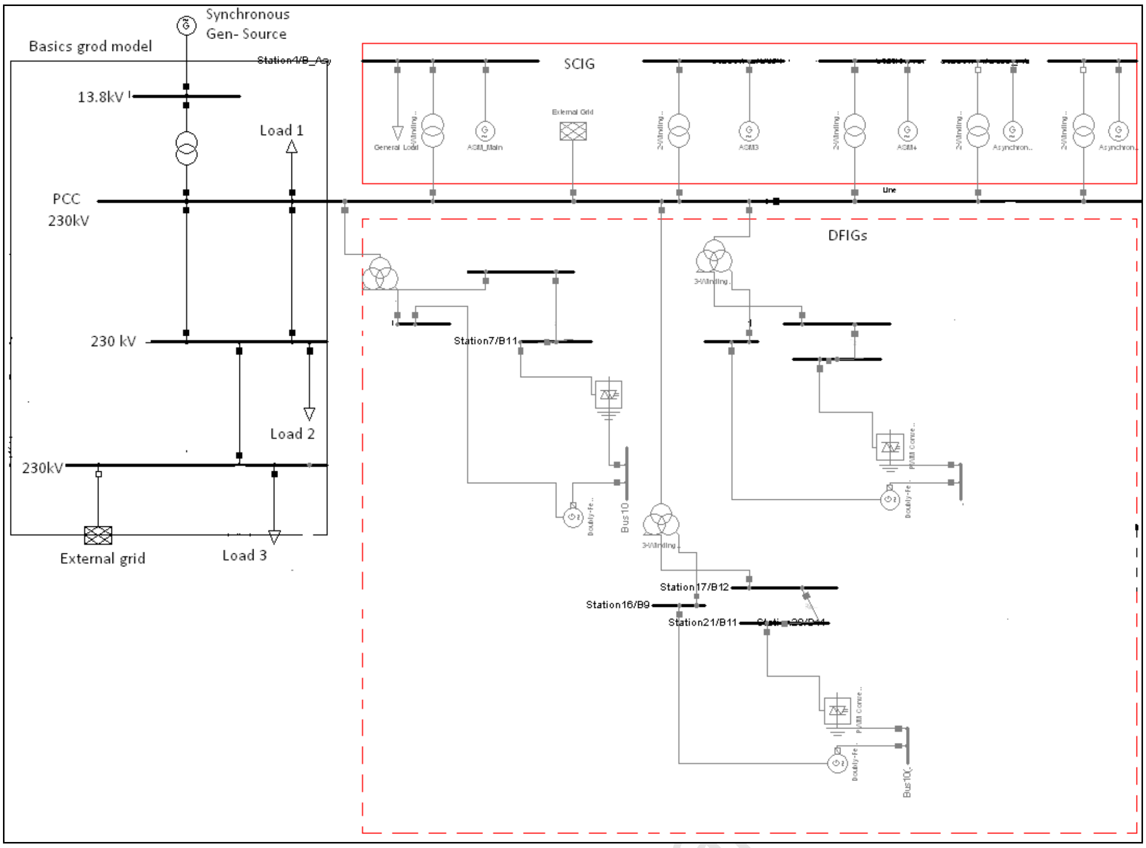
Table A3 Comparison of Voltage levels for a DFIG and DFIG system on a weak grid

Penetration level [MW]	Voltage level at B2 (Using SCIG)	Voltage level at B2 (Using DFIG)
0 MW	0.96	0.96
20 MW	0.91	1.00
40 MW	0.87	1.03
50 MW	0.84	1.05
80 MW	0.80	1.08
100 MW	0.70	1.12




Addition of voltage controllers (VCO) to mitigate voltage stabilty
Voltage level p.u.
1.2
1
0.8
0.6
0.4
0.2
0
-5
0
5
10
15
20
25
Time Scale (s)
X= 0.436 (with VCO)
X= 0.1 (with VCO)
X=0.05 (with VCO)

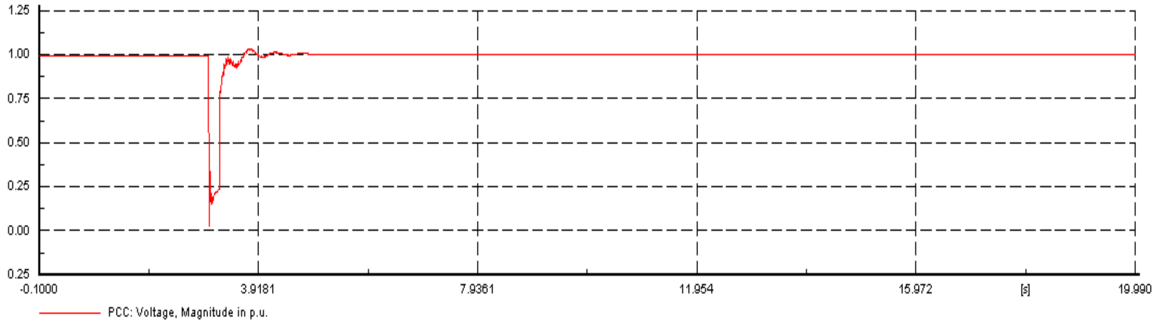

The impact of varying the grid impedance on the performance of the system during transients
Voltage level p.u.
1.2
1
0.8
0.6
0.4
0.2
0
-5
0
5
10
15
20
25
Time scale (s)
X=0.6
X= 0.436
X=0.1
X=0.05

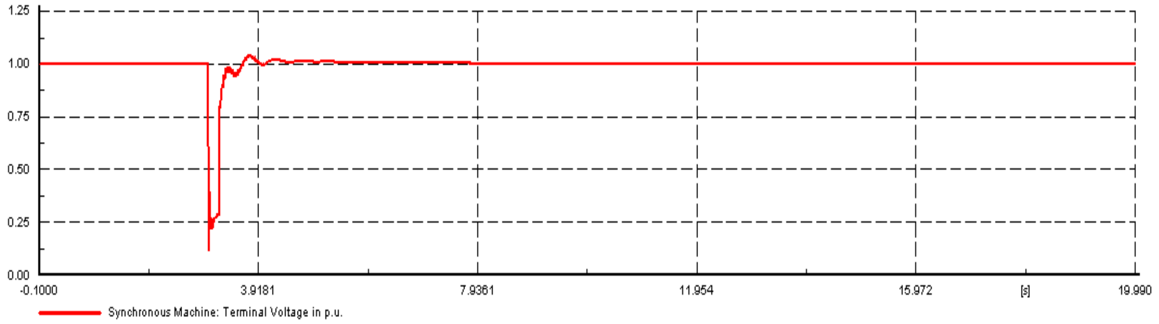


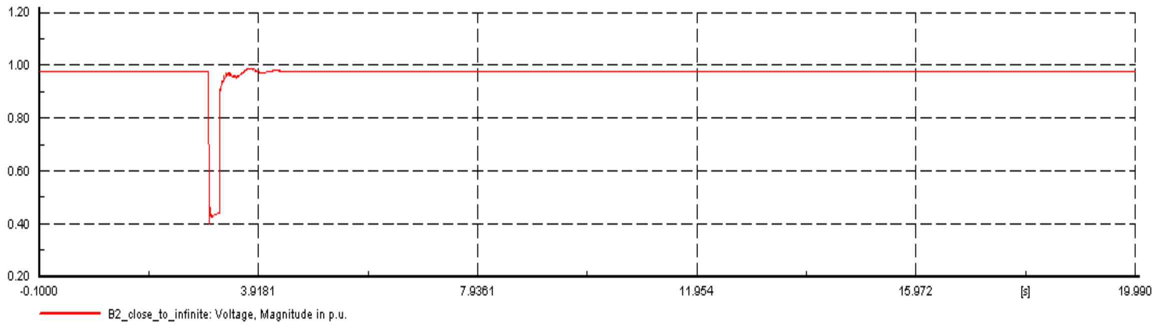
Simple Grid Model

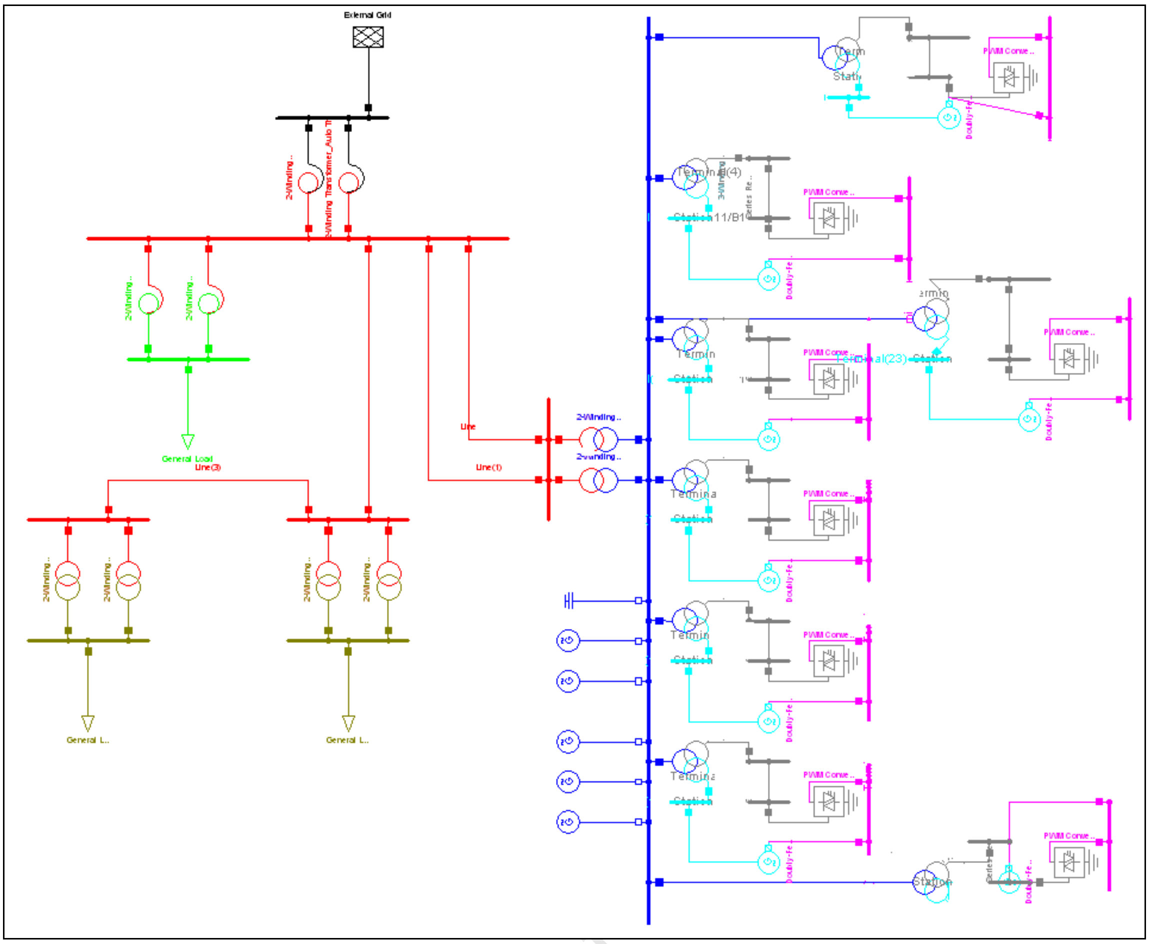
APPENDIX A8

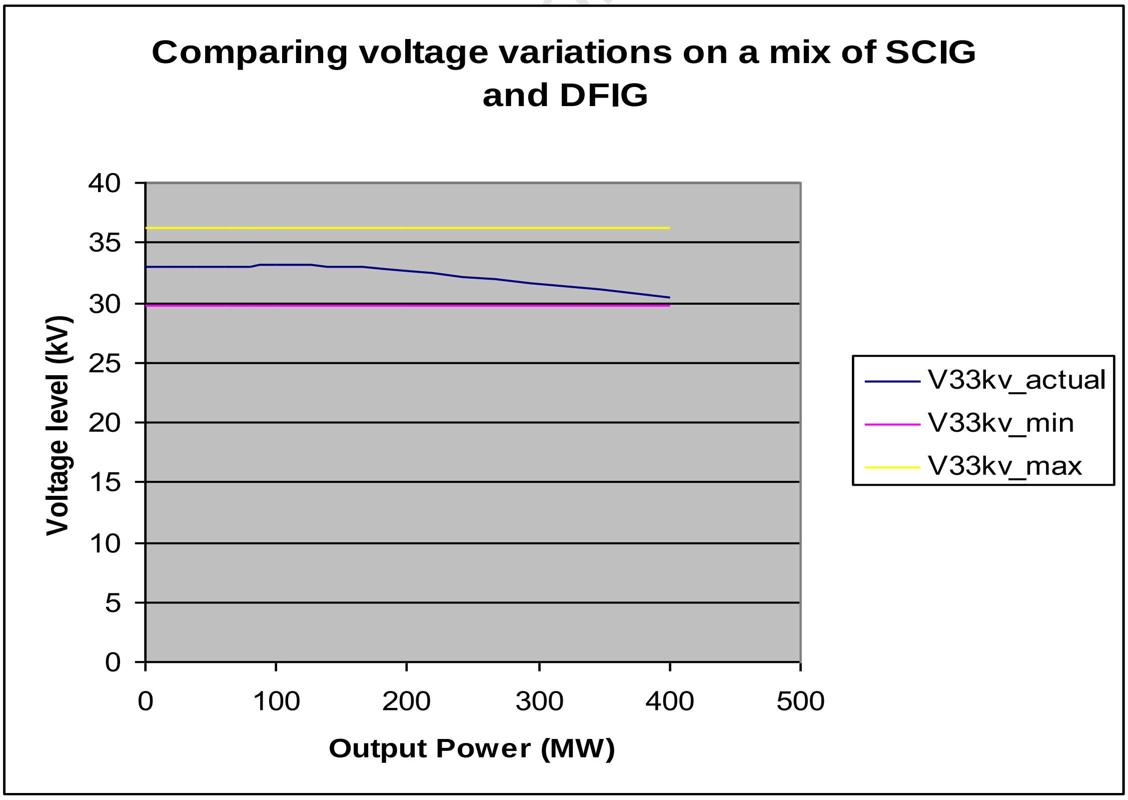
Impact of network disturbances on generator voltage levels

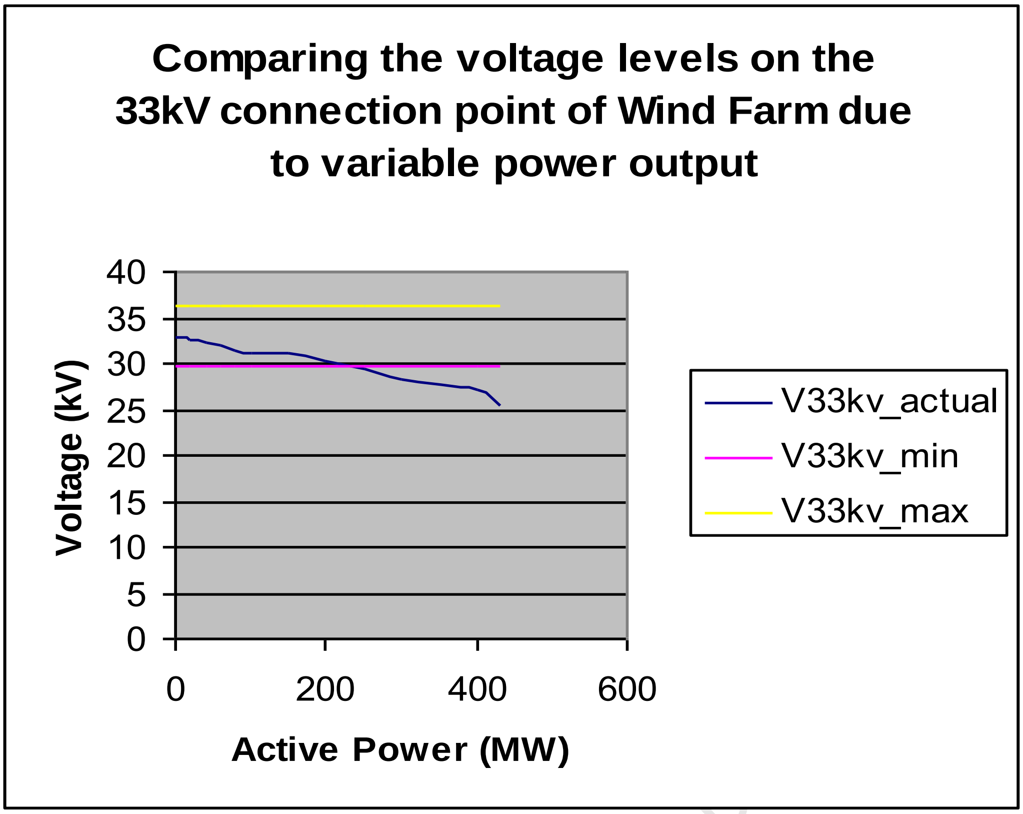


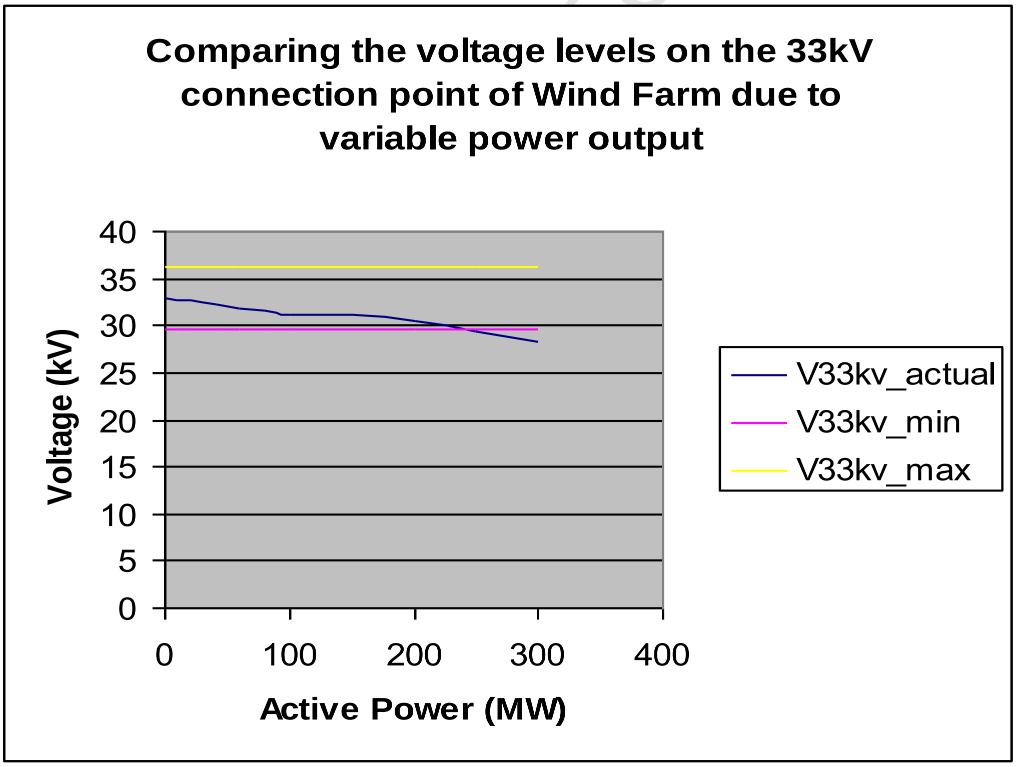





External Grid
General Load
Line(3)
Line
Line(1)
General L..
General L..


Comparing voltage variations on a mix of SCIG and DFIG
Voltage level (kV)
Output Power (MW)
V33kv_actual
V33kv_min
V33kv_max


Comparing the voltage levels on the 33kV connection point of Wind Farm due to variable power output
Voltage (kV)
40
35
30
25
20
15
10
5
0
0
200
400
600
Active Power (MW)
V33kv_actual
V33kv_min
V33kv_max


Comparing the voltage levels on the 33kV connection point of Wind Farm due to variable power output
Voltage (kV)
40
35
30
25
20
15
10
5
0
0
100
200
300
400
Active Power (MW)
V33kv_actual
V33kv_min
V33kv_max