Department of Electrical and Computer Engineering

Application of Double Fed Induction Generator Wind Systems to Weak Networks

Rene Rossi

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Declaration

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made.

This thesis contains no material that has been accepted for the award of any other degree or diploma in any university.

Signature: …… ………

Date: …23/05/2014………

ABSTRACT

Over the past three decades the installation of wind generation equipment interfaced to electric power networks has increased exponentially throughout the world and this has brought a considerable amount of research into the stability of such networks. Very large wind power installation making use of the latest technologies available such as induction generators, double fed induction generators and synchronous generators have been prolific especially in Europe, North America and China. In most cases, the installation of such large wind farms have included interface facilities to very robust networks capable of withstanding large swings brought about by adverse conditions which can trip complete wind farms and having a small impact on network stability. However, the utilisation of wind generation equipment interfaced to small and/or weak networks has been limited, especially when these networks have large industrial loads which exhibit transient conditions on a regular basis. This thesis reviews the issue of weak networks and proposes the most effective way to interface double fed induction generator (DFIG) based wind generation equipment to such weak networks.

Theoretical calculations used to establish rotor angle response curves make use of a theoretical inertia constant (H) for the wind generation units. Such a constant has not been used in the dynamic model of the wind generation unit given the complexity associated with such arrangements. Yet, the results obtained for computer models that assume H to be zero for the DFIG units give excellent transient responses outlining overall reactive power compensation contribution from the wind generators. Mathematical calculations making use of an inertia constant for DFIG units has proven to be quite effective in approximating rotor angle calculations.

Generator inertias are critical for islanded power station simulations with low speed machines offering the least stable results as part of the transient stability models completed. Rotor angle and frequency charts emphasize the

need to understand the implications of inertia constants. These results have been verified with islanded installations that can be found throughout the mining and mineral processing installations found in remote parts of Australia.

The first part of this thesis redefines the “weak network” and the limitations that must be considered when such networks are to make use of DFIG based wind generation. A clear definition of such a network is a matter of conjecture and preferences and has not been clearly identified in the literature.

The second part of this research considers a DFIG wind generation unit to be used as part of the system model. The networks selected to simulate two types of weak networks are based on existing installations for the weak network and proposed installations for an islanded network. On completion of these models it was then necessary to dynamically model a wind turbine offered in the market place as this can offer a realistic outcome to the research. The developed dynamic model was included in the load flow and transient stability models to provide accurate results, particularly to specific events that can cause instability to a weak network.

The third part of this work defines what makes a network weak, in particular, the generation side as well as the transmission and distribution end of a network.

The fourth part of this research work establishes the fundamental mathematical analyses to determine a theoretical quantity of wind generation that could be included in a weak network. This analysis makes extensive use of the swing equations and the equal area criteria to review such requirements.

The fifth part of this research considers the application of wind generation (dynamic model) to a weak interfaced network (the existing simulated network model) and establishes an ideal quantity of DFIG wind generation that can be interfaced to such a model while maintaining stability.

The sixth part of this thesis takes into consideration the weak network that forms part of a major power distribution system. In this case, the weak network forms part of a general network, although it is considered weak due to the line length used to interconnect as well as other attributes that compose such a weak section. A typical Western Australian network has been chosen for this part of research and carefully analyzed with wind generation included.

The seventh part of the research includes the application of DFIG wind generation systems applied to a small islanded network with a large industrial load. In this case the Western Australian network proposed is under consideration for a large mining operation with large mineral processing facilities. This case takes into consideration stability limits that are brought about by the inclusion of wind generation to such networks. This part of the research clearly identifies potential limitations with the network and proposes solutions to such limitations.

The eighth part of the research is associated with protection coordination issues that will arise by the use of wind generation interfaced to a weak network or when operating in an islanded basis. The requirements in this case will differ from normal arrangements given the specific critical fault clearing times required.

DEDICATION

To all those who have had patience enough to put up with me throughout the years.

ACKNOWLEDGMENT

I would like to express my special thanks to my supervisor, Professor Mohammad A. S. Masoum, for his invaluable advice, guidance and support all throughout my PhD studies. In addition, I am grateful to Mr. Ted Lambourne and Mr. James Langdon from Goldfields Australia Pty. Ltd. for their assistance and support throughout the research period, Mr. A. Whitham, Turhan Turker and Peter Walsh for their assistance with proofreading and commenting, and finally Mr. Glenn Dicker-Lee for his drafting assistance.

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List of Abbreviations

AVR	Automatic Voltage Regulator
CFCT	Critical Fault Clearing Time
DFIG	Double Fed Induction Generator
EAC	Equal Area Criteria
GE	General Electric
GSC	Grid-side Converter
IDMT	Inverse Definite Minimum Time
LVRT	Low Voltage Ride-through
OCGT	Open Cycle Gas Turbines
RMU	Ring Main Unit
ROCOF	Rate of Change of Frequency
RPM	Revolutions per Minute
SPF	Single Phase Fault
SWIS	South West Interconnect System
UDM	Universal Dynamic Model
UFLS	Under Frequency Load Shed
WT	Wind Turbine

List of Symbols

H – Inertia Constant

f_o - Frequency

δ – Electrical Power Angle

P_m – Mechanical Power

P_e – Electrical Power

θ – Admittance Angle

t - Time

P_{M_n}- Mechanical Power (Station)

P_{M_k}- Mechanical Power (Wind Generation)

P_{e_n}- Electrical Power (Station)

P_{e_k}- Electrical Power (Wind Generation)

Δδ – Small Disturbance

ξ - Dimensionless Damping Ratio

ω_n - Natural Frequency of Oscillation

ω_d - Damped Frequency of Oscillation

δ_0 – Initial Rotor Angle

δ_{max} – Maximum Rotor Angle

Chapter 1. Introduction

1.1 STATEMENT OF THE PROBLEM

The utilisation of wind generation equipment to supply large percentages of power generation as a replacement for conventional fossil fuel based power generation installations has proliferated over the past several decades. Most of the new wind farms make use of the latest wind generation equipment available, are large in generation capacity and are interconnected to very robust power transmission networks. Having a robust network with variable redundant nuclear and fossil fuel based generation and transmission systems simplify the network's ability to manage transient events such as faults, generation loss, load increases and other significant events.

Over the past two decades, wind generation technology has significantly progressed in capacity and integrability to all types of networks. The Aeolian technology offered includes induction type, Double Fed Induction Generators (DFIG), synchronous generators and various power electronic converters that improve equipment integration. The DFIG wind generation technology, given its ability to compensate voltage via reactive power generation even under no wind conditions, is the preferred technology to complete this research work. This, when considered, is particularly useful with weak networks that are subject to continuous transient load events.

The use of wind generation in Australia has been limited and, in most cases, interfaced to major networks (bulk arrangement). The only known arrangements (weak and islanded) installed in Western Australia are the Albany and Esperance systems that took place many years ago as test trial arrangements. The use of such technology in country areas of Australia has been limited, been given little importance and can be attributed to the weak state of the distribution networks.

There are two very classical cases of weak networks. The first would be a network that interconnects a region via single, radial feeders with long transmission/distribution overhead power lines (resulting in large impedances) and incorporates large transient loads at the far end of the network. The loads, in this case, can be high, thus making the such a proposed interface critical in the event of total transmission line loss. The second case would be an islanded system that is considered typical of a system used to supply an industrial load. This can involve large transient loads with heavy use of power electronic devices and large inductive loads.

The application of wind generation equipment to weak networks has not been fully explored to date, in particular, when applied to islanded networks with limited real and reactive power capacity. In remote areas most electrical installations are considered to be weak irrespective wether connected to a network or operating in an islanded mode. When operating in an islanded mode with large industrial loads it is necessary to accept that the power system will experience large transients (mostly as a consequence of the starting and stopping of large drives). This lack of research work has limited our ability to recommend the use of such technologies to control green house gases and reduce electricity costs.

This research work has been oriented at understanding technical issues associated with the application of DFIG type wind generation equipment interfaced to weak networks that have large industrial loads (transient loads) and establishes basic criteria required to successfully operate such installations.

1.2 NETWORK STABILITY ISSUES – WEAK NETWORKS

Networks that need to cover large surface areas with small loads and make extensive use of long radial feeders at voltages no higher than 36 kV can be defined as weak from an onset given the reactive compensation problems that these installations present. Protection of these distribution overhead power lines is limited to the most basic features (i.e. fuses, some degree of auto-reclosing with overcurrent, earth fault and sensitive earth fault protection) and are not designed to include power generation equipment operating in parallel to these lines (particularly when installed at the far end of the power distribution lines).

A large number of these radial lines exist in Western Australia in order to supply the agricultural regions of this state. These distribution lines are not designed to add parallel generation in general terms. This can be quite evident considering that any wind generation installations in this state are located near the coastlines where larger population centres exist (networks that are more robust) or have been interfaced to islanded networks as trial arrangements.

Transmission lines in this state are only used to supply the largest loads (Perth metropolitan areas or southwest region). Single radial transmission lines are used to supply the Goldfields and North West area (Geraldton region) only. The Goldfields transmission line is a radial 220 kV line that spans nearly 600 kilometres and includes parallel generation installed at the far end of the line. The Goldfields region is mostly industrial load and includes the use of 5 x LM6000 - 55 MVA gas turbines to supply power to a small group of private mining operations. Regional distribution power lines, which are mostly at 132 kV, are single circuit radial feeders, thus representing a limitation in load and transient capacity.

Radial systems present a complicated problem to utilities in that voltage and frequency control can become a challenge when the network experiences large transient events (i.e. faults or lightning strikes). The use of parallel generation at the far end of the transmission system can be positive (limiting the load the transmission line sees) on one side, and a difficulty on the other in the event that the transmission system protection auto-reclosing function operates (potential pole slipping issues). The addition of wind generation in regional centres has always been considered complicated, making a possible application of such technology unfeasible.

The Goldfields region presents an excellent opportunity to make use of wind generation and thus, the basis of this research work.

For installations that make use of islanded power stations (mostly regional installations) to meet all required regional loads, there will always be limitations from the real and reactive power perspective. This situation does not offer sufficient excuse to ignore the possible use of wind generation application to such networks. Wind generation interfaced to Islanded power stations (found throughout remote areas of WA) is yet to be developed due to a lack of understanding of technical interface requirements and operational issues.

1.3 LITERATURE REVIEW

The following literature review, completed in the early stages of the research work, offered an understanding of each specific subject matter:

i. The definition of weak networks and mathematical methods used to define such a state.

ii. The application of wind generation to weak networks. This would include all wind generation equipment available and the technology used to control such devices.

iii. The application of wind generation to small-islanded networks applied to industrial loads with large transient events.

iv. The application of the swing equation and other mathematical methods to networks with wind generation systems.

While plenty of information is available throughout the literature on DFIG wind generation systems, control algorithms and other mathematical arrangements [1-11], the same is not the case with the application of such systems when applied to weak networks.

Minor information on some unique applications is available on some installations completed by utility companies that have installed wind generation to what is defined a weak section of their networks [33-35]. The information supplied by these papers is limited and much has changed since publication.

Information on the application of wind generation to an islanded network with large industrial transient loads is not readily available. Research on this specific issue has not been forthcoming as literature on this subject is non-existent. This could be considered rather disappointing considering the amount of operations that make use of islanded power stations for industrial installation, especially in remote mining areas of Australia.

The research work conducted makes use of the most elemental mathematical techniques available for transient stability modelling from the swing equation and its application to the use of Equal Area Criteria calculations for system stability determination. This has proven to be quite effective in establishing the working limits of the application to wind generation (DFIG) to such weak networks. Some literature is available on this subject (transient stability issues using basic calculations) [17].

In considering the application of wind generation to weak networks it has been necessary to consider the protection coordination requirements of such a connection. The two main cases considered (weak network and islanded network) have not received wide consideration with limited literature on this matter. Various papers are available on the use of Directional Relays for transmission lines that have some bearing on the research done, especially load encroachment issues [43–45].

1.3.1 Weak Network - Definition

A variety of papers have been published in which weak systems have been reviewed and described based on the proposed interconnection to be made and its technology involved.

Rasmussen et al [28] have based their definition of a weak system on:

- The wind farms ability to assist the grid with fault event recovery.
- Whether the wind turbines will engage in power system oscillations.
- The ability of the wind farm to supply both real and reactive power.

Wiik et al [41] have identified a weak system as that where:

- Thermal rating of transmission and plant are important.
- The need to maintain a stable grid system as well as proper power quality.
- The ability to ride through fault incidents and assist the grid system to stabilize.
- Variations in power production will exist with certain predominant frequencies in the area where flicker can result.

In addition, H. M. Romanowitz [40] states, “A weak grid can be defined as one where the connected induction machine kilowatt rating exceeds 15% of the gateway short circuit S”.

All of these issues will be critical when wind farms are interfaced to weak systems. In the particular case of the far eastern areas of Western Australia, the following issues will be critical when considering a wind farm option to supply power to remote industrial operations:

- The transmission and distribution networks are small and limited to single radial feeders in most cases, thus limiting the system’s ability to sustain large transients.
- Limited regional generation with small fault levels.
- Energy storage requirements are not considered necessary as most of the load is industrial in nature and present 24 hours per day.
- Severe VAR restrictions for end users including any potential wind generation installations.

- Most transmission lines are long, radial, single circuit and exposed to high heat and heavy lightning events during the summer months.
- Due to the lengthy extent of the overhead power lines installed in the area and the use of very tight CFCT's, ride through capabilities of the wind farm will be critical if this is to assist with network stability restoration.
- The ability to supply real and reactive power in a controlled manner will be essential.
- Coordination with the relevant supply authorities will be most important to ensure that the transmission system and the wind farm operate with suitably designed protection systems in place (i.e.: auto-reclosing schemes, blocking schemes etc…).

Effectively, it can be agreed that the definition of a weak system will vary according to the system under consideration where a potential wind farm is to be installed. Each arrangement will have its own specific requirements, apart from those commonly identified, which are specific to the limitations imposed by the grid system.

1.4 RESEARCH OBJECTIVES

When researching the problem of the addition of wind generation to weak networks it is essential to consider that this research work is oriented to achieving a greater understanding of the network stability implications of such integration.

The principle objective of this research is to understand the following issues:

a. The effects that such an addition will have to a network irrespective of whether the addition is for an islanded or interconnected network.

b. The implications that such additions will have on the overall network's ability to handle general transient events such as faults, load acceptance, load rejection and other unusual events.

c. The maximum amount of wind generation that a network can accept prior to instability. This situation would apply to both interconnected and islanded networks.

d. The protection system changes required to integrate wind generation to islanded and interconnected networks and the effect this will have on the relevant networks.

1.5 THESIS STRUCTURE

This thesis includes eight chapters. Chapter 2 presents all information associated with the computer model construction. This includes the modelling of the gas turbine units as well as the DFIG wind generator. The DFIG has been mathematically modelled as a separate UDM closely following the recommendation of GE. In addition, a very detailed model of the networks is included with particular emphasis on the different loads used in the industrial facilities.

Chapter 3 examines all issues associated with the definition and description of what a weak network is. A new definition of such a network is proposed.

Chapter 4 has been dedicated to the use of well-known mathematical techniques used when analysing transient stability issues associated with networks. In this case, the swing equation and the equal area criteria are included to establish basic issues associated with the stability of any network when transient events take place. The mathematical treatment establishes preliminary calculations applied to a weak network when wind generation machines are included.

In Chapter 5, a detailed transient analysis is included that assists in establishing the maximum wind generation capacity that can be utilised in a weak network. This review establishes a basic process that assists in establishing an early determination of the allowable number of wind generators that a network ca accept.

In Chapter 6, a detailed treatise of the transient response when wind generation is included to weak network is analysed. In this case, a weak working network and added wind generation interfaced the far end of the network are considered. A simulated transient event (such as a fault) with the rotor angle of generators used in the area is included in the review. In addition, real and reactive power, current, frequency and voltage levels that can be expected before, during and after a fault simulation are examined. The results obtained assist in establishing relevant conclusions as to the contributions from the addition of wind generators to the area.

Chapter 7 presents a similar review, but as applied to an islanded network with a large industrial load. This model represents a working installation that has been considering the use of a private power station supplemented with wind generation. Results obtained show the effects of faults on such a network with varied wind and power station capacities.

Chapter 8 has been dedicated to the issue of protection coordination requirements for weak networks that make use of wind generation. In this case, the coordination must take into consideration the interface to the wind generation interconnections and possible use of ringed systems.

Finally, the research conclusions and proposals for future research are presented in Chapter 9.

1.6 LIST OF PUBLICATIONS

The main content of this thesis is based on the following published/submitted articles:

- **Journal papers:**

  J1. R. Rossi and M.A.S. Masoum, “A Practical Approach Based on Equal Area Criteria for Stability Analysis of Weak Networks with Wind Generation Penetration”, Journal of Energy and Power Engineering, Volume 6, Number 4, pp. 629-637, April 2012.

J2. R. Rossi and M.A.S. Masoum, “Application of Wind Generation on Weak Networks Considering Potential System Limitations Due to Transients and Faults”, Journal of Energy and Power Engineering, Volume 6, Number 5, pp. 817-825, May 2012.

J3. R. Rossi and M.A.S. Masoum, “The Effects of Wind Generation on an Islanded Network Based on Rotor Angle Dynamic Evaluation”, Australian Journal of Electrical and Electronic Engineering (AJEEE), Paper: E13-063R1, In Press, 2013.

J4. R. Rossi and M.A.S. Masoum, “Utilization of DFIG on an Islanded Power Generation and Distribution System”, Journal of Energy and Power Engineering **(**ISSN 1934-8975, USA**)**, Paper: JEPE 13070201, In Press, 2013.

J5. R. Rossi and M.A.S. Masoum, “Protection Coordination Issues With DFIG Wind Generation on Small Islanded Networks, Australian Journal of Electrical and Electronic Engineering (AJEEE), Paper: E13-064R1, In Press, 2013.

- **Conference Papers:**

C1. R. Rossi and Mohammad A. S. Masoum, “The application of wind generation on weak networks - equal area criteria approach”, The 9th International Power and Energy Conference, IPEC 2010, Singapore, pp. 122-127, Oct. 27-29, 2010.

C2. R. Rossi and Mohammad A. S. Masoum, “The Effects of Wind Generation on Weak Networks and Potential System Limitations”, The 9th International Power and Energy Conference, IPEC 2010, Oct. 27-29, pp. 390-395, Oct. 27-29, 2010.

C3. R. Rossi and Mohammad A. S. Masoum, “Protection Coordination Issues with DFIG Wind Generation on Weak Networks: Preliminary Issues”, Australasian Universities Power Engineering Conference (AUPEC 2011), Brisbane, Australia, pp. 1-7, Sep. 25-28, 2011.

C4. R. Rossi and Mohammad A. S. Masoum, "Application of Swing Equation and Equal Area Criteria to Determine Maximum Penetration of Wind Generation in an Islanded Network", Australasian Universities Power Engineering Conference (AUPEC 2013), Tasmania, Australia, pp. 1-5, Sep. 29-Oct. 3, 2013.

C5. R. Rossi and Mohammad A. S. Masoum, "Utilisation of DFIG on an Islanded Power Generation and Distribution System", Asia Smart Grid Electromobility 2013, Singapore, pp 1-9, 29 – 30 October, 2013.

Chapter 2. System Model

2.1 INTRODUCTION

In order to investigate the effects that the addition of wind generation equipment to a weak network has, it has been necessary to establish relevant computer models that would assist in this research. The main objective is to make use of networks that are, preferably, under consideration or operating and that supply large industrial operations in remote locations. This will emphasize the problem at hand. In order to meet the research requirements two separate networks have been chosen from installations that would be considered typical of such remote installations (these would represent specific weak networks).

The first network would be an integrated network (connected to a utility network) that supplies a remote location and that is known to represent a weak network. This network will only be an approximation due to limited access to information. The second network will be an islanded system which is used solely for the purpose of supplying a private installation (remote mining operation). This network model will have a high degree of accuracy as it represents an option for an existing network.

Each one of these networks will include the use of DFIG wind generation equipment installed as part of the network. The quantity of wind generation used will be the same for both networks (12 MW).

With the exception of the wind generation units all equipment forming part of the generation and distribution network will be modeled using a standard power system software package (ERACS) [20]. The wind generation unit will be modeled using a universal dynamic modeler that will then be incorporated into the relevant modeled networks.

2.1.1 Interconnected Weak Network

The interconnected weak network modelled in this case will be an existing installation found in Western Australia. A significant load found in the Eastern Goldfields region, interconnected to the SWIS via a radial, single circuit 220 kV overhead transmission line extending for close to 600 kilometres, is considered. The model that is used is not an “As Built” model, but simply an approximation of an existing installation. In this review, having an exact model of the network is not considered essential as an existing installation is not being assessed, but simulating a proposed arrangement in order to understand the outcome.

The 220 kV overhead line, once it reaches the Goldfields is transformed and distributed throughout the region using 132 kV and 66 kV overhead lines (radial and of single circuit type). Various local power generation stations (small scale and privately owned) can be found in the region and are mostly composed of LM6000 Gas Turbines – OCGT. Some 80% of the regional load is considered to be heavy industrial type (mining and mineral processing operations) while the remaining load is standard small town load.

2.1.2 Islanded Network

The second model under consideration is the utilization of a privately owned islanded power station making use of four small gas turbines (15 MVA) on an n+1 arrangement. The load is strictly industrial with large variable-speed drives, a significant number of heavy inductive loads (mostly AC motors) and transient operation in general. This installation interconnects various underground mining operations via the use of 66 kV overhead power lines which are radial, single circuit and heavily exposed to an aggressive environment (i.e. lightning, extreme heat, heavy pollutants).

2.2 GENERAL ASSUMPTIONS

When conducting any system modelling it will be necessary to make initial assumptions for the different networks under consideration as follows:

2.2.1 Interconnected Network

In modelling this network, it has been necessary to assume that the initial system voltage and frequency are constant and stable throughout prior to any transient stability simulations taking place. In this case, the small variations that take place with voltage levels will be affected by the networks "weakness" or reactive capacity limitations that may arise.

In general, the frequency will be stable considering that this network is interconnected to a large, robust network (SWIS) and no amount of generation loss in the remote region will affect the main network (maximum generator loss will not exceed the equivalent of a 55 MVA gas turbine).

2.2.2 Islanded Network

In the case of the islanded network, it is has been assumed that the voltage and frequency are constant and stable prior to the commencement of any transient stability simulation. Islanded networks with large industrial loads will have voltage and frequency variations considering the limitations imposed by the inertia of the power station machines (dependent on mechanical machine characteristics) and the large load changes that are occur in these installations. This limitation cannot be accurately modelled.

In modelling the generation equipment forming part of the remote or islanded arrangement, the use of accurate data takes precedence considering the effect that the inertia of these machines will have on the stability of the network. This is critical as will be seen by the results of the modelling conducted.

2.3 COMPUTER MODELS

Modelling of each network has been completed using the ERACS software that makes use of all relevant calculating modules – Load Flow, Fault Calculations, Transient Stability, Universal Dynamic Modeller and other modules. While there are a variety of computer modelling software packages, ERACS has been used given its ability to dynamically model the DFIG WT and has been widely supplied by some mining operations in the region.

The network-interconnected model represents an existing network section found in the Goldfields region of Western Australia. The islanded network model, with the proposed power station is a conceptual design under consideration for construction.

The following sections will outline method of modelling for each element employed including relevant data required to simulate existing loads and events.

2.3.1 Generation

For both the interconnected network as well as the islanded network, there is only the need to model gas turbines operating in the area. There are two different types used. First use of made of the GE LM6000 (55 MVA) and then the Solar Titan 130 (15 MVA) OCGT machines. In all cases, the generators are installed in rather aggressive environments, that is, in close proximity to mining operations that have transient loads on a continuous basis. All LM6000 GT's are interconnected to the utility network while the Titan 130 units are operating in the islanded model only.

In the islanded model, the GT's are operating in parallel in isochronous mode. When generation equipment is running in parallel with a utility network the tendency is to run them in droop mode.

Mathematical modelling of the Gas turbines is achieved using information obtained from the suppliers of the machinery (in this case GE and Solar Turbines). The calculations have been done based on Park's equations and as such, required the use of accurate data including direct and quadrature axis information, positive, negative and zero sequence fault data. Mechanical information on the GT's is also included, most critical being the moment of inertia or H.

In addition, each generator includes the use of a relevant AVR and Governor in order to ensure correct response to transient events. While various models of AVR and governors are available in industry, only typical arrangements are employed to complete the models. In each case, the intent is to make use of existing arrangements and not to attempt to innovate improved governors and AVRs.

The following dynamic model of a PID AVR is used in the simulations:

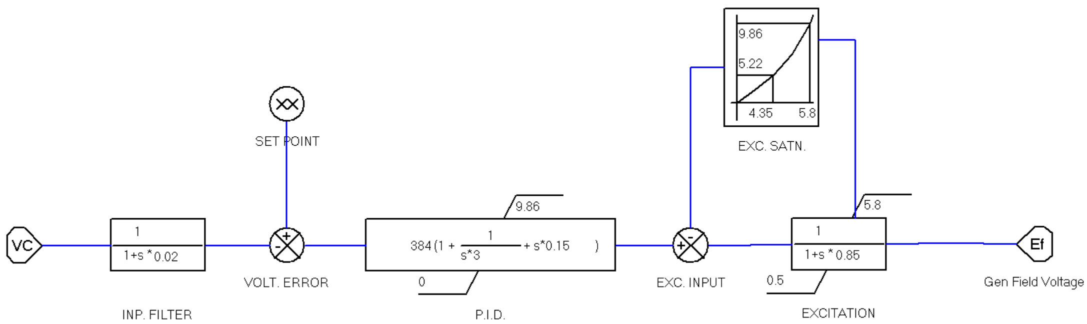


Figure 2.1 - PID Based AVR Dynamic Model

In the case, a typical type 4 PID with two rate acceleration governor is used in the model.

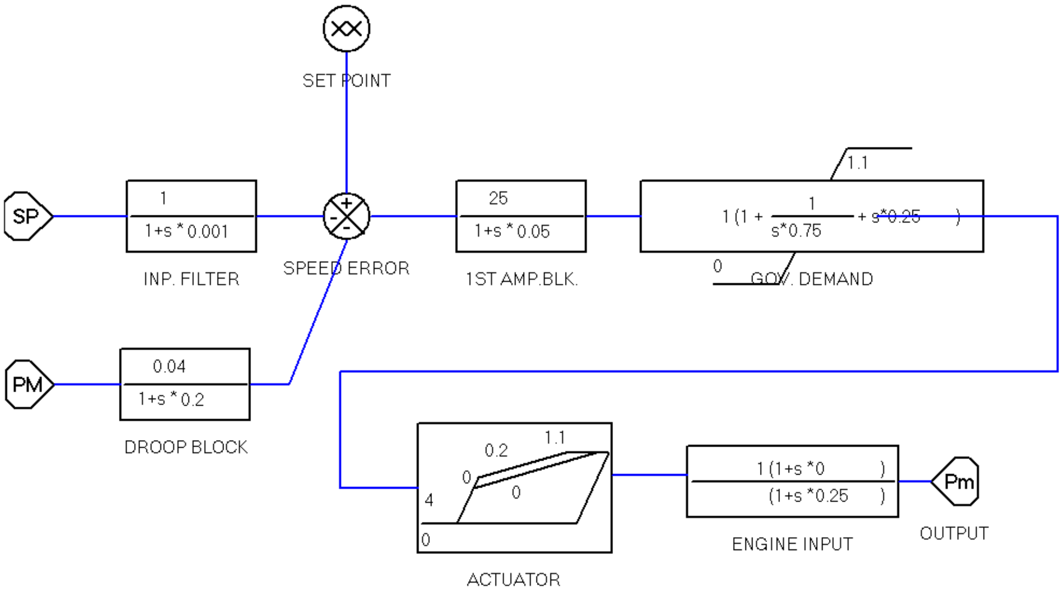


Figure 2.2 – Type 4 PID Governor with Two Rate Accelerator

These models are critical for transient stability assessments of each case under consideration, as the main power generation equipment (as compared to the wind generation units) will carry the bulk of the transient compensation.

2.3.2 DFIG Wind Generator

The modelling of the DFIG used is based on a wind generator sold in the market. The selected unit is the 1.5 MW GE DFIG wind generator as this was under consideration in the Goldfields region.

Information supplied by GE (USA) on the DFIG has been dynamically modelled for simulation purposes. GE has published technical information on these dynamic models [35].

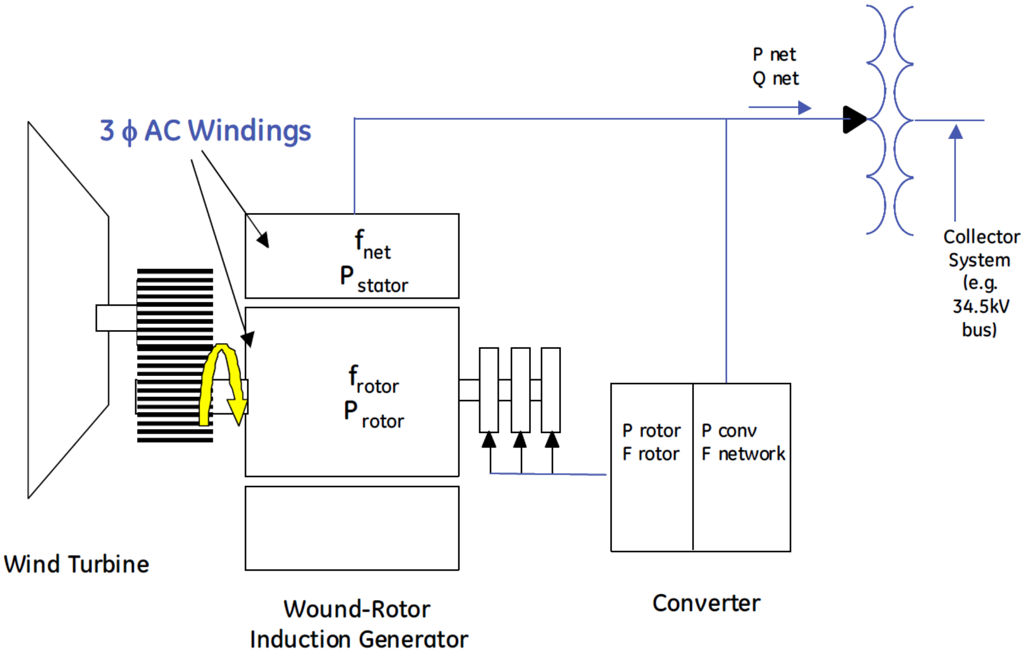


Figure 2.3 – GE Double Fed Asynchronous Wind Turbine

Each section of a DFIG modelled, is to meet the connectivity arrangement displayed in Figure 2.4. This incorporates the mechanical side, including blades, gearbox and wind model and the electrical side that includes the generator and converter that controls the field current and voltage requirements.

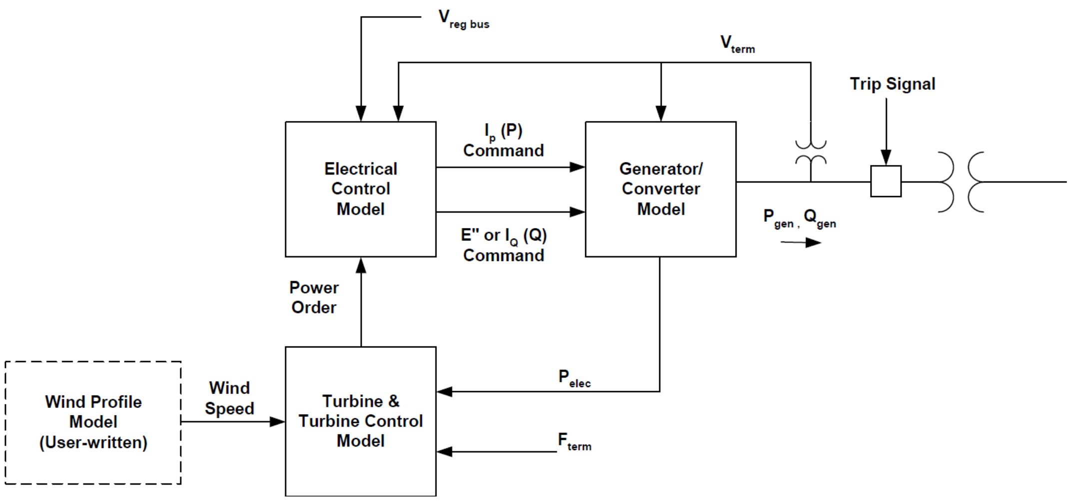


Figure 2.4 – GE WTG Dynamic Model Connectivity

Effectively, the dynamic model has been completed and tested to meet the requirements set out by GE.

Please refer to **Appendix A** for additional information on this dynamic model.

2.3.3 Network Loads

In order to obtain the greatest accuracy possible with the models completed, it has been necessary to include all possible expected loads found in an industrial installation. An existing network found in Western Australia has been relied on and this includes very detailed information on the loads used. This includes:

a. Motor Loads: Most motors used in large industrial installation are induction (Asynchronous) motors that have been modelled using nameplate information as group or individually, depending on concentration of these.

b. Where required, synchronous motors have been included (especially large motors) and all relevant information (d-q data) has been included, these motors will have a large impact on power factor levels (reactive power compensation) as well as fault current injection. Information related to these machines has been obtained from manufacturers in order to ensure accurate results.

c. All electrical motors included mechanical loads when modelled. This information is critical for transient stability studies, especially when considering large drives.

d. Motor drives that make use of variable-speed drives or cyclo-converters have been modelled based on PQ arrangements, as these would not contribute to fault levels. In general, these have been modelled using high power factor levels as this is representative of such devices.

e. All non-motor loads have been included as PQ loads as these will not contribute to the fault levels. Each PQ load includes power factor information which is obtained from typical industrial site data.

f. All relevant power factor correction systems, as well as harmonic filters, have been included where possible, as these will have an impact on transient calculations.

The models completed do not make use of specific algorithms or separate mathematical or dynamic models (outside the DFIG Unit) as this is not the main research objective. Irrespective of software employed, most electrical devices are accurately modelled relying on the included software calculations that form part of the power system software.

2.3.4 General Network Equipment

As part of the network models, a large amount of equipment that forms the relevant network was included in the computer models. All general equipment (cables, overhead conductor, transformers, etc…) has been modelled based on manufacturers data. Transformers, in particular, have been modelled with impedance data and make full use of auto tap changers were applicable.

In most cases, information associated with cable installations, obtained from manufacturer's data, forms part of the models. In the case of high voltage cables, the information includes positive, negative and zero sequence data, AC resistance and reactance as well as current carrying capacity based on method of installation.

In cases where harmonic filters or power factor correction systems are installed these have been added to the models using the manufacturers' data as well.

2.4 ADDITIONAL INFORMATION

Additional information associated with the networks under consideration includes the following:

2.4.1 Weak Interconnected Network Model

In the case of the interconnected network, it is essential to consider that the utility that owns and operates this network have stability problems with the remote section, which is where the wind generation system is to be installed. Instability on this network is largely due to a large industrial load, local generation (gas turbines) and an interconnecting arrangement composed of a single radial feeder with a length in excess of 600 kilometres. Severe loading conditions at this remote location could trip the transmission line and cause instability of the network at the opposing end, a condition that could black out the complete region. Thus, the need for a very conservative approach to system design at the remote end will be essential.

2.4.2 Islanded Network Model

In the case of an islanded power system, use is made of a typical remote industrial installation that includes transient loads, limited reactive power capacity and heavy exposure to the elements. The addition of wind generators to such a network will always be limited to the load minus the use of a single power station generator. The load will also present a significant influence on the overall network design and consideration of wind generation.

The power station in these cases is designed as an n+1 arrangement limiting excess capacity to emergency requirements only. The distribution system is, in general, radial and designed to meet the local requirements only (not designed for future customers). While the power system design selected makes use of machine-generator units with adequate inertia constants (with sufficient “weight” behind the system to manage all load transients) this is not generally the case with other installations. As will be demonstrated, this requirement (inertia) is critical for system stability and can represent the success or failure of a wind generation interface arrangement.

2.5 CONCLUSIONS

This section outlines the method relied on to model the networks and test the performance of these when under transient events. Having accurate data to model each part of the network is important, as this will establish the network's ability to make possible the use of wind generation on weak networks that have limited operational margins. The distribution network used to simulate such installation is an existing network with a long operating history.

Modelling of the DFIG wind generation has been difficult and time consuming, but necessary to obtain acceptable results. Considering that the main objective of this research work is not improving wind generation design, but understanding the impact these will have on weak networks, it was essential to model such a network in an accurate manner irrespective of how difficult it was to obtain information (i.e. dynamic model) from existing suppliers.

Information for the power station generators has been easy to obtain and found to have a high degree of accuracy. The use of small type generation equipment is well understood in the heavy industry and can be accurately simulated to generate credible results.

Chapter 3. The Definition of a Weak Network

3.1 DEFINITIONS

Irrespective of size and location, all electrical networks will have inherent weaknesses that must be understood and managed in order to limit any potential loss of supply. A network considered robust, in general terms, can have sections that, based on their characteristics, will cause weaknesses to arise to various sections of the network at one time or another.

Various attempts at defining a network 'WEAK' have been made in various publications, yet none would agree on a simple definition of how best to measure a weak network from a robust arrangement. Based on this research work a weak network can be defined as one that:

"Under a variety of transient events or disturbances a network would be considered weak if such events bring sufficient change to the stability of the network to commence system disruptions and/or blackouts"

Attempting to quantify these events with equations can prove to be very difficult as each network is physically different and with different operational requirements.

The simplest way to establish the weakness of a network would be to consider critical issues such as frequency, rotor angle of the generation equipment, real and reactive power capacity, voltage fluctuations and other minor parameters. Frequency and rotor angle have been the preferred method when considering rotating machines. Failure to control these basic parameters will have the expected consequences that bring about system instability. In determining the weakness of a network the above mentioned parameters will be the preferred parameters to consider in this research work when adding wind generation.

3.2 GENERATION WEAKNESSES

All electrical network arrangements will make use of some method of power generation (i.e. steam, heavy fuel, gas, renewable etc…) that will form the general supply of real and reactive powers. In order to meet the required load the power stations must include machinery that accommodates some level of transient events (short duration events) and long-term load changes. In most cases, the available spinning reserve of about 15% must accommodate such changes and will always be dependent on generation and transmission equipment availability (redundancy in design).

The single largest cause of network interruptions can be attributed to insufficient generation capacity availability that can ultimately make the network “weak” as previously defined. Availability of generation capacity is necessary in order to meet demand and network maintenance events completed to achieve maximum availability. All this forms the basis of when a network can be reclassified from weak to robust.

In addition, having sufficient generation may prove to be insufficient if the generation units do not have sufficient stored inertia to meet the continuous transient events so prevalent within “weak” networks. The higher the speed of the generation equipment the more effective will it be to manage transients. Low-speed machines, used on remote installations will not necessarily meet transient events making the arrangement weak to the point of becoming unreliable to meet the occurring loads.

Dynamic analysis of these situations, a well-proven situation, can be of great assistance in understanding what considerations must be met prior to network design or extensions. The use of rotor angle and frequency deviations can be used to great accuracy in determining how a network will respond when under transient event characteristics.

When wind generation is considered for a weak network, it is essential to understand what contribution these units will bring to the stored inertia of the regional or installed network. It has always been traditional to assume that H (inertia constant) in this case will be zero, but based on recent research a value of H can be estimated for wind generation units, further assisting with stored inertia calculations for weak networks. While the increase in inertia will be evident, there are limitations as to how this will assist with inertia storage.

3.3 TRANSMISSION AND DISTRIBUTION WEAKNESSES

In robust networks the use of fully redundant transmission and distribution arrangements are evident and avert potential interruptions to power demands. As with generation stations, transmission and distribution system have a limiting capacity and this must not be exceeded. With robust networks, the loss of a transmission line can be tolerated based on excess capacity of other parallel lines or by simply making use of line compensation equipment (i.e. FACTS). All this though, still has a limit that can bring about interruptions to service if power capacity is exceeded or transient events are significant enough to trip transmission lines.

Many utility networks have to be able to provide power to remote locations and, in some cases, at long distances from major high-voltage switchyards. Considering the expected load maximum demand and cost of such installations, it becomes evident that the interface used via transmission lines will be limited. As the load increases, the line capacity is tested when radial and single circuit transmission lines are in use; a typical arrangement with weak networks. The most critical stage in this case becomes apparent when the transmission line trips on fault (sustained fault), thus dropping a significant load that could bring the main network into instability. This could lead to blackouts and further instability of the network. In addition, the use of auto-reclosing schemes can cause serious interruptions to remote locations with local generation (pole-slip case of synchronous generators) when faults occur with the transmission lines.

The use of wind generation in this case can assist with ride-through capability, but for limited events and duration only. Having wind generation installed at the far end of a weak network (as this research has concentrated on) will limit the load on the transmission lines, but can cause serious transient impacts on the line if this wind generation is lost due to a fault trip event. In this case, the protection equipment can island the last section of the network and bring about a blackout situation.

With distribution networks, it is generally very difficult to limit interruptions under transient events, as it is not usual to have redundancy included in such arrangements. The CFCT in this case will be critical. In order to limit interruptions to major sections of the networks it will be essential to ensure that each distribution line will not cause the loss of large loads that could cause instability (load diversity).

3.4 CONCLUSIONS

There can be no doubt that having an intimate knowledge of the power networks under consideration for wind generation penetration will assist in identifying issues that could make all or parts of the network weak. Once the vulnerable parts of the network are known, an engineered solution can be implemented. The single most critical aspect of any network will always be the inertia energy storage capacity of any weak or islanded system as this will have a large impact on network stability when under large transient.

This section takes into consideration the many design and operational issues of a network that can make the system weak. While attempts have been made to define the weakness of a network based on system fault levels, it has insufficient accuracy given the fault characteristics of changing networks (i.e. the addition of wind generation or the varying nature of the loads that can be expected in an industrial application).

Chapter 4. Dynamic Analysis and Modelling

4.1 INTRODUCTIONS

In order to understand the main purpose of this research work it has been necessary to consider the issues associated with a weak network and how they differ from a standard network.

Any network identified as weak would have a specific arrangement or condition that makes it weak and, as such, needs to be considered as a unique entity (no other similar properties).

The analysis used to represent or assess a weak network is no different to any other network including robust networks. The significant change in a network that is contemplating the use of wind generation (DFIG) would be the way these machines and generators are represented and how they will affect the overall, or at least, sections of the network arrangement. This will be reviewed next as this has an important effect on transient analysis.

4.2 THE SWING EQUATION THEORETICAL ANALYSIS

Over the past few decades extensive work has continued in the area of Transient Stability and the most effective method to conduct relevant calculations. Kimbark [18] in his publication “Power System Stability” clearly outlined the most effective way to mathematically deal with transient calculations and the application of the swing equation to such events.

When analysing network stability issues the most effective way to obtain accurate results would be via the use of the Swing Equation and the determination of the Rotor Angle and frequency fluctuations for the duration of the instability period. This will assist in establishing the network's ability to maintain stability or avoid total blackout events. Having an understanding of the maximum rotor angle and the duration of this change can effectively establish the operational limits of any transient event. The results can be further enhanced via the use of equal area criteria (EAC) as will be demonstrated.

The work that Kimbark did in establishing rotor angle calculations applied to very solid networks with large generating systems (i.e. stream, hydro generation). In this research, this concept is applied to a weak network with the inclusion of wind generation equipment.

In addition, having an understanding of the rotor angle fluctuation will also give an understanding of the current (Amps) fluctuation that can be expected under transient events. This will be essential in establishing protection settings in weak networks.

When wind generation is under consideration it will always be essential to determine the locations (network location) where the wind generation is to be interconnected to the network. At this point, the connection interface location between the wind generation and the rest of the network represents the two-generation source (based on network reduction). This can be seen in Figure 4.1.

The installation of a wind generation system at the weakest possible location, considered to be at the end of the transmission system, allows for a clear interface point. This would then simplify the network to two connecting points (the two-machine system).

A similar network would be that of an islanded system making use of a local power station supplying a private network that makes use of wind generation through connections at opposing sides of the network ends.

From Figure 4.1 the lower side of the network would be the wind generation section as compared to the upper side that would represent the overall power generation and distribution network. In this case, the generation sections are connected via a standard arrangement that can be modelled as a set of impedance based lines. This allows for a reduction arrangement that simplifies the network irrespective of how large or complex this may be.

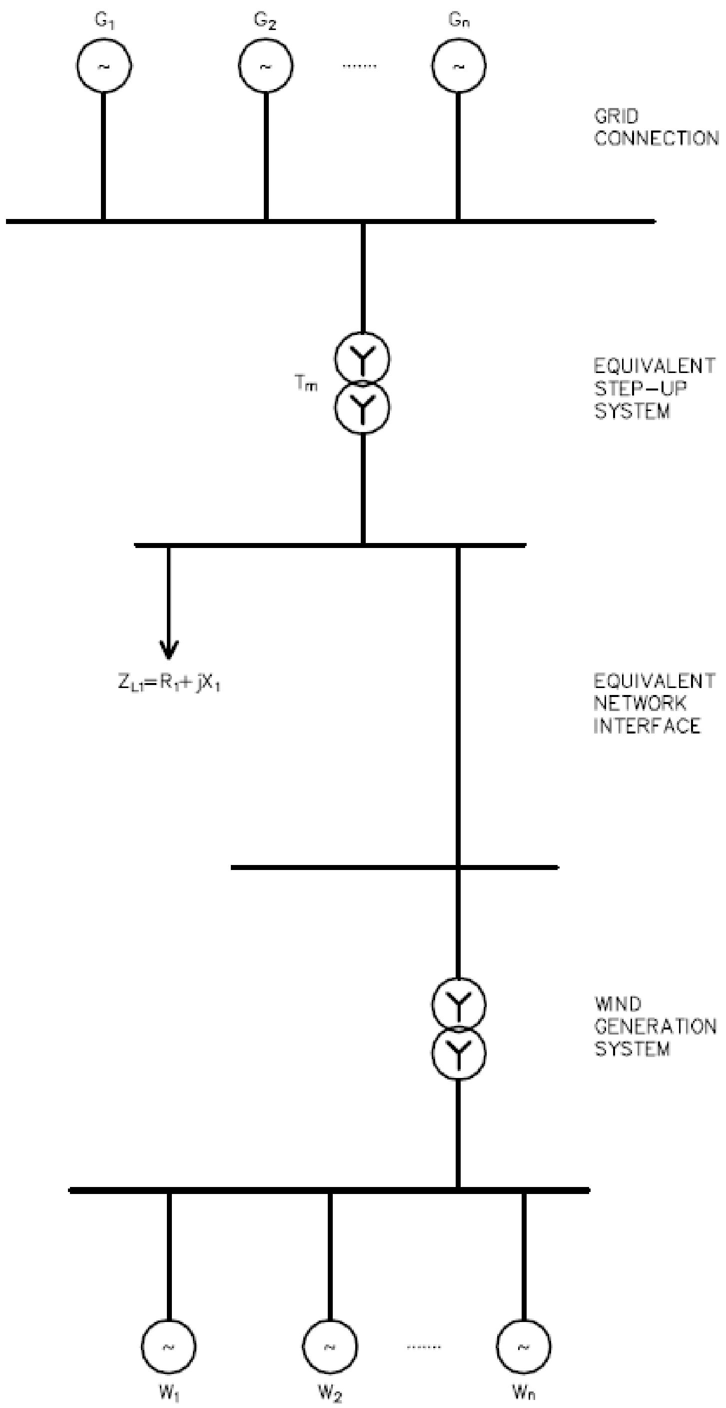


Figure 4.1 – Reduced Network

This network has been reduced to represent a two-finite machine arrangement that would consist of one finite machine and an infinite bus [18]. In order to represent each end of the network by the relevant swing equation use is made of the standard swing equation (damping neglected) for machines n and k [13]:

$$\frac{H_n}{\pi f_0}\frac{d^2\delta_n}{dt^2} = P_{M_n} - \sum_{j=1}^{m} |E_n^{'}||E_j^{'}|\,|Y_{nj}|\cos(\theta_{nj} - \delta_n + \delta_j) \qquad (4-1)$$

where

$$\frac{H_n}{\pi f_0}\frac{d^2\delta_1}{dt^2} = P_{M_n} - P_{e_n} \qquad (4-2)$$

and

$$\frac{H_k}{\pi f_0}\frac{d^2\delta_k}{dt^2} = P_{M_k} - \sum_{j=1}^{m} |E_k^{'}||E_j^{'}|\,|Y_{kj}|\cos(\theta_{kj} - \delta_k + \delta_j) \qquad (4-3)$$

and

$$\frac{H_k}{\pi f_0}\frac{d^2\delta_2}{dt^2} = P_{M_k} - P_{e_k} \qquad (4-4)$$

Please refer to **Appendix B** for additional information on the swing equation application to weak networks.

At this point, the necessary addition of a small disturbance Δδ to the swing equation is done and obtain the necessary response to this small transient via the following equations [19]:

$$\delta = \delta_0 + \frac{\Delta\delta_0}{\sqrt{1-\xi^2}} \exp[-\xi\omega_n t] * \sin(\omega_d t + \theta)] \qquad (4-5)$$

$$\omega = \omega_0 - \frac{\omega_n \Delta\delta_0}{\sqrt{1-\xi^2}} \exp[-\xi\omega_n t] * \sin(\omega_d t) \qquad (4-6)$$

Once the small disturbance swing equation has been obtained it will be necessary to obtain the equivalent power – angle equations for the two-machine problem, these being [19]:

$$P_{en} = E_1^2 Y_{11} \cos\theta_{11} + E_1 E_2 Y_{12} \cos(\theta_{12} - \delta_1 + \delta_2) \qquad (4\text{ - }7)$$

$$P_{ek} = E_2 E_1 Y_{21} \cos(\theta_{21} - \delta_2 + \delta_1) + E_2^2 Y_{22} \cos\theta_{22} \qquad (4\text{ - }8)$$

When analysing equations (4-1) and (4-2) it is evident the most critical information is:

- ⇨ H, the moment of inertia of each machine and
- ⇨ δ_0, the starting rotor angle prior to any transient event.

Obtaining the inertia constant for standard diesel, steam or gas machines is a simple task and made available by suppliers of such industrial generation equipment. In order to understand the constant H as applied to wind generation the task is rather more complicated and needs to be calculated.

In order to obtain the inertia constants H for each DFIG wind generator it will be necessary to approximate this via the following formula [37]:

$$H = 1.87 * P^{0.0597} \qquad (4-9)$$

where P is the wind generation power in watts. This approximation is very useful when considering groups of wind turbines.

The moment of inertia of the machines under consideration will have a large impact on the system’s ability to manage transient events that can occur on weak networks (limited reactive capacity) supplying large industrial installations (i.e. large inductive motors with regular start/stop events). The machines normal operating RPM's will have a large impact on response expectations of an islanded network in particular. Equation (4 – 9) establishes the inertia constant for DFIG machines whether they are a single machine as well as for a group of machines.

4.3 SWING EQUATION CALCULATIONS & SIMULATIONS

Calculations associated with the swing equation can be easily achieved by using standard mathematical packages.

In order to understand the application of the swing equation take into consideration a small islanded power station that makes use of turbines or reciprocating engines and feeds a power distribution network (Similar calculations can be done for an interconnected network). In the first instance, consider the case where we have no wind generation, as this will establish a basic benchmark when comparing power systems with wind generation.

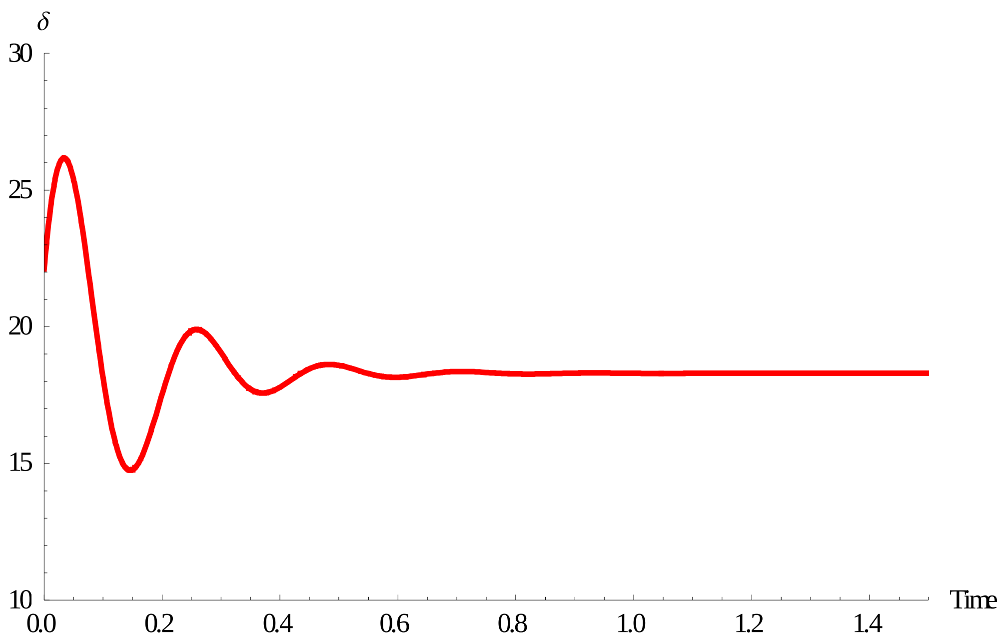


Figure 4.2 – Rotor Angle for Small Power Station Transient Response

Figure 4.2 shows a typical rotor angle response to a small transient event with a small load loss. The time to settle can be longer depending on the degree of transient impact applied and the amount of damping applied to simulate the network.

When considering the interface of wind generation to a weak network, it must take into consideration the following points:

- There can only be a limited amount of wind generation and this would be determined by the size of the power station (maximum generating capacity) vs. the load.
- The calculated value of machine inertia H for the wind generation units is based on best available data as compared to the power station sets.
- The power station will always have a generating set in operation acting as frequency leader for the network as well as providing some degree of spinning reserve.

Figure 4.3 shows the addition of wind generation to a gas turbine based power station network where, in some cases, the reduction of power station gas sets has been simulated in order to establish a realistic working arrangement. The scenarios are as follows:

a. No Wind Generation 3 x Gas Turbines
b. 4 x 1.5 MW Wind generators and 2 x Gas Turbines
c. 8 x 1.5 MW Wind Generation and 2 x Gas Turbines
d. 12 x 1.5 MW Wind Turbines and 1 x Gas Turbine

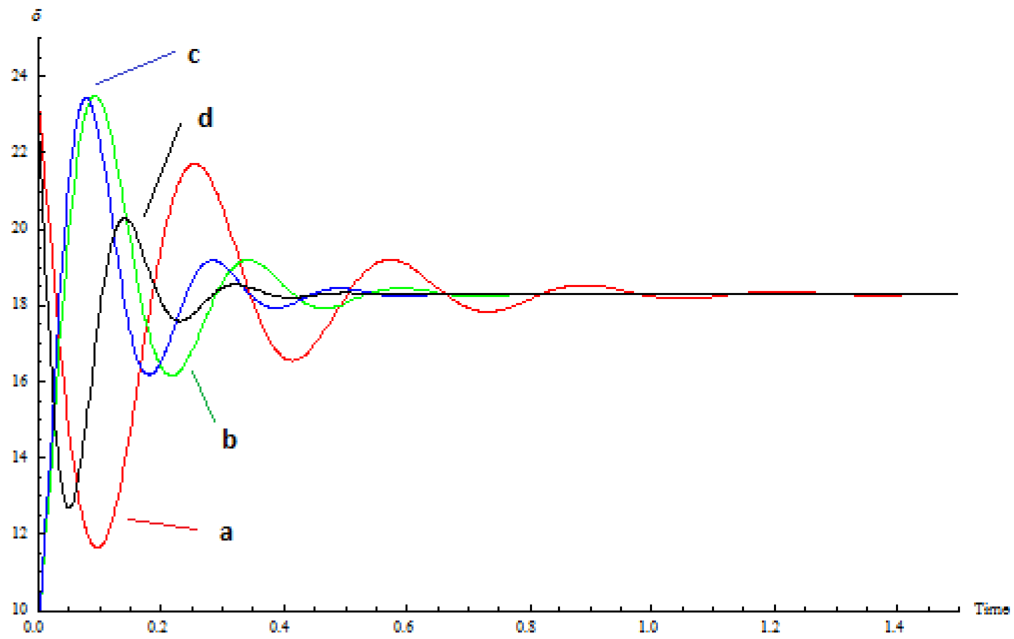


Figure 4.3 – Rotor Angle for Various GT Scenarios

Figure 4.3 shows that as wind generation sets are added to the network the rotor angle perturbations become smaller offering greater stability under a small disturbance (i.e. load increase). While this information is an approximation it can establish a basis for an understanding of the stability problem with the addition of wind generation interfaced to a weak network.

In a similar manner, relevant curves have been prepared for a case where the power station makes use of gas reciprocating engines (low speed as compared with gas turbines). Figure 4.4 displays the results of such simulations when load is decreased. The addition of wind generation is as stated in the figure:

a. No Wind Generation 4 x Gas Reciprocating Engines
b. 4 x 1.5 MW Wind generators and 3 x Reciprocating Engines
c. 8 x 1.5 MW Wind Generation and 3 x Reciprocating Engines
d. 12 x 1.5 MW Wind Turbines and 2 x Reciprocating Engines

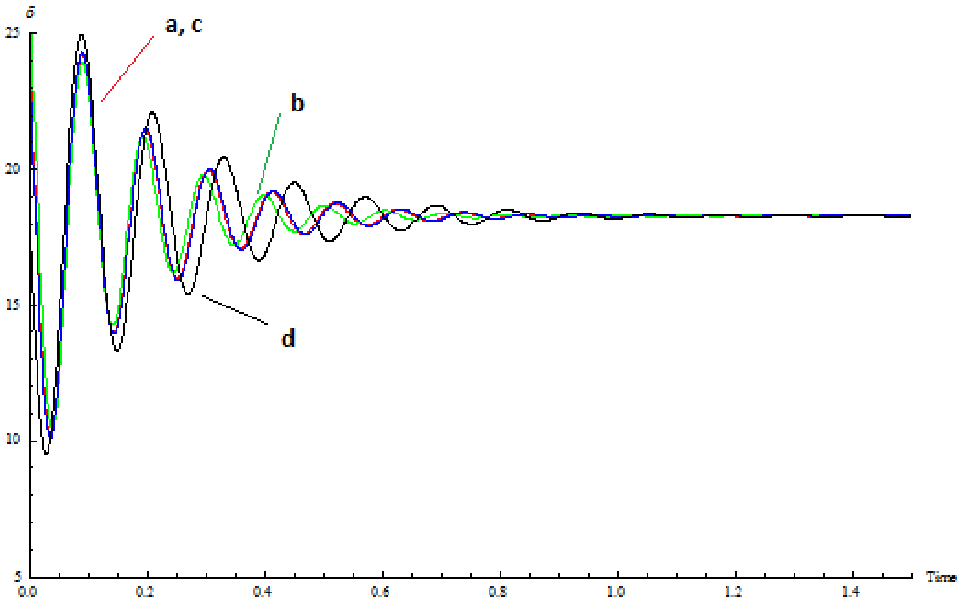


Figure 4.4 – Rotor Angle for Various Gas Reciprocating Engine Scenarios

In this case, the addition of wind generation has not made a large impact on rotor angle calculations response, as can be explained by the low-speed machines installed at the power station. The inertia on these low-speed machines is not sufficient to make an impact when the wind generation units are included. As compared to GT's (i.e. high-speed machines) the use of low-speed machines establishes a clear limitation to transient stability response.

Low speed gas reciprocating engines are widely used for remote mining operations and have always demonstrated a limited capacity to manage transient events such as load rejection and load acceptance of large drives. These preliminary calculations indicate that such installation would not benefit from the use of wind generation. In fact, experience has shown that in some applications gas reciprocating engine power stations make use of diesel sets as a supplement to withstand transient events.

Effectively, having an understanding of the implications brought about by the inertia constant (H) offered by power station machines proves to be critical for network stability.

In summary, the use of the swing equation shows that:

- The information obtained from such calculations can give a preliminary understanding of the type of rotor angle response that could be obtained at a power station by the addition of wind generation units.
- The calculations can establish a time-to-reach-stability after the transient fault has been applied. This can prove to be critical and in these two examples outlined on the relevant figures it can be concluded that the reciprocating engines – being low speed – will take a longer period of time to settle.
- The time to settle will have an impact on protection settings, in particular, those that apply to the power station generators considering that the oscillations of rotor angle will cause an oscillation of the current for each generator.

This type of calculations have also been achieved on a distribution system that is interconnected to a utility network, although in this case, the basic calculations would become more complicated due to the larger network that requires conceptual analysis and reduction. The most significant calculations in this case would be the network equivalent reactance and the damping factor to be used. Calculations of this nature have indicated good correlation between models with equivalent results.

The transient event in this case is the total loss of the wind generation system (feeder circuit breaker trip). This simulation is quite useful in determining what effect can be expected from the loss of the wind generation (up to 12 MW) on the weak network.

Figure 4.5 displays the results of such a simulation. This indicates that the response time for such a transient disturbance would be in excess of 2.6 seconds. When the same calculation was done using a computer simulations software called ERACS the results show some similarities with the calculated results – refer to Figure 4.6.

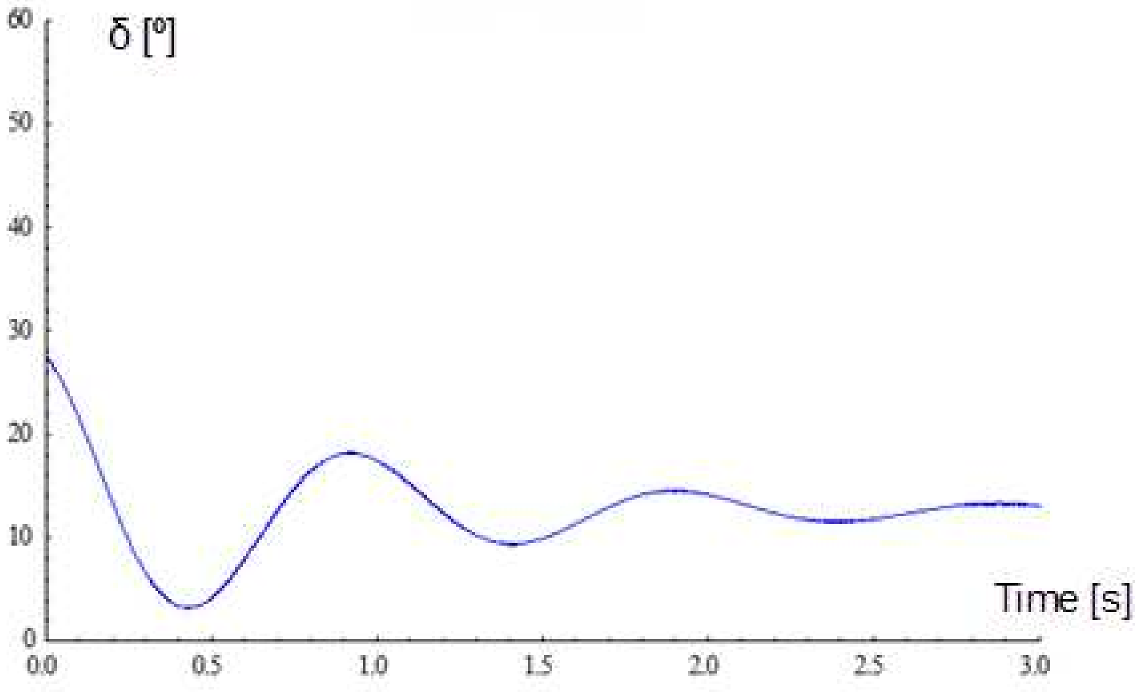


Figure 4.5 – Calculated Rotor Angle for Interconnected Network.

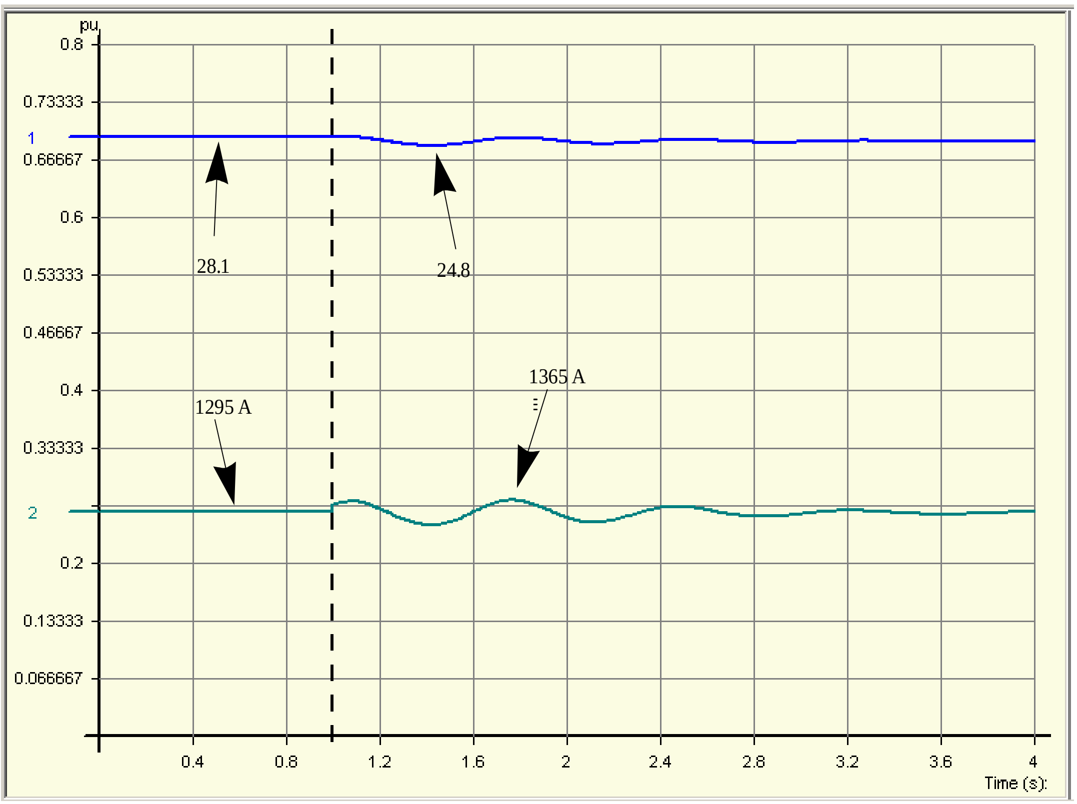


Figure 4.6 – Computer Simulation Results for Rotor Angle

Figure 4.6 shows the rotor angle (blue line) and the network current (green Line).

In order to compare results of such simulations a brief single phase to earth fault case was completed. Figure 4.7 shows the obtained results for the calculated δ(t) and Figure 4.8 for the computer simulation result for δ(t) and i(t). In this case the wind generation system is active with 12 MW of generation injected into the network.

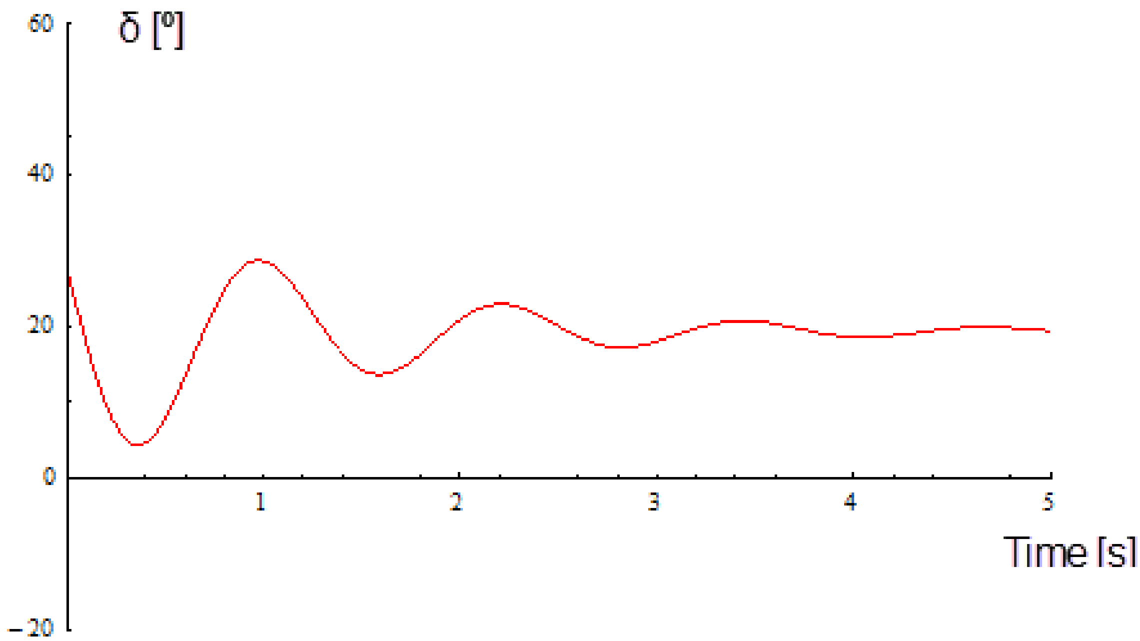


Figure 4.7 – Calculated Rotor Angle for Brief Single –Phase to Earth Fault

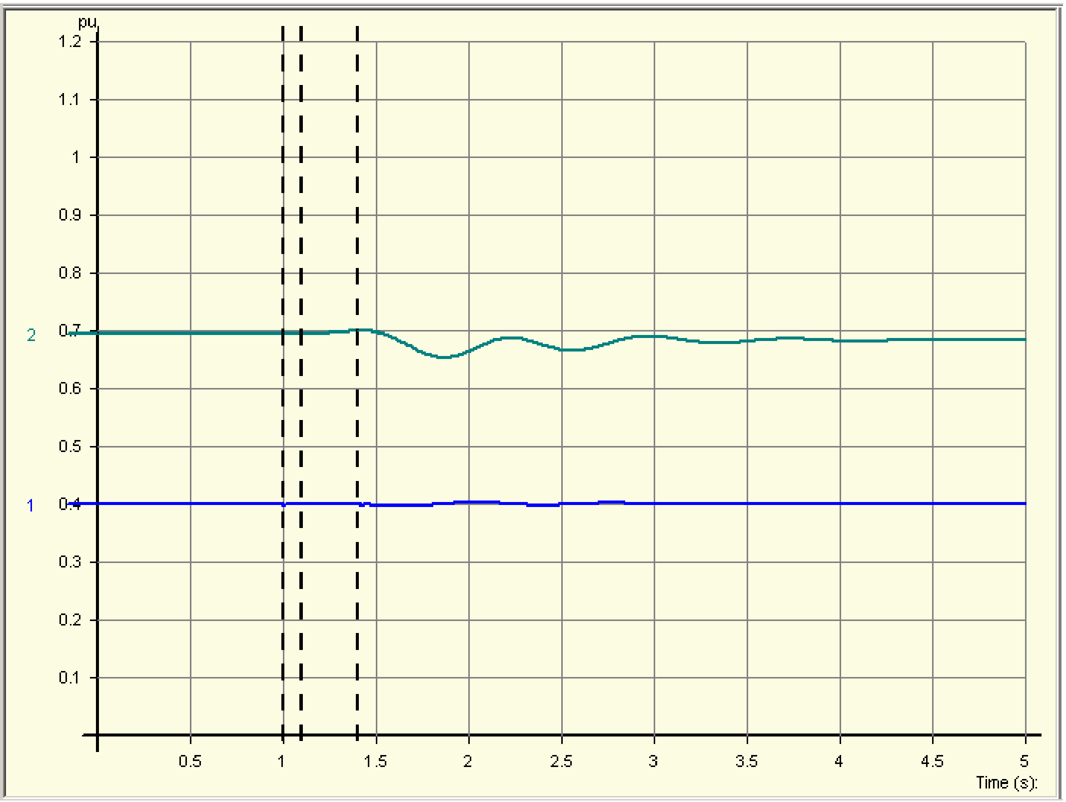


Figure 4.8 – Simulation Result for Brief Single-Phase to Earth Fault.

These calculations in the first instance can be of great use to determine the suitability of the proposed wind generation integration. The calculations are simple and results easily obtained.

4.4 EQUAL AREA CRITERIA (EAC) ANALYSIS

4.4.1 Governing Equations of the EAC

The equal area criteria has been in use for many years and can still be used to determine the effect wind generation equipment interface will have on system stability analysis.

These criteria together with the swing equation formulation are relied on to establish stability analysis results in a simple and effective way for any network that has wind generation equipment installed.

The concept of the equal area criteria makes use of graphical representation to show the type of response that can expect from a faulted system (prior, during and after disturbance). The critical information on such a graph includes the use of the rotor angle at each stage as duly calculated (pre fault rotor angle, critical rotor angle and maximum rotor angle).

During normal plant operation and making use of the swing equation in its basic form it yields:

$$\left(\frac{H}{\pi f_0}\right)\frac{d^2\delta}{dt^2} = P_m - P_e = P_a \qquad (4-10)$$

In solving this equation for rotor angle we obtain:

$$\frac{d\delta}{dt} = \sqrt{\frac{2\pi f_0}{H}\int_{\delta_0}^{\delta}(P_m - P_e)d\delta} \qquad (4-11)$$

At the first instance and prior to any disturbance, the criteria required for stability would be:

$$\int_{\delta_0}^{\delta}(P_m - P_e)d\delta = 0 \qquad (4-12)$$

In this case δ_0 would represent the starting point for any calculations (the steady-state rotor angle prior to a disturbance). In this case, the solution to equation (4-10) yields:

$$P_a = \frac{E_1 E_2}{X}\sin\delta \qquad (4-13)$$

Similar equations are obtained for the time during a fault and the time after the fault. These three equations would generate the necessary equal area graph that would establish the area criteria.

Substituting these equations into (4 - 13) and reducing will, in effect, yield the necessary formulas to obtain all relevant equations required to establish the equal area criteria curves (pre, during and post fault events). Thus [18]:

$$P_u = P_c + P_m \cos(\delta - \gamma) \qquad (4-14)$$

where

$$P_c = \frac{M_k E_1^2 Y_{11} \cos\theta_{11} - M_n E_2^2 Y_{22} \cos\theta_{22}}{M_n + M_k} \qquad (4-15)$$

and

$$\gamma = -\tan^{-1}\left(\frac{M_n + M_k}{M_n - M_k} \tan\theta_{12}\right) - 90^\circ \qquad (4-16)$$

while

$$P_m = \frac{E_1 E_2 Y_{12}\sqrt{M_1^2 + M_2^2 - 2M_1M_2\cos 2\theta_{12}}}{M_1 + M_2} \qquad (4-17)$$

From these constants and making use of equation (4-18), it is possible establish the EAC equations for the cases “During Fault” and “Fault Cleared” graphs.

While the calculations for rotor angle can determine the level of instability it is essential to remember that the duration of the fault will have a large impact on any potential level of instability.

In order to determine the critical clearing angle δ_0 it is necessary to find [13]:

$$\int_{\delta_0}^{\delta_c} P_m d\delta = \int_{\delta_c}^{\delta_{max}} (P_{max} \sin\delta - P_m)\, d\delta \qquad (4-18)$$

yielding the critical angle δ_c:

$$\delta_c = \cos^{-1}\left[\frac{P_m}{P_{max}}(\delta_{max} - \delta_0\Big) + \cos\delta_{max}\right] \qquad (4-19)$$

The critical angle, in this case, establishes the point of no return: any potential fault can no longer be present by the time this angle is reached in order to avoid potential instability in the network resulting from a transient event.

In order to find the critical clearing time it is necessary to ensure that during the fault $P_e = 0$ thus:

$$\frac{H}{\pi f_0}\frac{d^2\delta}{dt^2} = P_m \qquad (4-20)$$

yielding:

$$t = [\frac{2H(\delta - \delta_0)}{P_a}]^{0.5} \qquad (4-21)$$

Figure 4.10 displays such a curve and the time to clear a fault cannot exceed this calculated value. Above this calculated value of t, there is only instability and the potential loss of all generation.

4.4.2 EAC System Modelling

The Equal Area Criteria is a graphical representation of a network response to transient events and can be quite effective in establishing the overall limits of performance of such a network. This graphical representation method makes use of the equations stated in the previous section.

The graphical method will display the pre-fault, during-fault and post-fault responses and relevant rotor angles identifying the starting angle, the critical angle and maximum angle that would be seen under a fault. With the use of this information it is possible to graph the necessary clearing time that can be tolerated by the network prior to total loss of synchronism on the power station machines.

The equal area criteria represents a simple method of determining whether a power system will remain stable after a disturbance via the use of swing-curve plots. If the curves show that the angle between any two machines tends to increase without limit, then the system is considered to be unstable. The analysis of such a system would start with the use of the well known swing equation:

$$(H/\pi f_0)\left[\frac{d^2\delta}{dt^2}\right] = P_m - P_e = P_a \qquad (4-22)$$

where P_a is the accelerated power.

In order to make use of this equation for equal area criteria, it is manipulated to establish an area criterion as follows:

$$\left[\frac{d^2\delta}{dt^2}\right] = (\pi f_0/H)(P_m - P_e) \qquad (4-23)$$

Multiplying both sides by $2\frac{\boldsymbol{d\delta}}{\boldsymbol{dt}}$ yields:

$$2\frac{d\delta}{dt}\left[\frac{d^2\delta}{dt^2}\right] = (2\,\pi f_0/H)(P_m - P_e)\left(\frac{d\delta}{dt}\right) \qquad (4-24)$$

Reducing and integrating yields:

$$(\frac{d\delta}{dt})^2 = (\pi f_0/H)\int_{\delta_0}^{\delta_m}(P_m - P_e)\,d\delta \qquad (4-25)$$

and

$$\left(\frac{d\delta}{dt}\right) = \sqrt{(\pi f_0/H)\int_{\delta_0}^{\delta_m}(P_m - P_e)\,d\delta} \qquad (4-26)$$

Therefore, this yields an equation that establishes a change in rotor angle with respect to the synchronously revolving reference frame. Having established that the EAC makes use of the swing equation to establish the overall system response under various conditions it is evident that the results will outline key parameters in network stability as was found in the solutions to the swing equations.

Calculations performed, in this case, have made use of the data listed in Table 4.1 and displayed in Figure 4.9. This case represents an event where the wind generation connection feeder has tripped (total loss of wind generation) leaving only the power station (or network) to manage the fault and load.

Table 4.1 – Data for Rotor Angle Calculations.

Sending End Voltage	1	pu
Receiving End Voltage	0.95	pu
Reactance - Normal	0.45	
Reactance During Fault	0.95	
Reactance Post Fault	0.55	
Power	0.8	pu
C1	2.19	pu
C2	1.04	pu
C3	2.67	pu

δ1	21.35	degrees
δm	162.5	degrees
δc	102.5	degrees

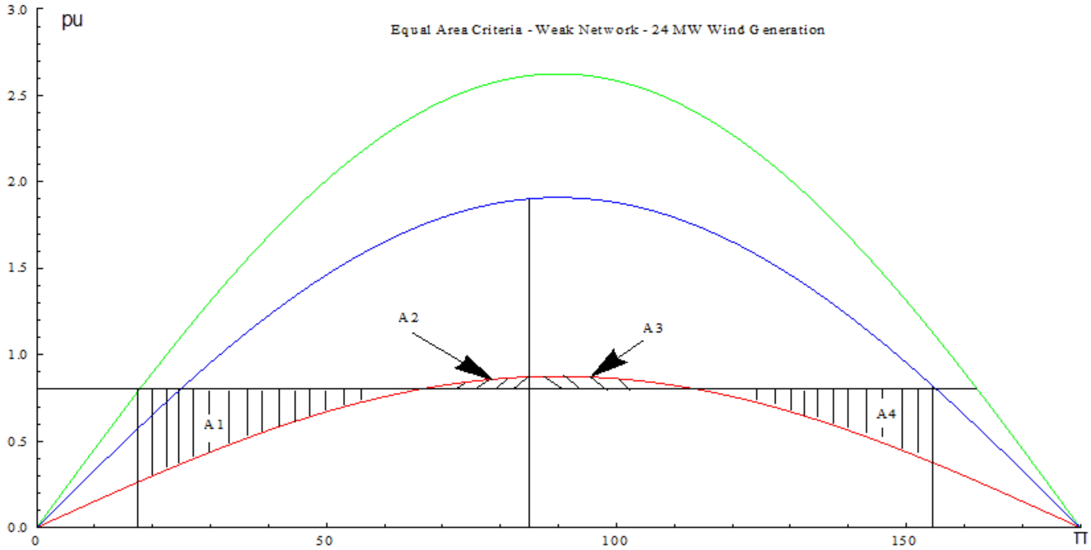


Figure 4.9 Equal Area Criteria Graph

Figure 4.9 shows the outcome of establishing an EAC graph with all the relevant information associated with a system fault and recovery.

Based on Equation (4-21) it is possible to plot the time vs. rotor angle that would give an indication of the potential for synchronism loss on the machines. Figure 4.10 displays the relevant curve.

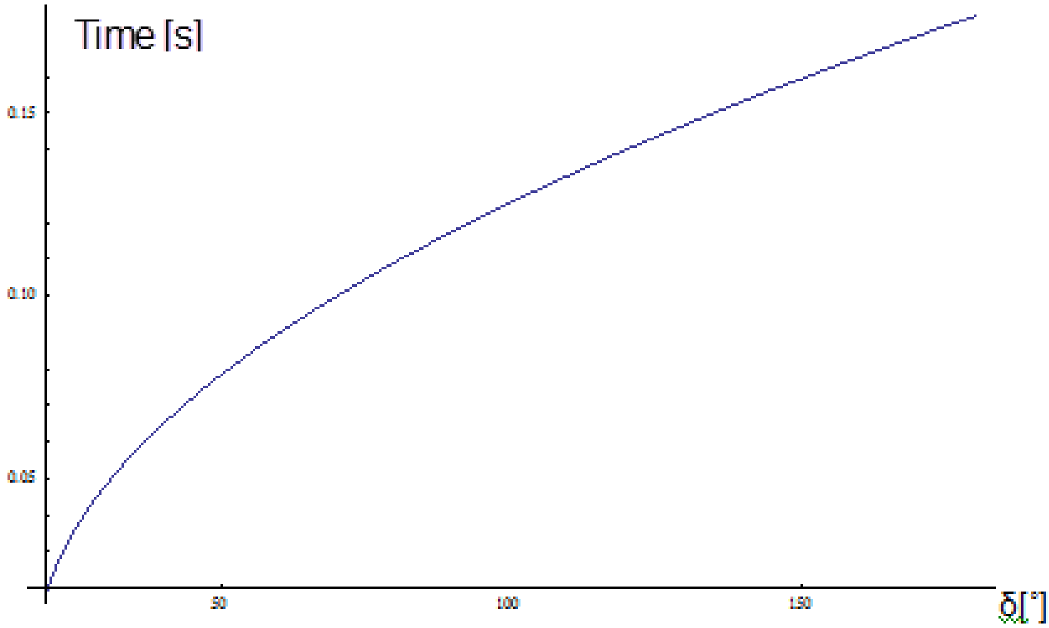


Figure 4.10 – Clearing Time (t) vs. Rotor Angle δ

In this case the fault duration would be selected from the chart based on the critical rotor angle calculated from Equation (4-19).

4.5 CONCLUSIONS

The understanding and utilisation of the Swing Equation and the Equal Area Criteria methods of stability analysis have been in application for many years, although, in this case, the application of wind generation to a weak network replaces a standard power system arrangement.

The calculations achieved with this method of analysis prove to be quite effective as a preliminary review of the application of wind generation to weak networks, in a utility interconnected configuration or islanded arrangement. The calculations required to achieve preliminary results are simple and can be quite effective in establishing a general response to transient events. The equations do not change significantly as long as the wind generation used is dealt with as standard generators with a suitable calculated inertia constant. In particular, the EAC can provide information critical to the protection settings required in order to trip any generator that approach instability (this prior to pole slip or synchronisation loss).

The use of the EAC charts can be useful to establish a preliminary critical angle at which point the network runs the risk of losing synchronism (or pole slipping) when under transient events such as caused by a fault. With weak networks, the time available for such an extreme event is short and critical. These conditions must not be ignored when the application of wind generation is under consideration.

Chapter 5. Wind Generation Quantity Usage on Weak Interconnected Networks

5.1 INTRODUCTION

When wind generation application is considered for a weak network that is interconnected to a utility system it would need to be done on the basis that an understanding of how susceptible the network would be to transient events exists and their ability to cause minor or major interruptions to the supply service is well understood.

Given the situation that each network would be different with varying generation and distribution characteristics, it will be critical to ensure an understanding of how much wind generation the network can tolerate has been completed prior to proceeding with any additional work.

This section outlines a process to understand the limitations that may exist with an interconnected network when wind generation is under consideration and to determine a possible maximum in such cases. The process used to assess this situation concentrates on calculating the rotor angle changes that occur under transient events as well as the voltage and current levels that are to be expected from these events. The current levels seen by such transients are important information in order to determine the adequacy of the protection relay settings.

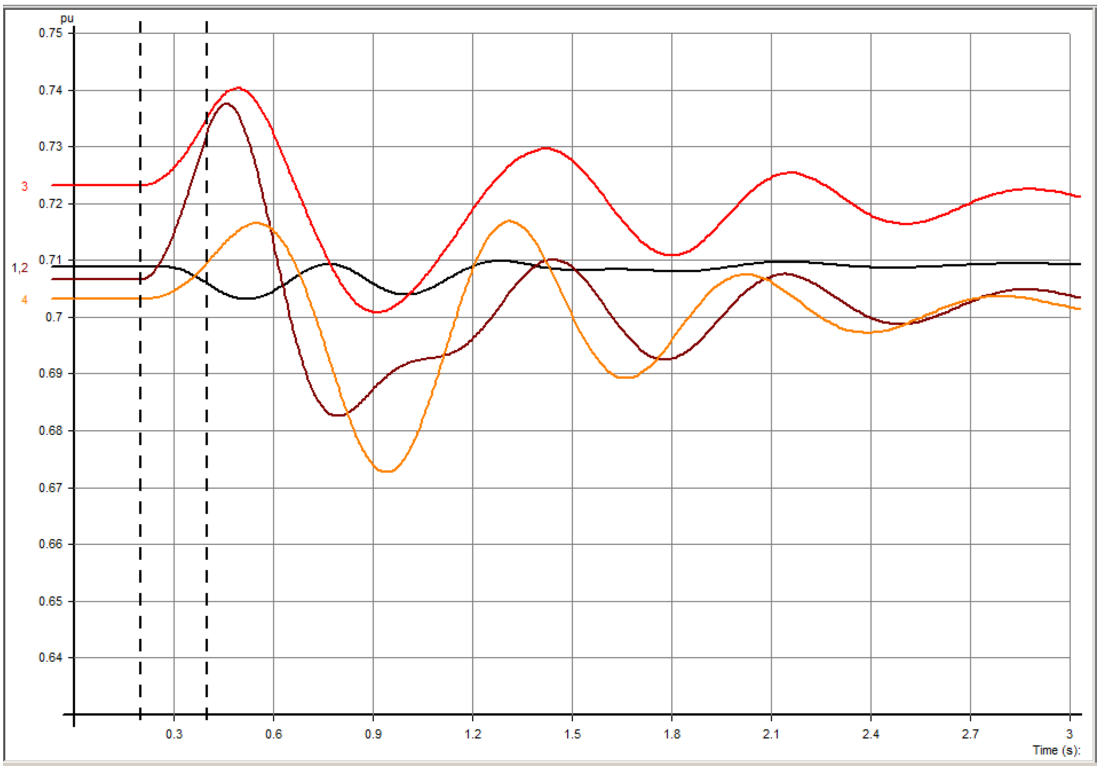
The wind generator included in the study is the GE 1.5 MW DFIG type as has been used throughout this review.

5.2 WIND GENERATION QUANTIFICATION

The number and size of each wind generator was selected based on preliminary calculations done to determine the most effective amount of wind generation that the region in question could make use of (each network would have a specific requirement or limitation). This determination was reached by considering the rotor angle changes that would be seen by the local generators (5 x 55 MVA gas turbines – only 4 units operating at any time) and the steam power station located some 600 kilometres away.

From the various simulations completed, the use of 12 MW of wind generation presented the most effective option. The application of a larger wind generation base can lead to network instability for this particular network.

The first completed model starts with the application of a small transient event and the relevant calculation of the rotor angle for the network without wind generators being interconnected. This establishes a bench mark for the rest of the simulations. Refer to Figure 5.1.



Graph Details

No.	Element	ID	Plot Description	Offset	Mult.
1	Synchronous Ge	GS-0002	Absolute Rotor Angle (°	-180	300
2	Synchronous Ge	KNO GT1	Absolute Rotor Angle (°	-180	300
3	Synchronous Ge	KNS GT1	Absolute Rotor Angle (°	-180	300
4	Synchronous Ge	ParkGen1	Absolute Rotor Angle (°	-180	300

Figure 5.1 – No Wind Generation & SFP at 132 kV Far End Bus Rotor Angles

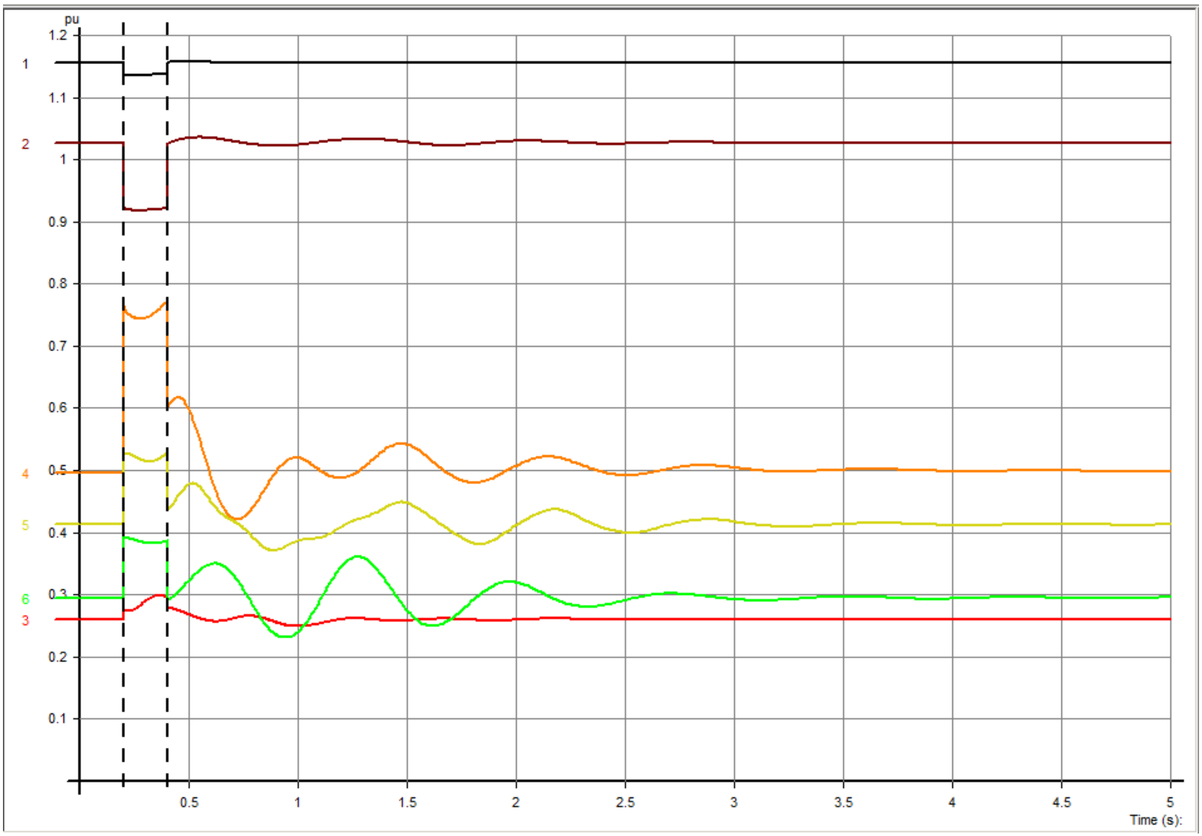
In the case where wind generation is not present, when applying a single-phase fault on the 132 kV transmission (Far End) the largest rotor angle oscillation is obtained on the closest Gas Turbine to the fault (KNO GT1). This is to be expected considering the largest voltage drop of the network would be closer to the fault location (less reactive compensation). The closest GT would see the largest reactive capacity demand having no other correction source than the generator AVR.

The rotor angles vary as follows:

Table 5.1 – No Wind Generation & SFP at 132 kV Far End Bus Rotor Angles

Machine	Pre-Fault Rotor Angle	Maximum Rotor Angle	Minimum Rotor Angle	Settling Time (sec)
GS-002	32.7º	32.8	31º	1.5
KNO GT1	30.7º	38.5º	25º	3.1
KNS GT1	35.8º	40.0º	30º	3.7
Park Gen 1	29.9º	33.0º	22.1º	3.6

As would be expected when the rotor angle of each generator oscillates the current produced by each generator will also oscillate bringing the system into instability. Considering the need to limit such oscillations in weak remote networks, the protection relays will not have much leeway causing interruption to the distribution and transmission lines that interconnect such a network. This would limit the instability to a small section of the network (isolate the fault) and thus, limit the possibility of a complete blackout in the area that would most certainly cause a large impact on the main network causing frequency fluctuations.



Graph Details

No.	Element	ID	Plot Description	Offset	Mult.
1	Busbar	Muja 220 kV	Bus Voltage (kV)	0	200
2	Busbar	WK Inc Bus	Bus Voltage (kV)	0	200
3	Synchronous Ge	GS-0002	Current (kA)	0	5
4	Synchronous Ge	KNO GT1	Current (kA)	0	5
5	Synchronous Ge	KNS GT1	Current (kA)	0	5
6	Synchronous Ge	ParkGen1	Current (kA)	0	5

Figure 5.2 – No Wind Generation & SFP at 132 kV Far End Bus Voltages & Currents

Figure 5.2 indicates that under faulted condition the local transmission system voltage (132 kV) can drop up to 9% and all area GTs will experience some rotor angle disturbance with a duration of up to 3 seconds. Those GTs with a larger load see a larger rotor angle impact.

In this case, the current fluctuations are critical, as this will give us a clear understanding whether the protection relays will trip. The following table 5.2 shows the results:

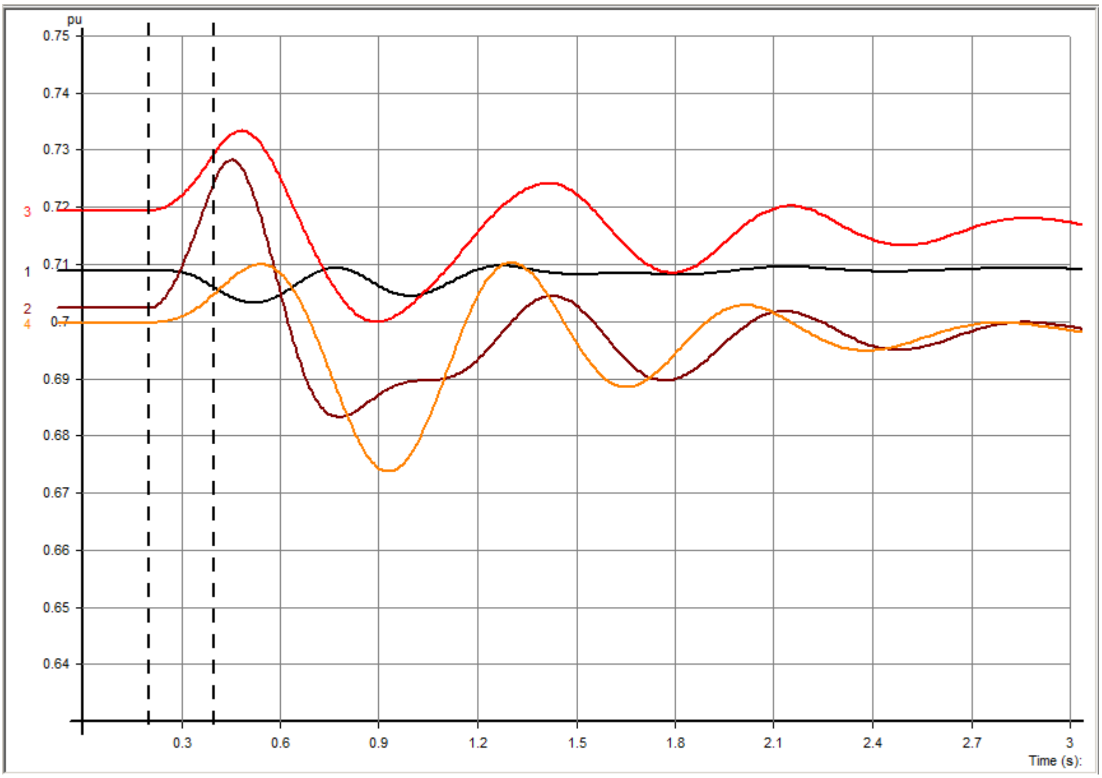
Table 5.2 – No Wind Generation & SPF at 132 kV Far End Bus Currents and Voltage

Machine	Pre-Fault Current (A)	Maximum Current (A)	Minimum Current	Settling Time (sec)
GS-002	1301	1494	1245	1.5
KNO GT1	2481	3863	2107	3.3
KNS GT1	2063	2638	1856	3.2
Park Gen 1	1477	1965	1157	2.7

The information displayed in Table 5.2 is critical and must be compared with Table 5.3 (the case where 12 MW of wind generation is interconnected).

The voltage levels displayed are only the 220 kV voltages at the start of the transmission line (Curve 1) and the voltage levels at the end of the line (Curve 2). Some degree of oscillation is evident at the far end of the 220 kV line (closest to the fault) which is to be expected.

Figure 5.6 shows the rotor angle results for a network that includes 12 MW of WT installed at the far end of the 132 kV system and very close to the fault. The results do not change significantly from the "no WT" case, but it does reduce the oscillation levels and duration of these.



Graph Details

No.	Element	ID	Plot Description	Offset	Mult.
1	Synchronous Ge	GS-0002	Absolute Rotor Angle (°	-180	300
2	Synchronous Ge	KNO GT1	Absolute Rotor Angle (°	-180	300
3	Synchronous Ge	KNS GT1	Absolute Rotor Angle (°	-180	300
4	Synchronous Ge	ParkGen1	Absolute Rotor Angle (°	-180	300

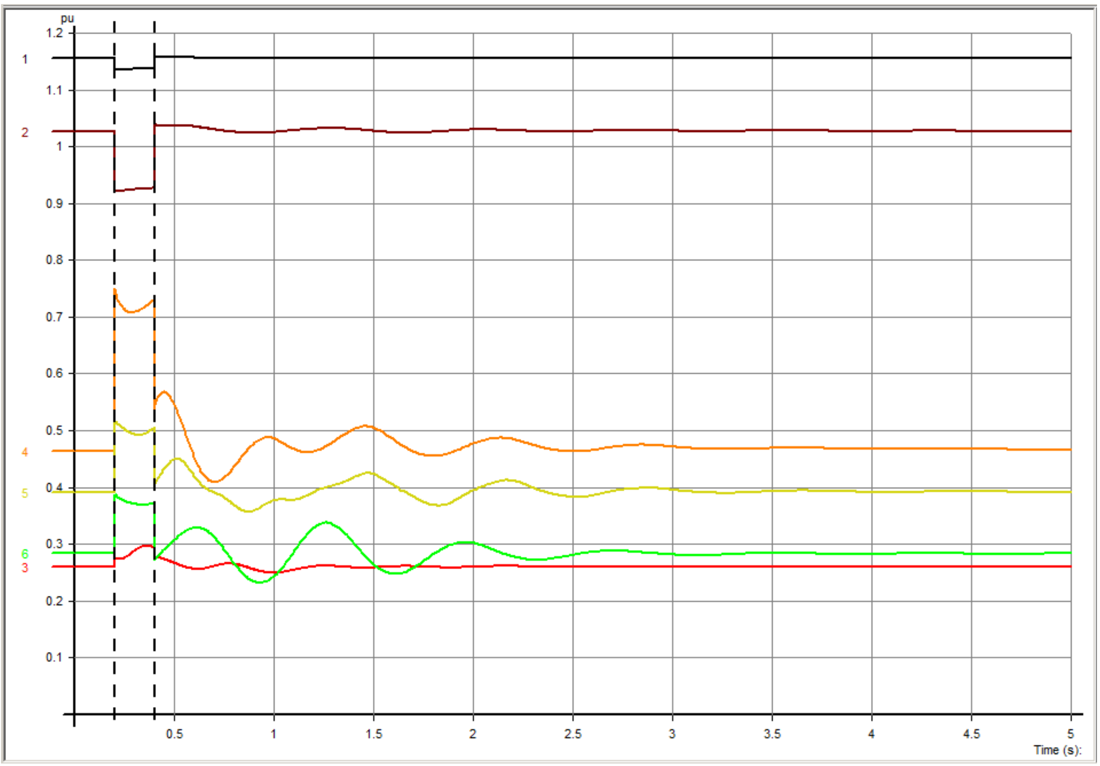
Figure 5.3 – 12 MW Wind Generation & SPF at 132 kV Far End Bus Rotor Angles

In the case where wind generation is present (12 MW), when applying a single-phase fault on the 132 kV transmission (Far End) the largest rotor angle oscillation is obtained on the closest Gas Turbine (KNO GT1) as well, although, of a lesser magnitude when compared with the case of no wind generation. The fluctuations vary as follows:

Table 5.3 – Rotor Angle Fluctuations – With 12 MW Wind Generation

Machine	Pre-Fault Rotor Angle	Maximum Rotor Angle	Minimum Rotor Angle	Settling Time (sec)
GS-002	32.7º	32.8	31º	1.5
KNO GT1	30.7º	38.5º	25º	3.1
KNS GT1	35.8º	40.0º	30º	3.7
Park Gen 1	29.9º	33.0º	22.1º	3.6

In reviewing the rotor angle, it is essential to consider the voltage drops and current fluctuations expected from such a fault on the network. Figure 5.4 shows the case for a network with 12 MW of wind generation.



Graph Details

No.	Element	ID	Plot Description	Offset	Mult.
1	Busbar	Muja 220 kV	Bus Voltage (kV)	0	200
2	Busbar	WK Inc Bus	Bus Voltage (kV)	0	200
3	Synchronous Ge	GS-0002	Current (kA)	0	5
4	Synchronous Ge	KNO GT1	Current (kA)	0	5
5	Synchronous Ge	KNS GT1	Current (kA)	0	5
6	Synchronous Ge	ParkGen1	Current (kA)	0	5

Figure 5.4 – 12 MW Wind Generation & SPF at 132 kV Far End Bus Voltages & Currents

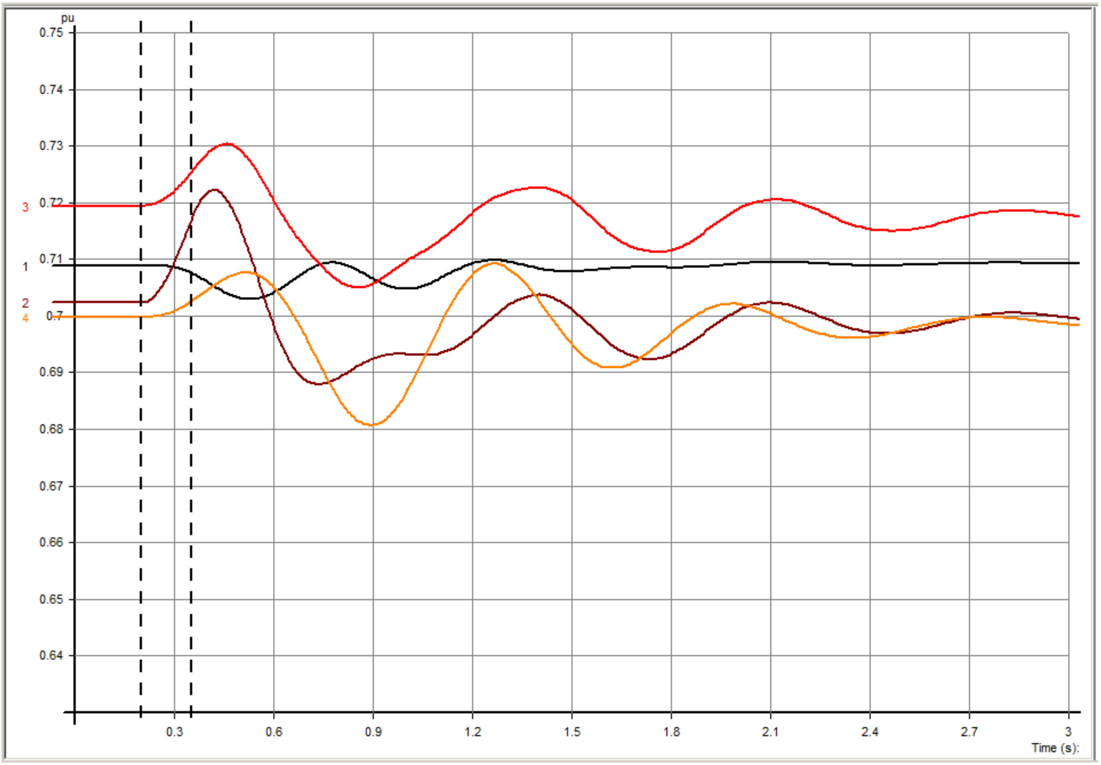
In this case, the current fluctuations are critical, as this will give us a clear understanding whether the protection relays will trip. Table 5.4 shows the results:

Table 5.4 – 12 MW Wind Generation & SPF at 132 kV Far End Bus Currents and Voltage

Machine	**Pre-Fault Current (A)**	**Maximum Current (A)**	**Minimum Current**	**Settling Time (sec)**
GS-002	1301	1486	1250	1.0
KNO GT1	2323	3755	2048	2.7
KNS GT1	1960	2574	1786	2.5
Park Gen 1	1418	1938	1162	2.7

If consideration were given to the case that tripping times for the 132 kV circuit breakers could be faster than 200 ms, we would then have a rotor angle whose oscillation would be less pronounced. Figure 5.5 shows the rotor angle for a fault cleared within 150 ms and Table 5.5 outlines the relevant data. Effectively, the lower the fault duration the less instability to the network. The CFCT would have to be set based on these results to limit the fault duration.

In order to limit any potential additional generation loss, the fault durations need to be limited and such a requirement is possible with fast protection relays.



Graph Details

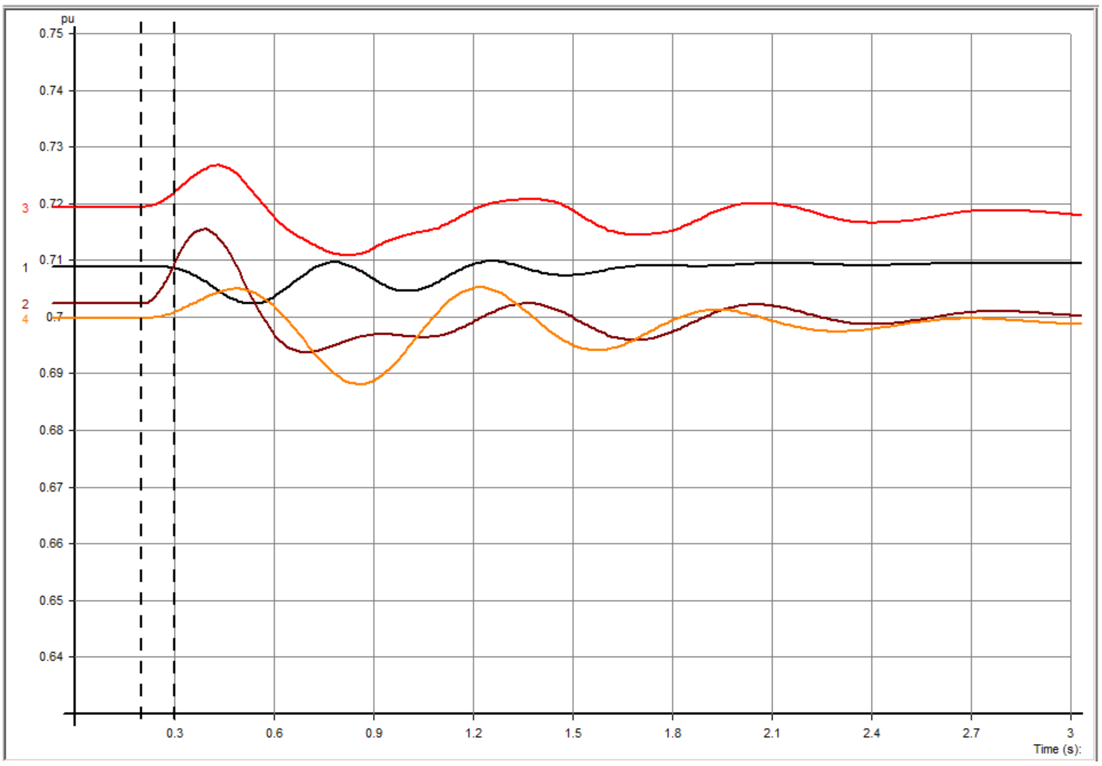
No.	Element	ID	Plot Description	Offset	Mult.
1	Synchronous Ge	GS-0002	Absolute Rotor Angle (°	-180	300
2	Synchronous Ge	KNO GT1	Absolute Rotor Angle (°	-180	300
3	Synchronous Ge	KNS GT1	Absolute Rotor Angle (°	-180	300
4	Synchronous Ge	ParkGen1	Absolute Rotor Angle (°	-180	300

Figure 5.5 - 12 MW Wind Generation & SPF at 132 kV Far End Bus Rotor Angles – 150 ms Clearing Time

Table 5.5 - 12 MW Wind Generation & SPF at 132 kV Far End Bus Currents and Voltage – 150 ms Clearing Time

Machine	Pre-Fault Rotor Angle	Maximum Rotor Angle	Minimum Rotor Angle	Settling Time (sec)
GS-002	32.7º	32.9º	30.8º	1.5
KNO GT1	30.7º	36.7º	26.4º	3.0
KNS GT1	35.8º	39.1º	31.5º	3.2
Park Gen 1	29.9º	32.8º	24.2º	3.2

In a similar manner, Figure 5.6 shows the rotor angle for a fault cleared in 100 msec and Table 5.6 shows the related information.



Graph Details

No.	Element	ID	Plot Description	Offset	Mult.
1	Synchronous Ge	GS-0002	Absolute Rotor Angle (°	-180	300
2	Synchronous Ge	KNO GT1	Absolute Rotor Angle (°	-180	300
3	Synchronous Ge	KNS GT1	Absolute Rotor Angle (°	-180	300
4	Synchronous Ge	ParkGen1	Absolute Rotor Angle (°	-180	300

Figure 5.6 - 12 MW Wind Generation & SPF at 132 kV Far End Bus Rotor Angles – 100 ms Clearing Time

Table 5.6 - 12 MW Wind Generation & SPF at 132 kV Far End Bus Currents and Voltage – 100 ms Clearing Time

Machine	Pre-Fault Rotor Angle	Maximum Rotor Angle	Minimum Rotor Angle	Settling Time (sec)
GS-002	32.7º	32.8º	30.7º	1.5
KNO GT1	30.7º	34.6º	28.1º	2.4
KNS GT1	35.8º	38.0º	33.2º	2.9
Park Gen 1	29.9º	31.5º	26.4º	2.7

What is evident in this case is the reduced duration of the oscillatory period as the fault clearing time becomes faster.

Additional simulations with smaller wind generation capacities were required. In all cases, the swings obtained from the studies above a wind generation capacity of 12 MW are considerable. At this point, the use of larger wind generation connections require faster tripping times to limit oscillations due to transient events.

5.3 THEORETICAL ESTIMATE FOR WIND GENERATION APPLICATION

In attempting to establish a possible means of theoretically determining a capacity of wind generation the weak network could withstand there is the need to consider:

- The CFCT imposed by the supply authority on the network as it pertains the end of the transmission system where the wind generators are to be installed. This will impose a protection coordination limitation.

- The maximum rotor angle that the network can sustain prior to selective or automatic tripping.

- The maximum amplitude and duration of frequency fluctuations (ROCOF) under transient conditions imposed by the utility.

Notwithstanding these issues, while such a determination is important, it is possible to consider the fault contribution that could be expected from both ends of the reduced network. In this case, by network reduction and overall fault contribution it is possible to establish basic limits that wind generation contribution will have on a weak network.

By taking into consideration a simple weak network (interconnected to a utility), it is possible to reduce the network into two specific sections as follows:

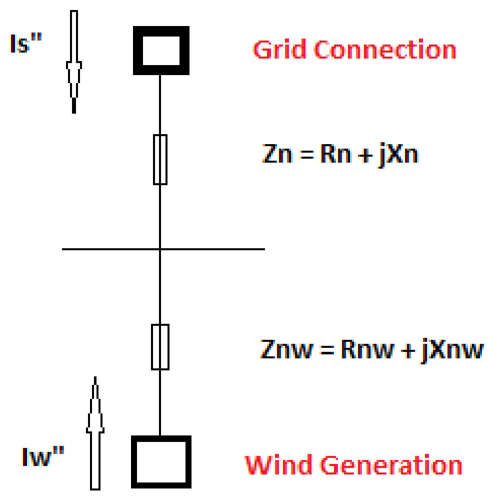


Figure 5.7 – Reduced Network

The following equations describe each section of the reduced network:

$$Z_S = \frac{c\,U_{ns}}{\sqrt{3}\,I''_{ks}} \qquad (5-1)$$

$$Z_W = \frac{c\,U_{nw}}{\sqrt{3}\,I''_{kw}} \qquad (5-2)$$

$$Z_N = R_N + jX_N \qquad (5-3)$$

$$Z_{NW} = R_{NW} + jX_{NW} \qquad (5-4)$$

- ⇨ In this case Z_S is the impedance of the source that includes the fault level at the point of connection to the utility and Z_W is the impedance of the wind generators.
- ⇨ Z_N and Z_{NW} are the respective network impedances for the source and wind generation connections.

The source Z_S and wind generator Z_W impedances can be converted to R and X based impedances such that

$$Z_S = R_S + jX_S \qquad (5-5)$$

and

$$Z_W = R_W + jX_W \qquad (5-6)$$

Reducing the impedances for each side yields:

$$(R_s + R_N) + j(X_S + X_N) \ // \ (R_W + R_{NW}) + j(X_W + X_{NW}) \qquad (5-7)$$

which is equivalent to:

$$R_{SN} + jX_{SN} \ // \ R_{WNW} + jX_{WNW} \qquad (5-8)$$

By developing this relation, equation 5-8 can be reduced as follows:

$$\frac{(R_{SN} + jX_{SN}\ ) * (R_{WNW} + jX_{WNW})}{(R_{SN} + jX_{SN}) + (R_{WNW} + jX_{WNW})} \qquad (5-9)$$

$$\frac{(R_{SN} + jX_{SN}\ )R_{WNW} + X_{WNW}(-X_{SN} + jR_{SN})}{(R_{SN} + jX_{SN}) + (R_{WNW} + jX_{WNW})} \qquad (5-10)$$

By reintroducing equations 5-1 and 5-2 this yields:

$$\frac{[I''_{ks} + (R_N + jX_N R_{WNW}) + X_{WNW}(-X_{SN} + jR_{SN})]}{[I''_{kn} + (R_N + jX_N) + [I''_{kw} + (R_{NW} + jX_{NW})]} \qquad (5-11)$$

Reducing this equivalence further:

$$\frac{\left[I''_{kw} + (R_{NW} + jX_{NW})\right]}{\left[I''_{kn} + (R_N + jX_N)\right]} = (R_{WNW} - 1) + X_{WNW}(-X_{SN} + jR_{SN}) \qquad (5-12)$$

This relation provides a ratio of the weak network to the wind generation network and includes the relevant impedances of the distribution networks for each side. By further reduction, this equation becomes:

$$\mathrm{I}_{\mathrm{kw}}^{''} = \mathrm{I}_{\mathrm{kn}}^{''} * \mathrm{A} + \mathrm{B} \qquad (5-13)$$

Where:

$$A = (\mathrm{R}_{\mathrm{WNW}} - 1) + \mathrm{X}_{\mathrm{WNW}}(-\mathrm{X}_{\mathrm{SN}} + \mathrm{jR}_{\mathrm{SN}}) \qquad (5-14)$$

$$B = \mathrm{R}_{\mathrm{N}} + \mathrm{jX}_{\mathrm{N}}[(\mathrm{R}_{\mathrm{WNW}} - 1) + \mathrm{X}_{\mathrm{WNW}}(-\mathrm{X}_{\mathrm{SN}} + \mathrm{jR}_{\mathrm{SN}}) - \mathrm{R}_{\mathrm{NW}} + \mathrm{jX}_{\mathrm{NW}} \qquad (5-15)$$

By inspection for small values of B

$$\frac{\mathrm{I}_{\mathrm{kw}}^{''}}{\mathrm{I}_{\mathrm{kn}}^{''}} = A \qquad (5-16)$$

This ratio, when carefully considered, will assist in establishing a maximum wind generation contribution (by total wind generation fault contribution). The constant A includes all relevant information on the networks. This will be important, as each weak network will be unique.

The overall impedance of the source side of the network will be much smaller than the impedance of the wind generation side and that would indicate a larger fault contribution from the source network. Thus:

$$\mathrm{I}_{\mathrm{kn}}^{''} \gg \mathrm{I}_{\mathrm{kw}}^{''} \qquad (5-17)$$

5.4 CONCLUSIONS

When considering the use of wind generation interfaced to a weak network, it will always be necessary to consider the capacity of such generation a network can tolerate under transient events prior to instability. The approach used will assist in developing a simple method to determine the limitations of the weak network to manage wind generation additions. The theoretical calculations developed assist in estimating an acceptable wind generation interface by using the fault level contributions from each end of the network and including the relevant distribution system impedances.

This section has reviewed the use of up to 12 MW of wind generation interfaced at the end of a weak network with special emphasis placed on the rotor angle response to system disturbances. Consideration of the current fluctuations under faulted conditions has been included, as this will become a key issue when designing a suitable protection system. Critically, the current levels of the local generators will be affected by the rotor angle fluctuations.

Chapter 6. Interconnected Weak Networks

6.1 INTRODUCTION

In this chapter consideration is given to the application of wind generation to a network that is not islanded and that interfaces to a commercial network such as a utility company or other similar entity. The need to have a clear understanding of why a particular network is weak is paramount and it is necessary to identify those areas/issues that make a network weak.

For the purpose of this research, the network selected has some similarities with an existing remote interfaced network, but it is not exact. This network has always been vulnerable to extreme weather conditions, is radial in design and supplies a large industrial load. The region it covers has excellent environmental conditions for the application of renewal energy technology.

The addition of wind generators (DFIG) to this network is to be interfaced at the far end of the transmission system. This option represents a connection with the highest potential for instability.

The review will include the effect that this additional generation, when operational, will have on network stability when either under fault or large transient events (i.e. load acceptance and load rejection).

6.2 THE WEAK NETWORK UNDER CONSIDERATION

This research project can be justified given the scarce utilisation of wind generation equipment at remote industrial operations of Western Australia and, as such, the existing network is used to simulate such issues as network stability, network capacity and its ability to interface renewable technology.

This network, while not accurately simulated, demands difficult interface requirements when additional generation equipment (in general) is considered for connection in such a remote location.

This remote network interfaces to the main body of the network via a single radial 220 kV transmission line that is some 600 kilometres in length and susceptible to all kinds of environmental issues such as lightning strikes, tornados, etc… The weak network at the far end of the transmission line includes the following:

- ⇨ The total load can exceed 250 MW in the region with 85% industrial (Mining and Mineral Processing) load. As with all remote industrial loads, it is transient in nature with heavy machinery in operation (mostly inductive load).
- ⇨ The network losses in this case are high due to long transmission (132 kV) and distribution lines. The need to inject reactive compensation is high at all times and achieved via the use of a limited amount of capacitor bank utilisation and some local generation.
- ⇨ Local generation is found in various sections of the remote network, mostly in the form of industrial Gas Turbines (55 MVA) which supply large, private industrial loads.
- ⇨ At times, the load can significantly drop when major maintenance programs take place.
- ⇨ The most significant transient event would be the loss of a section of the local generation, which is backed up by the network interface capacity. A sufficiently large local generation loss might be associated with a surge in demand from the main distribution network potentially bringing some degree of instability to the main network (mostly frequency fluctuations).

The network under consideration includes long radial transmission lines, radial distribution lines and some level of generation that is mostly concentrated in small areas or sections of the network. Figure 6.1 shows the selected network.

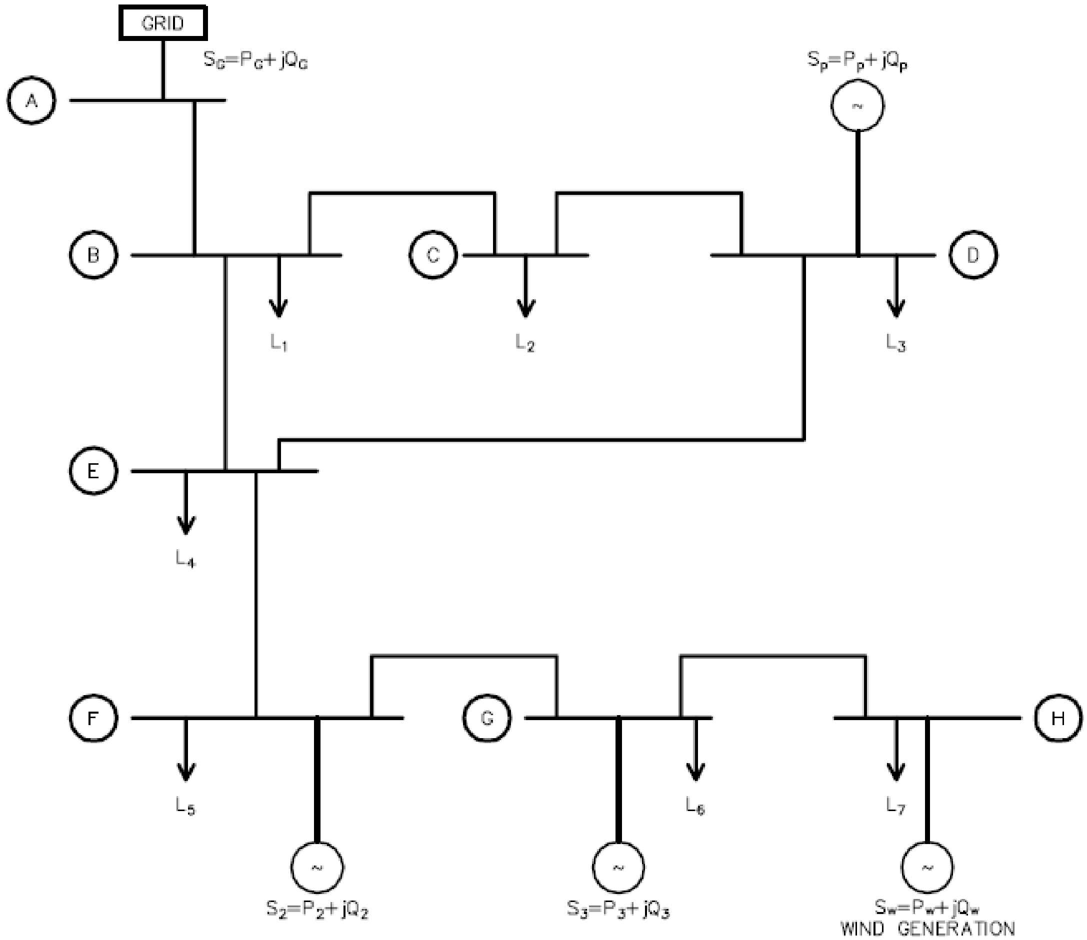


Figure 6.1 Radial Interconnected Network Under Consideration

The southern section of this network is composed of mining operations only.

All wind generators are connected at the far end of the distribution system, a location that is representative of an extreme location for a weak network. In this case, the installation of wind generation has been connected at two separate locations with equal generating capacity (4 x 1.5 MW), thus generating a maximum of 12 MW.

The computer model completed is very detailed and includes all areas of the network (includes surface and underground mining installations). A reduction of the model was required in order to consider the most critical parts of the network – in this case the transmission and sub-transmission sections of the network.

This network has also been modelled to include the main power station that supplies the 220 kV power transmission line which then connects to the weak network located some 600 kilometres away.

Figure 6.2 shows, in detail, the wind generation interface installed at the far end of the transmission line. The split wind generation system interfaces to a radial 132 kV transmission lines that then interfaces to the rest of the remote network.

The wind turbine installation is composed of two separate groups in order to limit any potential transient event that could arise from a section loss (i.e. fault trip). This option offers the opportunity to add further wind generation units to the weak network considering the small amount of units that could trip from the network under fault.

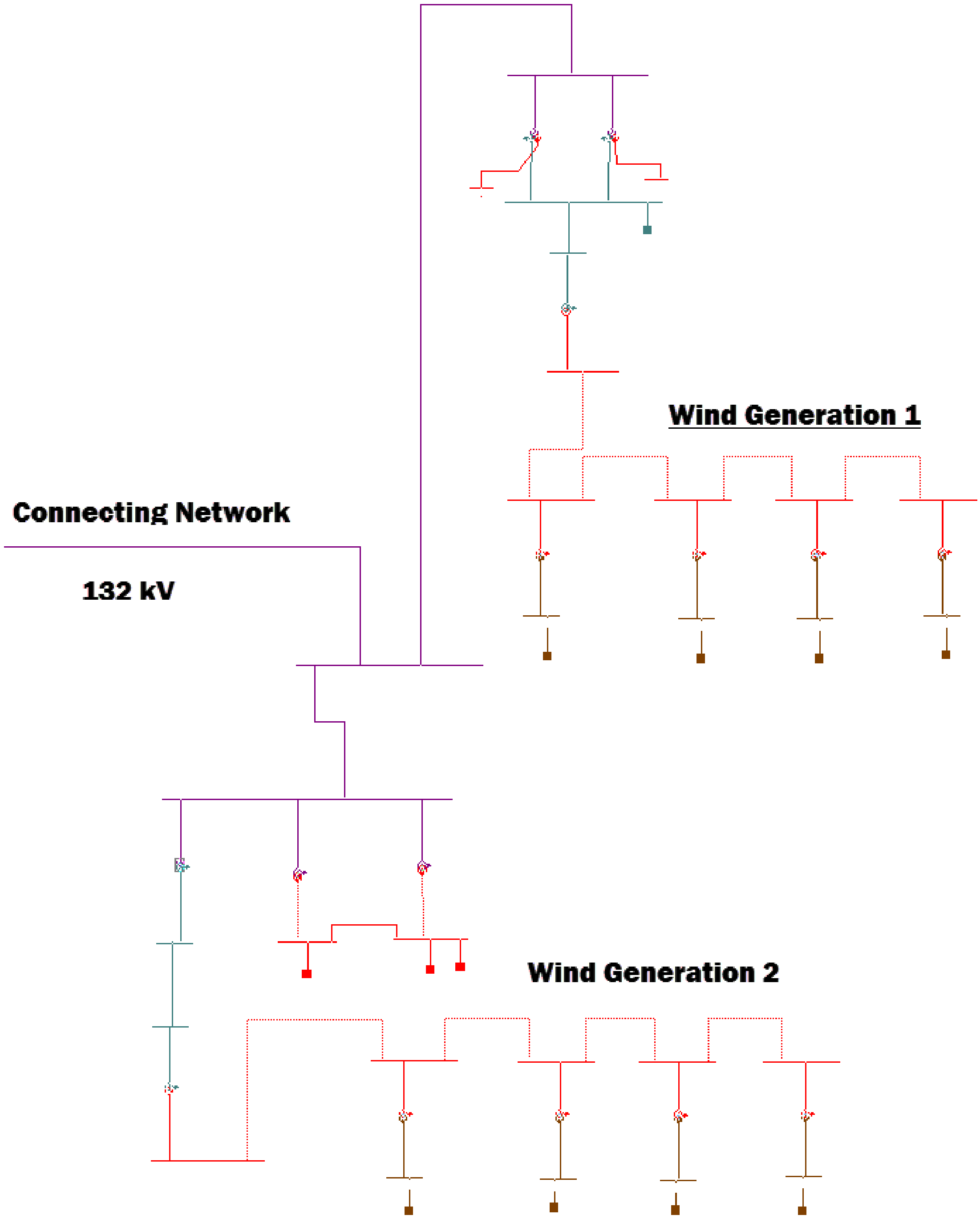


Figure 6.2 – Wind Generation Interface – Two Separate Locations

The wind generation arrangement selected emulates a typical installation where the wind generation unit operates on low voltage directly connected to a step-up transformer that interfaces to the local network. Figure 6.3 shows a typical installation.

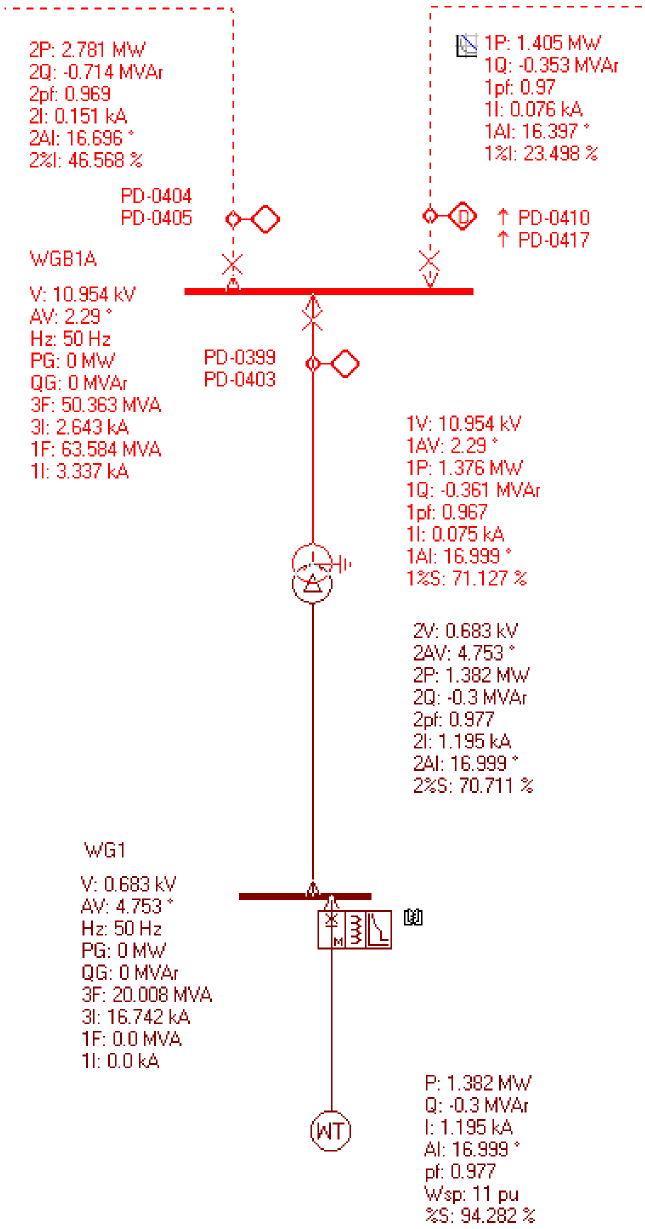


Figure 6.3 – Wind Generation Interface

The interface of wind generation to any network will vary according to the type of WT used and the earthing characteristic of the network interface arrangement (usually at 11 kV). The power step-up transformer vector group could slightly vary according to the arrangements found at the switchyard interface.

6.3 TRANSIENT EVENTS UNDER CONSIDERATION

Considering that the network under review is very similar to an existing network it has been necessary to simulate typical transient events that can be expected in these industrial installations. The more traditional events can been considered as follows:

- ⇨ Three-Phase fault that could occur in any section of the transmission and distribution system. Generally, this could be more frequent in the distribution areas.
- ⇨ Single-phase fault that could take place in the transmission and distribution system with particular emphasis being possible lightning strikes that are common in this region.
- ⇨ Load acceptance and load rejection of large drives installed in the network. The single largest drive installed is a cyclo-converter based 13 MW drive (Sag Mill Drive).

These events have been well documented in the past and can be considered simple to model. With the application of wind generation at the far end of the network (also the location where the largest drives are installed) it would be necessary to have the models re-calculate the transient events that would take place and see what contribution these had under such transient occurrences. Ride-through capabilities of the wind generation machines is also important.

6.4 SINGLE AND THREE-PHASE FAULT EVENTS

The dynamic model of the wind generators used (DFIG) includes the ability to ride-through at all times in order to assist with voltage stability under faulted conditions.

The application of fault events on the network are applied close to the wind generation units and preferably, on the 132 kV transmission lines, although faults at 11 kV levels have also been simulated.

The fault durations have been set to be in line with existing protection settings used in the network - no longer than 200 ms.

Figure 6.4 shows a transient simulation with two voltage level outcomes; at a distant 132 kV bus (from the fault) and the regional transmission line incomer 220 kV bus without wind generation at the far end.

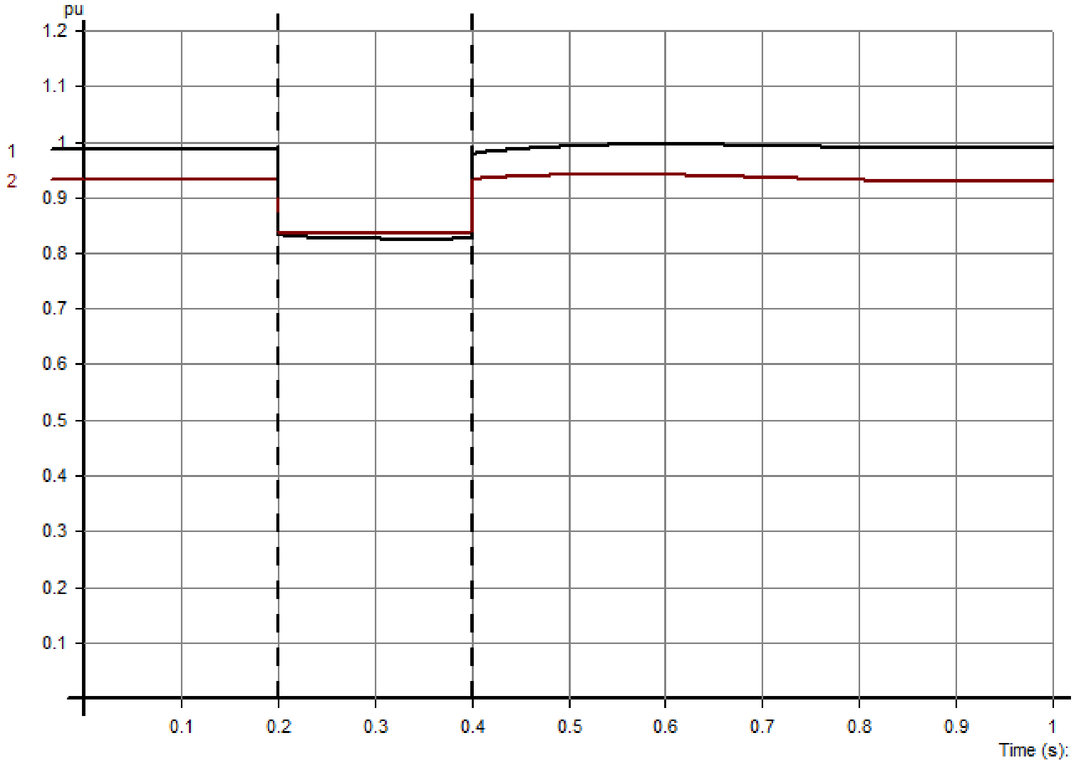


Figure 6.4 – Voltage Levels (No Wind Generation)

Curve 1 (Black) – 220 kV

Curve 2 (Brown) – 132 kV

Figure 6.5 shows the same transient stability model with two sets of 4 x 1.5 MW wind generation units and this clearly shows that the wind generation assists with voltage stability at the distant switchyards.

In both cases, the inherent weakness of the network is evident given the large voltage drop that takes place under any type of fault. Yet, the wind generation will have a voltage support for the network and this provides sufficient argument to increase the amount of wind generation as long as this does not exceed the expected load of the interconnecting 132 kV transmission line that interfaces the wind generation units and the rest of the network.

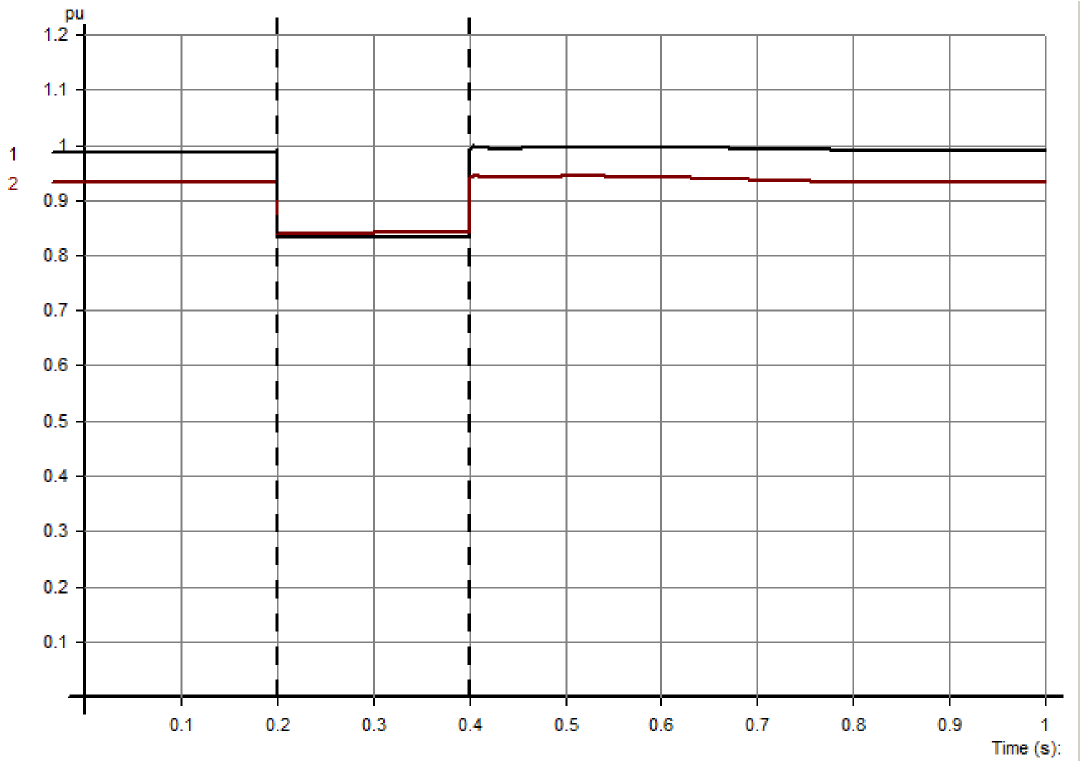


Figure 6.5 – Voltage Levels (With Wind Generation)

Curve 1 (Black) – 220 kV

Curve 2 (Brown) – 132 kV

While this argument could hold for a voltage-based analysis, it is essential to look at the rotor angle of the generation equipment installed in the region. There are three locations where Gas Turbine installations form part of this network. Their response to transients, including the total loss of wind generation due to a fault, must be understood and considered when establishing a final location for wind generation interface.

Simulations have been conducted and, initially, a fault on the 132 kV transmission system close to the wind generators was implemented. Figure 6.6 shows the rotor angle responses to a single-phase fault. In this case, the duration of the singe phase fault is 200 ms and the rotor angle fluctuates from 35.8 º degrees to a maximum of 38.8 º degrees and a minimum of 30.9 º degrees for the red line.

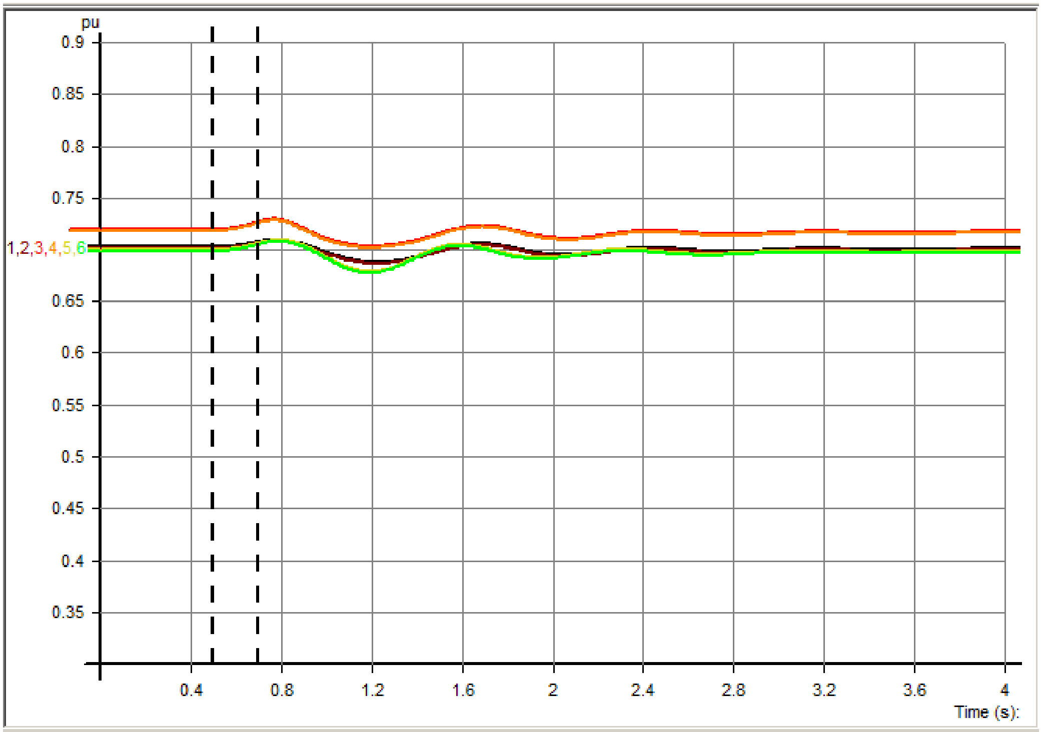


Figure 6.6 – Rotor Angle of Local Gas Turbine Generators with a Single-Phase Fault on 132 kV Transmission Line.

Numbers 1,2,3,4,5,6 – Rotor Angle for all six GTs used in the region

As can be expected, the rotor angle responses for the three GT's will be less oscillatory when under a single-phase fault. This response can be managed and possibly limit a loss of the transmission system (due to overload protection trip) in the network. Each generator has a slightly different transient response based on the load that they have at the time of the fault.

The duration of the oscillation is relatively short and the amplitude of the oscillation is limited to no more than 10º. When considering this event the possibility of having a protection relay trip will be dependent on how limiting the protection settings used are (CFCT related).

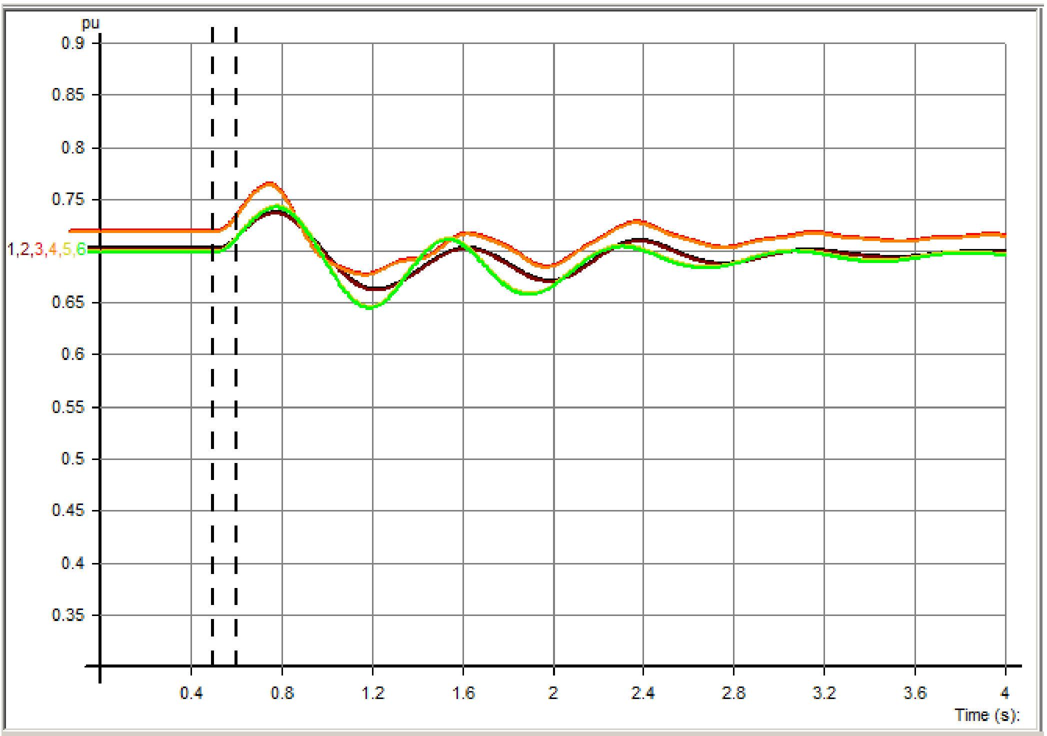
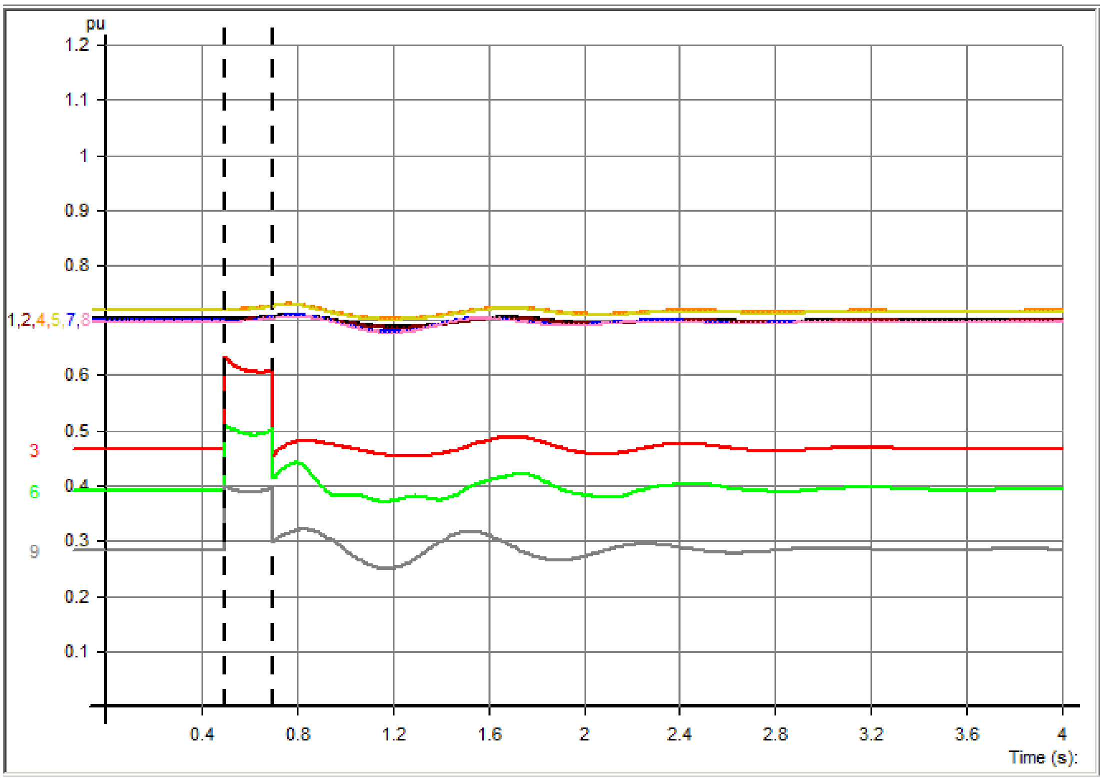


Figure 6.7 – Rotor Angle of Local Gas Turbine Generators with a Three Phase Fault on 132 kV Transmission Line.

Numbers 1,2,3,4,5,6 – Rotor Angle for all six GTs used in the region

In Figure 6.7, as can be expected, the rotor angles are more pronounced and varied, starting at 35.8 º degrees to a maximum of 49.4 º degrees and down to a minimum of 23.4 º degrees.

When looking at this same event and including the current generated by the gas turbines, it is possible to see quite a variation during and after the fault. Figure 6.8 shows the case for a single-phase fault and Figure 6.9 for the three-phase fault case.

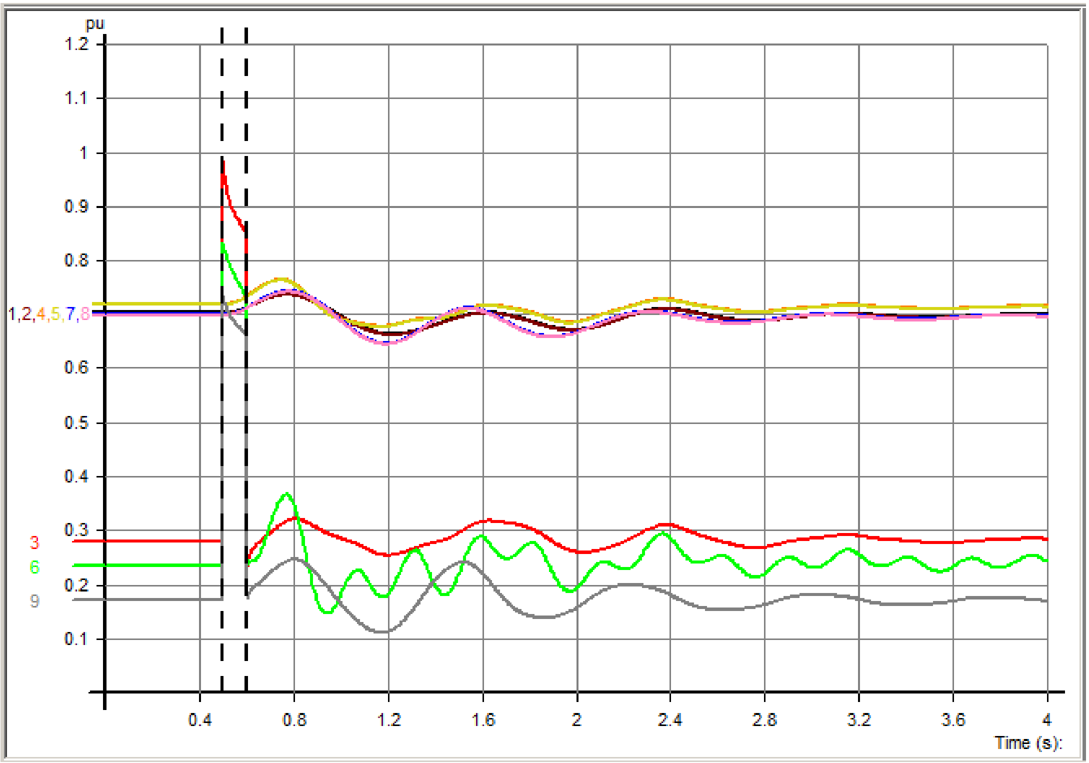


Graph Details

No.	Element	ID	Plot Description	Offset	Mult.
1	Synchronous Ge	KNO GT1	Absolute Rotor Angle (°	-180	300
2	Synchronous Ge	KNO GT1	Relative Rotor Angle (°)	-180	300
3	Synchronous Ge	KNO GT1	Current (kA)	0	5
4	Synchronous Ge	KNS GT1	Absolute Rotor Angle (°	-180	300
5	Synchronous Ge	KNS GT1	Relative Rotor Angle (°)	-180	300
6	Synchronous Ge	KNS GT1	Current (kA)	0	5
7	Synchronous Ge	ParkGen1	Absolute Rotor Angle (°	-180	300
8	Synchronous Ge	ParkGen1	Relative Rotor Angle (°)	-180	300
9	Synchronous Ge	ParkGen1	Current (kA)	0	5

Figure 6.8 – Single-Phase Fault on 132 kV Transmission Line Including Current Response for Each Generator

The current fluctuations in these cases are very critical as they will activate the protection relays and could trip when the fluctuations exceed the established settings. This situation could further compound the problem of stability to the supply network (loss of the 220 kV incoming transmission line).



Graph Details

No.	Element	ID	Plot Description	Offset	Mult.
1	Synchronous Ge	KNO GT1	Absolute Rotor Angle (°	-180	300
2	Synchronous Ge	KNO GT1	Relative Rotor Angle (°)	-180	300
3	Synchronous Ge	KNO GT1	Current (kA)	0	8.33
4	Synchronous Ge	KNS GT1	Absolute Rotor Angle (°	-180	300
5	Synchronous Ge	KNS GT1	Relative Rotor Angle (°)	-180	300
6	Synchronous Ge	KNS GT1	Current (kA)	0	8.33
7	Synchronous Ge	ParkGen1	Absolute Rotor Angle (°	-180	300
8	Synchronous Ge	ParkGen1	Relative Rotor Angle (°)	-180	300
9	Synchronous Ge	ParkGen1	Current (kA)	0	8.33

Figure 6.9 – Three-Phase Fault on 132 kV Transmission Including Current Response for Each Generator

Figure 6.8 shows the single-phase fault current amplitude and overall time response during and after the fault. The wind generators, in this case, can help with recovery as long as the fault clearing time does not exceed the critical time.

Figure 6.9 clearly indicates that irrespective of how much wind generation is included in the model the demands imposed by the 3-phase fault exceed the network capabilities. The protection settings, although isolating the fault, would not be fast enough to avoid a blackout and further instability for the network. In addition, a further case where, under such extreme conditions, the possibility of pole slipping of the generators could take place if the protection equipment fails to trip the gas turbine units.

These events are extreme cases, although the possibilities of such occurrences, rare as they may seem, could take place.

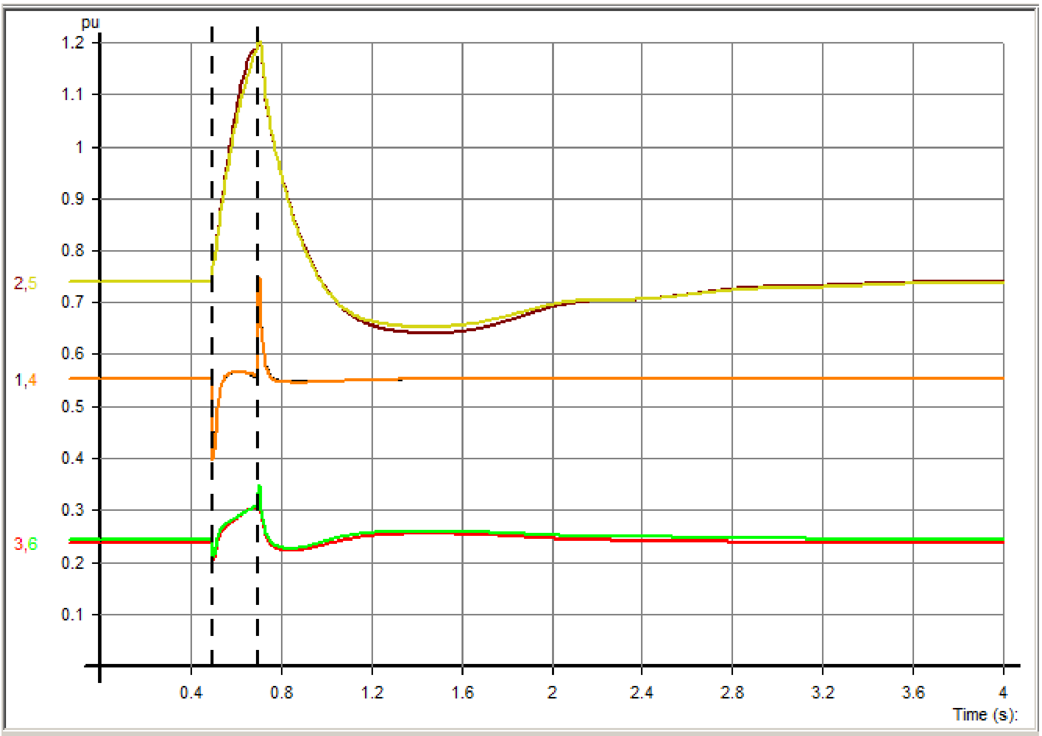
6.5 WIND GENERATION RESPONSE

While it is possible to consider the overall response of the network under such extreme events, it is essential to determine how the wind generation equipment will respond to these transients.

The wind generation equipment installed at the extreme end of the network would be vulnerable to any such faults limiting its ability to ride-through.

One generator forming part of each leg has been selected for a transient stability graph (these will be synonymous of all other unit’s response). Figure 6.10 shows the single-phase fault case on the 132 kV line.

The response of both sets of turbines is identical implying that all wind turbines are sharing the transient load and assisting with voltage ride-through. On clearing of the fault incident, the system tends toward stability within a short period of time as would be expected.

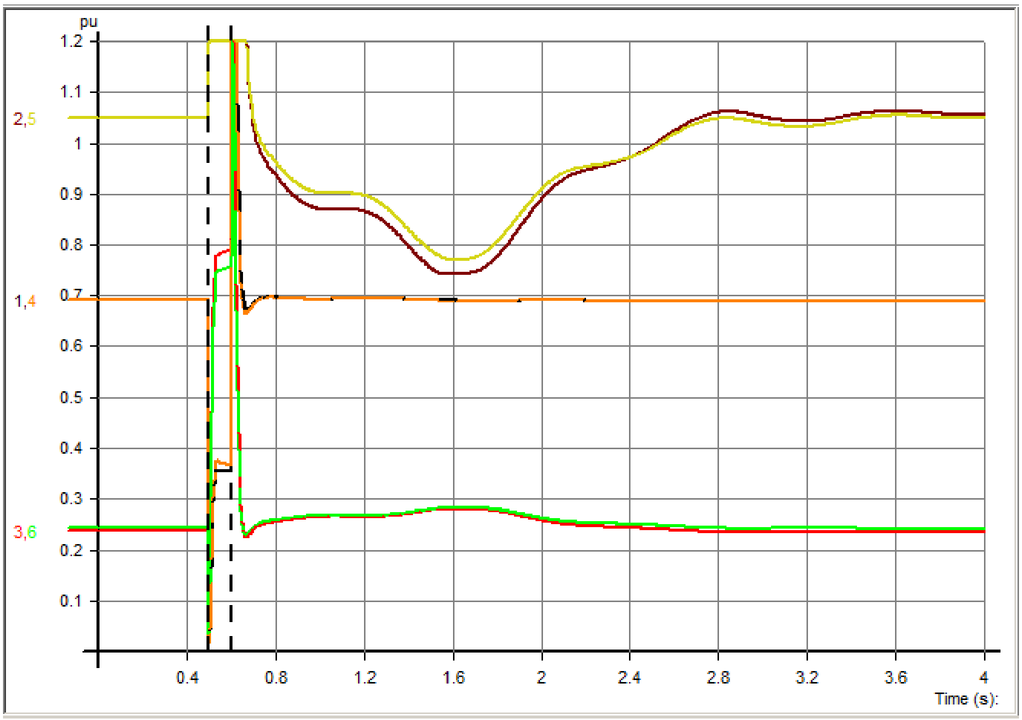


Graph Details

No.	Element	ID	Plot Description	Offset	Mult.
1	Wind Turbine Ge	WT-0001	Electrical Power (MW)	0	2.5
2	Wind Turbine Ge	WT-0001	Reactive Power (MVAr)	-2.4	2.83
3	Wind Turbine Ge	WT-0001	Current Magnitude (kA)	0	5
4	Wind Turbine Ge	WT-0002	Electrical Power (MW)	0	2.5
5	Wind Turbine Ge	WT-0002	Reactive Power (MVAr)	-2.4	2.83
6	Wind Turbine Ge	WT-0002	Current Magnitude (kA)	0	5

Figure 6.10 – Ride-Through Data for Wind Generation Units Under Single Phase Fault.

The reactive power injected by each of the eight wind generation units will assist in maintaining voltage control, in particular, for the single-phase fault case as long as the protection relays do not operate in haste. The maximum fault duration must not exceed the 200 ms in order to avert a total feeder connection loss. This particular subject matter forms part of Section 8 under protection coordination issues.



Graph Details

No.	Element	ID	Plot Description	Offset	Mult.
1	Wind Turbine Ge	WT-0001	Electrical Power (MW)	0	2
2	Wind Turbine Ge	WT-0001	Reactive Power (MVAr)	-2.4	2
3	Wind Turbine Ge	WT-0001	Current Magnitude (kA)	0	5
4	Wind Turbine Ge	WT-0002	Electrical Power (MW)	0	2
5	Wind Turbine Ge	WT-0002	Reactive Power (MVAr)	-2.4	2
6	Wind Turbine Ge	WT-0002	Current Magnitude (kA)	0	5

Figure 6.11 - Ride-Through Data for Wind Generation Units Under Three Phase Fault.

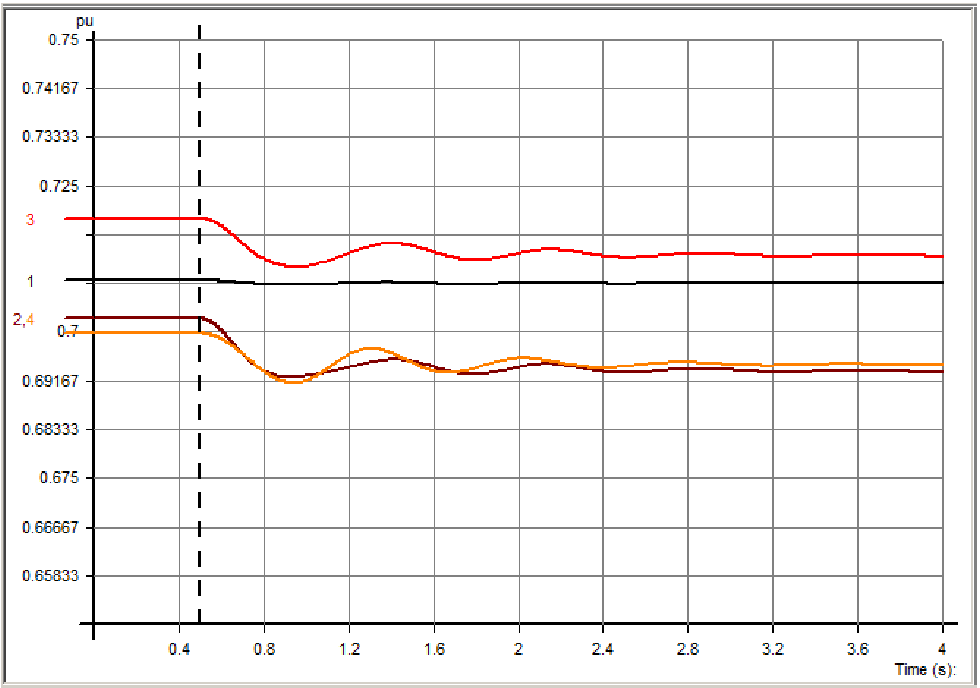
Figure 6.11 shows a similar result for a three-phase fault. The impact is significant and the ability of the wind generation system to assist with voltage support is very limited. In this case, the wind generation protection relays would trip on overload.

6.6 MAXIMUM WIND GENERATION

The application of wind generation to a weak network with these characteristics will impose, above all things, a limitation initiated by the characteristics of the weak network.

In attempting to establish the maximum safe quantity of wind generation acceptable to a weak interconnected network it has been necessary to simulate various wind capacities as connected to the network (Refer to Chapter 5).

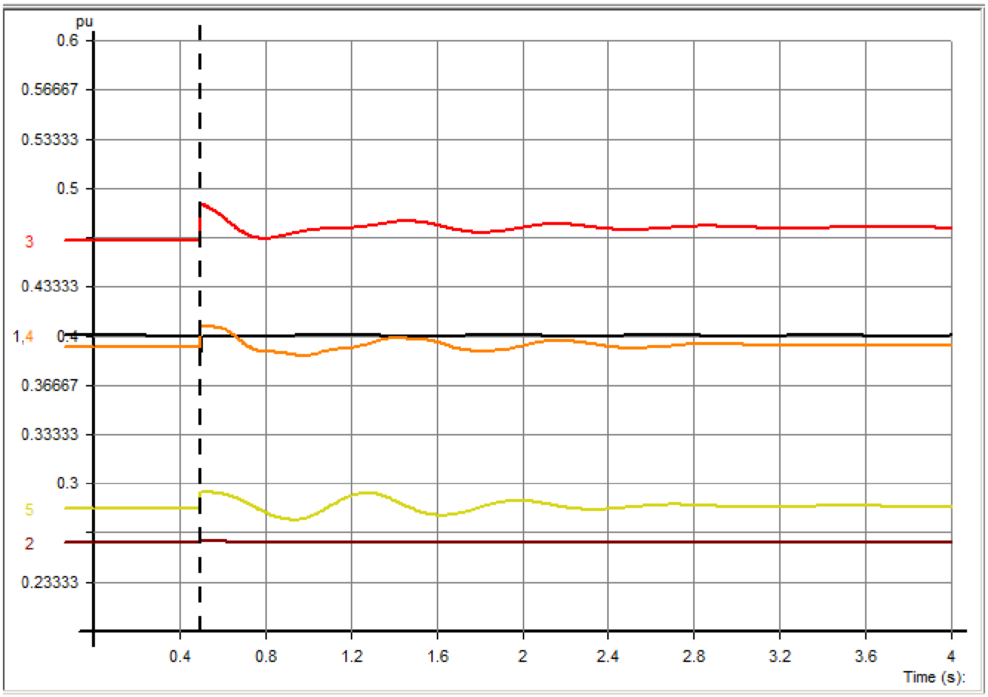
The most critical aspects of such an event would be the fluctuations brought about by the rotor angle that would cause a large fluctuation on the current load the generator could see. This could be large enough to set off all overcurrent protection relays in the overhead power lines and generators themselves. Figures 6.12 and 6.13 show such events when 12 MW of wind generation trips (assuming a single point of connection).



Graph Details

No.	Element	ID	Plot Description	Offset	Mult.
1	Synchronous Ge	GS-0002	Absolute Rotor Angle (°	-180	300
2	Synchronous Ge	KNO GT1	Absolute Rotor Angle (°	-180	300
3	Synchronous Ge	KNS GT1	Absolute Rotor Angle (°	-180	300
4	Synchronous Ge	ParkGen1	Absolute Rotor Angle (°	-180	300

Figure 6.12 – Rotor Angles of Various Generators in the Network



Graph Details

No.	Element	ID	Plot Description	Offset	Mult.
1	Busbar	Boul HV Bus	Bus Frequency (Hz)	40	25
2	Synchronous Ge	GS-0002	Current (kA)	0	5
3	Synchronous Ge	KNO GT1	Current (kA)	0	5
4	Synchronous Ge	KNS GT1	Current (kA)	0	5
5	Synchronous Ge	ParkGen1	Current (kA)	0	5

Figure 6.13 – Current Fluctuation on Network Generators Due to Wind Generation Loss.

Regional generators would see the transient event in a more pronounced mode as compared to distant units. In this case, the loss of any additional regional generation would bring about a larger transient on the network, potentially causing a domino effect and significant blackouts that could affect large sections of the main network.

The maximum amount of acceptable wind generation interconnected to a weak network is determined via the use of the swing equation as has been previously mentioned in Section 4. A network reduction equivalent arrangement can be done and include the wind generation as the second set of generation stream.

$$\frac{H_n}{\pi f_0}\frac{d^2\delta_n}{dt^2} = P_{M_n} - \sum_{j=1}^{m}|E_n^{'}||E_j^{'}|\,|Y_{nj}|\cos(\theta_{nj} - \delta_n + \delta_j) \qquad (6\text{-}1)$$

and

$$\frac{H_k}{\pi f_0}\frac{d^2\delta_k}{dt^2} = P_{M_k} - \sum_{j=1}^{m}|E_k^{'}||E_j^{'}|\,|Y_{kj}|\cos(\theta_{kj} - \delta_k + \delta_j) \qquad (6\text{-}2)$$

These equations assist in estimating the maximum amount of wind generation acceptable by simulating the effect of the rotor angle to minor transients. Refer to **Appendix B** for additional calculations.

6.7 CONCLUSIONS

The utilisation of wind generation in weak networks requires an intimate understanding of the network as a basis for any generation extension. Every weak network will be different and what will make them weak shall be unique. Understanding these weaknesses will make the interfacing of wind generation successful.

This chapter has concentrated on demonstrating that the rotor angle of all generators forming part of the weak interconnected section of the network are a key parameter to establish the maximum wind generation that could be used and what response could be expected under transient conditions. Each additional generator connected to a weak network will change the overall characteristic of the network by changing relevant equivalent impedances and thus, the overall response due to transient conditions.

The need to diversify the location of the wind generators is essential in order to limit network instability when the wind generator feeders trip. This is implementable in a simple manner, in particular, when interfacing at distribution or sub-transmission voltage level (below 72 kV).

The maximum wind generation that a weak network can interface would be dependent on the rotor angle changes that take place when under transient conditions.

The simulations completed show that the wind generation will assist with voltage stability (reactive power compensation) when transient interactions take place. The wind generators ability to generate reactive power will be dependent on the capacity of generators selected. For these DFIG machines modelled, they have excellent reactive power capacity at all times and prove to be excellent voltage compensators.

Chapter 7. The Islanded Network and Wind Generation

7.1 INTRODUCTION

When analysing a weak network it is essential to consider one that is islanded from all other networks such as a typical remote area power generation and distribution system. Many industrial installations are remote from all power networks and are required to provide all electrical power requirements locally via the use of diesel or gas turbine based power generation. These installations are, in general, simple to operate and designed to include very little redundancy. They will meet the required continuous (base load) and transient loads such as those expected of large industrial drive applications.

Having a clear understanding of the expected load is paramount prior to generator equipment selection. Incorrect generator selec tion will lead to continuous supply interruptions considering that most remote industrial sites can include over 80% inductive load (i.e. motor drives).

For this research work, the selected power generation equipment chosen is similar to an existing islanded installation that supplies power to a single private operator. Concurrently, the use of wind generation as a means of kWh unit cost reduction is under consideration.

Detailed transient stability simulations for an islanded network with the inclusion of wind generators are presented in this section in order to establish network limitations. As will be shown the power station generation equipment selected is critical when establishing overall stability as this will establish the basis of any network that incorporates wind generation.

7.2 THE ISLANDED NETWORK

The islanded network under consideration includes:

- ⇨ A suitably designed power station that under all conditions would meet the required transient and normal load of the operation.
- ⇨ The distribution system is based on 66 kV main overhead power lines. These are limited to the transfer of bulk power to each individual site.
- ⇨ Within each site power is distributed at 11 kV and this includes all surface and underground installations.
- ⇨ The addition of up to eight 1.5 MW DFIG wind generation forms part of the power system.

Figure 7.1 shows a single-line diagram of the proposed power system.

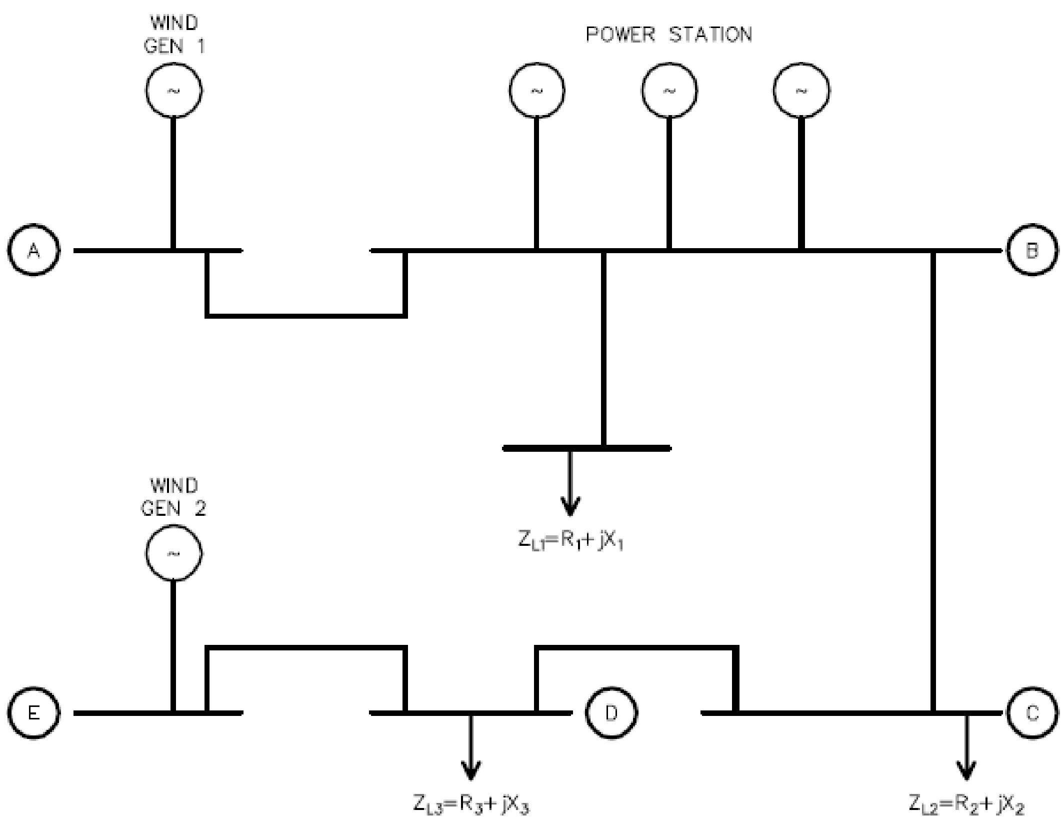


Figure 7.1 – Islanded Power Generation & Distribution System

This network has been modeled in extensive detail considering that it is an existing network. The computer model can be seen in Figure 7.2.

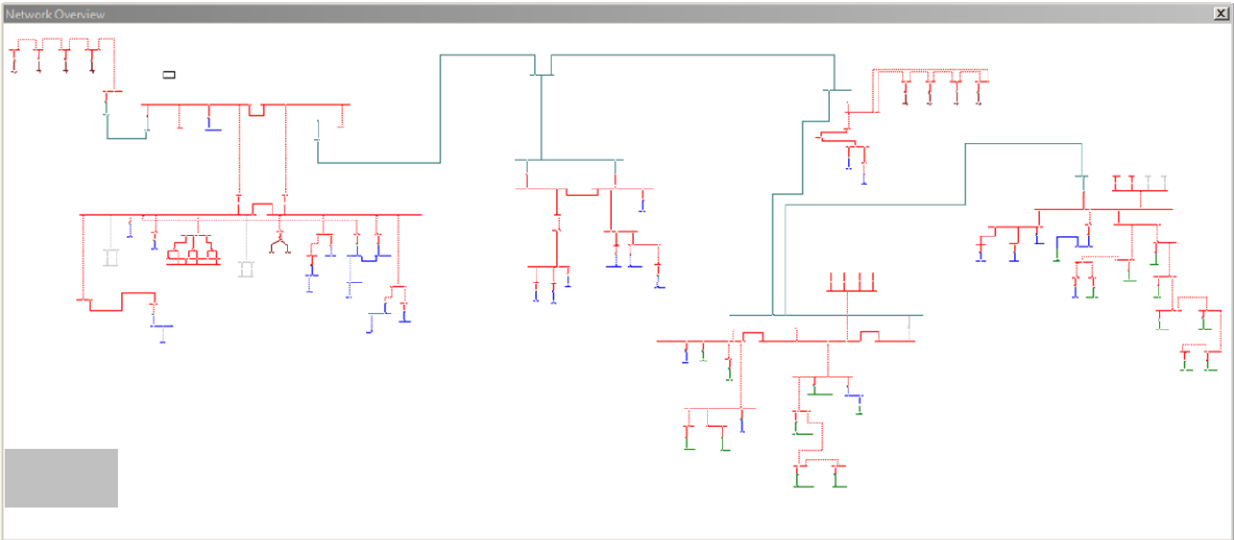


Figure 7.2 Overall Computer Model of the Islanded Network

The wind generation equipment has been split into two separate groups. One has been located close to the power station and the other at the opposite end of the network.

The main objective of this installation methodology is to limit any transient event that could trip the wind generation interface feeder.

7.3 Load Characteristics

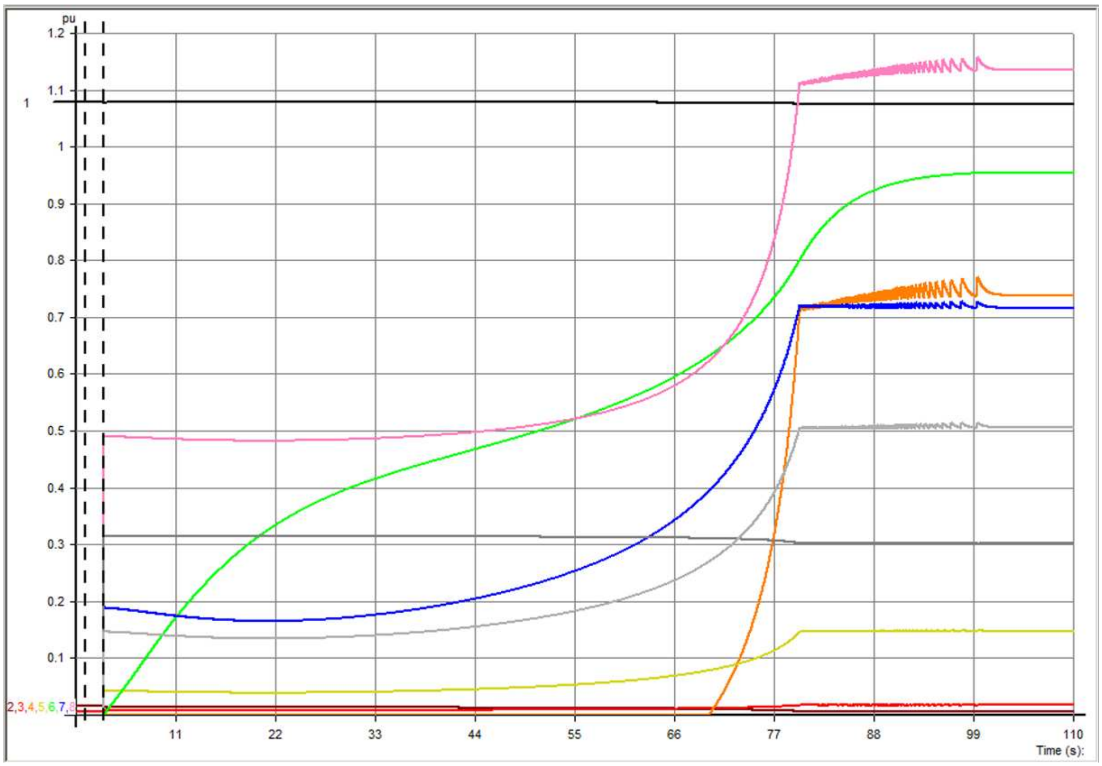
The islanded network that is under consideration includes a large industrial installation that makes use of a very large cyclo-converter feeding a synchronous machine (SAG Mill) rated at 13 MW. This unit alone represents nearly 40 % of the area load and will have a large impact on the power station design and the voltage ride-through capability offered by the wind generation under load acceptance and load rejection events.

Other loads include large drives (up to 2 MW soft-started drives) and shifting loads based on operational daily changes. Most of the additional load is inductive with some power factor correction equipment installed at 11 kV only.

The most critical load characteristic for the system design is the SAG Mill start characteristic. Figure 7.3 shows the recordings of the starting period for the SAG Mill. The starting period has a duration of up to 100 seconds and has a relatively steady load increase. This has the advantage of limiting current inrush and, as such, network instability.

Figure 7.3 – Cyclo-converter Start Event (Actual Recording)

This starting characteristic for the SAG Mill required simulation as part of the transient stability model. This requirement was possible by considering the similarities of a resistance starter. Please refer to Figure 7.4.



Graph Details

No.	Element	ID	Plot Description	Offset	Mult.
1	Busbar	Boul HV Bus	Bus Voltage (kV)	0	121
2	Transmission Lin	KNS OHline	First End Current (kA)	0	5
3	Transmission Lin	SIGPO/HLin	First End Current (kA)	0	5
4	Transmission Lin	SIGPO/HLin	First End Reactive Pow	0	5
5	Cable	NSIGPCBCY	First End Current (kA)	0	5
6	Induction Motor	MI-0023	Shaft Speed (pu)	0	1
7	Induction Motor	MI-0023	Power (MW)	0	16.7
8	Induction Motor	MI-0023	Reactive Power (MVAr)	0	5
9	Induction Motor	MI-0023	Terminal Voltage (kV)	0	10
10	Induction Motor	MI-0023	Current (kA)	0	5

Figure 7.4 – 13 MW Cyclo-converter System Start (Simulated)

For an islanded network, this represents a very singular event that will test the wind generation system when the power station has limited reactive power capacity or generator sets available.

7.4 MACHINE BASED TRANSIENT EVENTS

In addition to the load acceptance and load rejection simulations, it has also been necessary to consider standard three-phase and single-phase faults within the network.

The most important simulations conducted include:

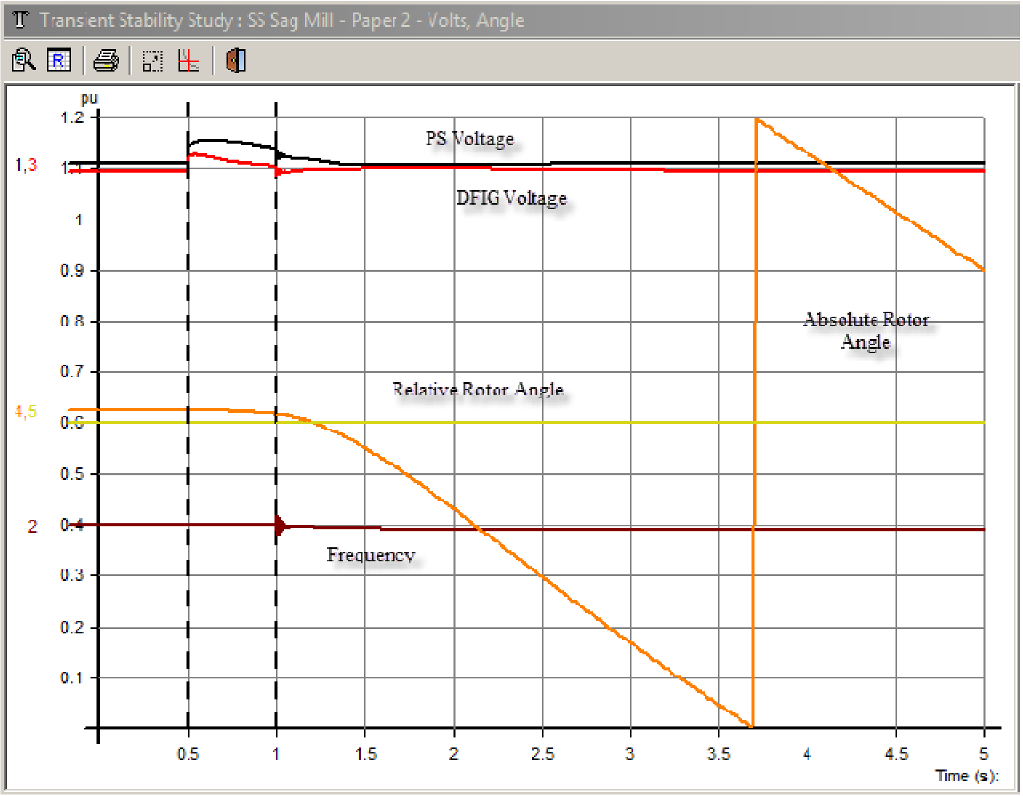
- Load acceptance of the single largest load on site – 13 MW Sag Mill start-up.
- Load rejection of the single largest load on site – 13 MW Sag Mill trip.
- Single-phase fault on the 66 kV distribution network.
- Three-phase fault on the 11 kV distribution network.

The wind generation modelled as part of the network includes a 12 MW arrangement (2 x (4 x 1.5) MW DFIG units). The critical objective in these models is to determine the network's ability to maintain stability under each of the above events stated. The power station is fully operational (3 x 15 MVA units running) initially and as wind generation is added, one and two sets are turned off in order to maintain a realistic operation.

7.4.1 Load Acceptance Transient

The first simulation to consider is the starting of the 13 MW SAG Mill based on the start-up characteristics shown in Figure 7.3 and Figure 7.4. In this case, prior to mill start-up it is essential to energise two filters of 4.0 MVAr each that will assist with voltage stability and reduce harmonics in the first place.

Figure 7.5 shows only the first 5 seconds of the simulation as this is the critical period. In the first instance the closure of the harmonic filters (include 8.0 MVAr in total) increase the bus bar voltage as expected. At the start of the Mill, the voltage for both the power station and DFIG busbar (11 kV) remain very constant. The frequency sees a small fluctuation, but the governor reacts accordingly maintaining a stable frequency.



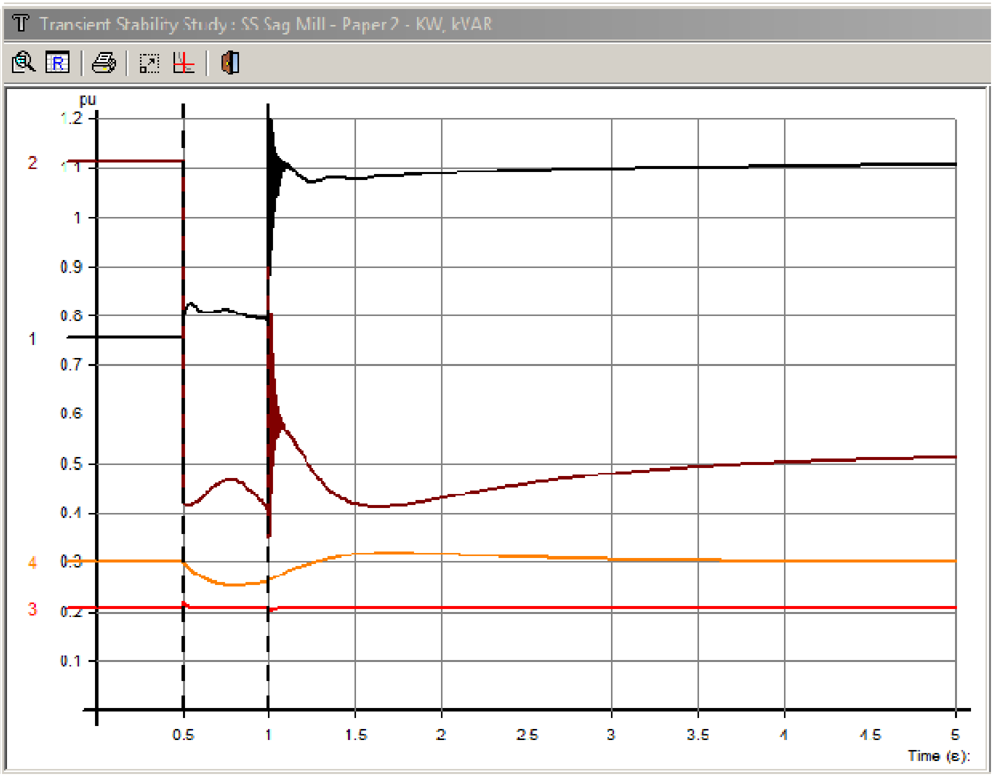
Graph Details

No.	Element	ID	Plot Description	Offset	Mult.
1	Busbar	PS Bus #1	Bus Voltage (kV)	0	10
2	Busbar	PS Bus #1	Bus Frequency (Hz)	40	25
3	Busbar	WGB1A	Bus Voltage (kV)	0	10
4	Synchronous Ge	GS-0011	Absolute Rotor Angle (°	-180	300
5	Synchronous Ge	GS-0011	Relative Rotor Angle (°)	-180	300

Figure 7.5 – Load Acceptance Simulation

Figure 7.6 shows additional information on the mill start-up and includes the response from the power station as well as one of the eight DFIG wind generators. The reactive power response from both the power station gas turbine and DFIG wind generators is in line with the closure of 8 MVAR capacitor banks. Based on the load these machines then compensate reactive power as required during the SAG Mill start.

When multiple power station generators are in use comparing the absolute rotor angle with the relative rotor angle can give an indication of potential pole slipping issues when large loads are energised.



Graph Details

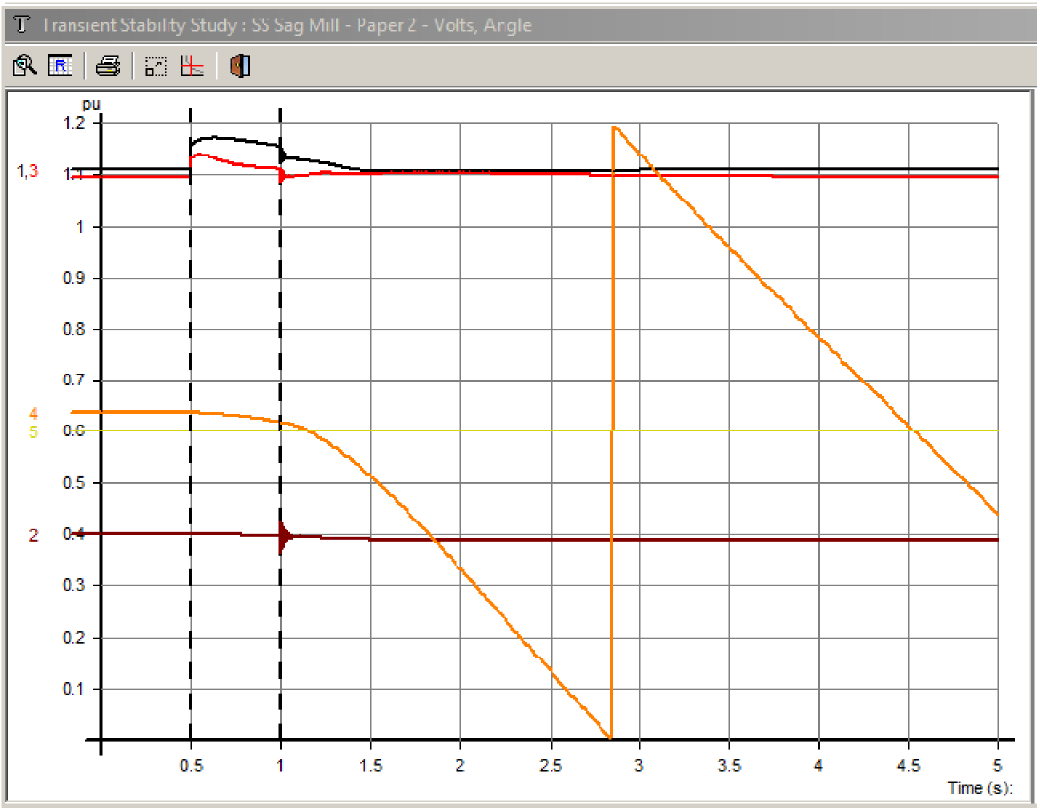
No.	Element	ID	Plot Description	Offset	Mult.
1	Synchronous Ge	GS-0011	Power (MW)	0	3.33
2	Synchronous Ge	GS-0011	Reactive Power (MVAr)	0	3.33
3	Wind Turbine Ge	WT-0006	Electrical Power (MW)	0	6.67
4	Wind Turbine Ge	WT-0006	Reactive Power (MVAr)	-2.4	7

Figure 7.6 Power Station and DFIG Characteristics

7.4.2 Reduced Power Station Generation

Under the condition when all wind generation units operate it is possible to disconnect one or more gas turbines altogether. The main objective of adding wind generation to any islanded network is to reduce dependence on power station generation.

The simulation of this particular case was required in order to determine if such an arrangement would still allow the load acceptance event of the SAG mill. Refer to Figures 7.7 and 7.8.



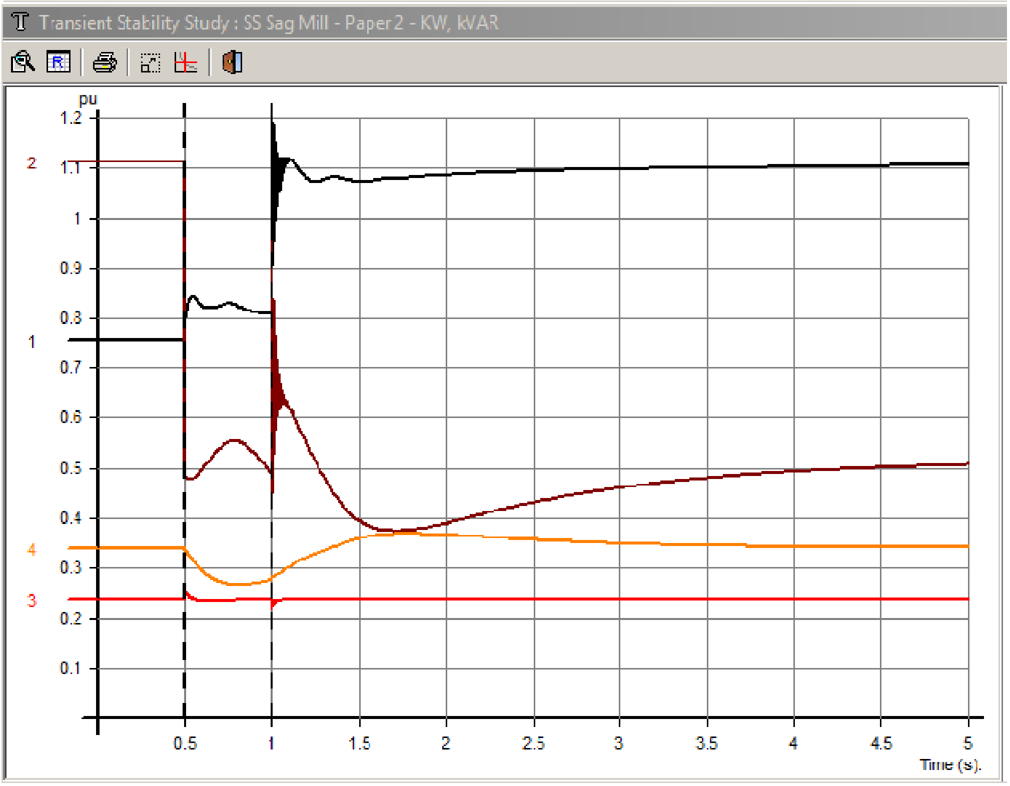
Graph Details

No.	Element	ID	Plot Description	Offset	Mult.
1	Busbar	PS Bus #1	Bus Voltage (kV)	0	10
2	Busbar	PS Bus #1	Bus Frequency (Hz)	40	25
3	Busbar	WGB1A	Bus Voltage (kV)	0	10
4	Synchronous Ge	GS-0011	Absolute Rotor Angle (°	-180	300
5	Synchronous Ge	GS-0011	Relative Rotor Angle (°)	-180	300

Figure 7.7 – Reduced Power Station Capacity / Full DFIG Capacity

When considering the results of Figure 7.7 it is evident that the reduced capacity of the power station has had a small impact on the frequency level during the start-up process. In addition, given the lower system inertia the rotor angle is more pronounced, which can be expected.

Figure 7.8 outlines a similar result as that of Figure 7.6 only with the relevant reduction in power generation (one less gas turbine).



Graph Details

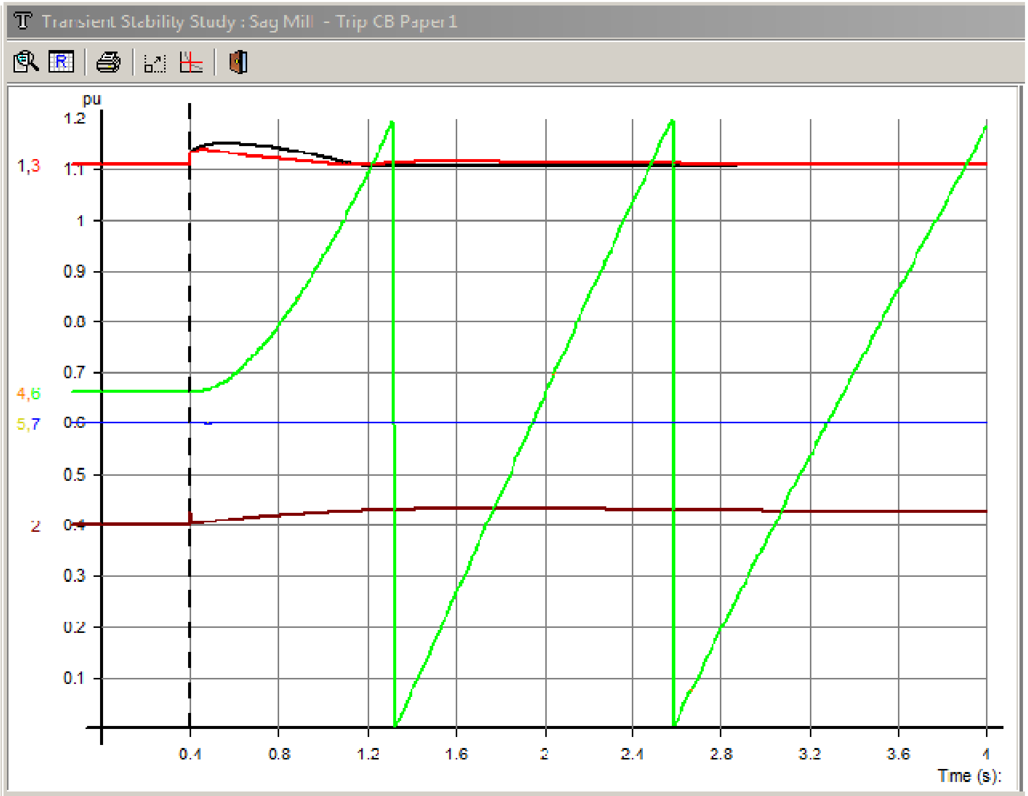
No.	Element	ID	Plot Description	Offset	Mult.
1	Synchronous Ge	GS-0011	Power (MW)	0	5
2	Synchronous Ge	GS-0011	Reactive Power (MVAr)	0	5
3	Wind Turbine Ge	WT-0006	Electrical Power (MW)	0	5.83
4	Wind Turbine Ge	WT-0006	Reactive Power (MVAr)	-2.4	6.17

Figure 7.8 – Reduced Power Station Output on SAG Mil Stat-Up

Figure 7.8 shows the need for additional reactive power generation from both the power station GT's and the wind generation system. This also indicates that starting the SAG Mill is achievable with a reduced power station capacity as long as the wind generators are operational.

7.4.3 Load Rejection Simulations

For the same SAG Mill the need to consider a total loss of load (mostly due to a fault related loss) is essential in order to ensure that the power station will not blackout. In this case, it is assumed that the main circuit breaker that feeds the Mill trips on fault and the network's response to such an incident is considered.



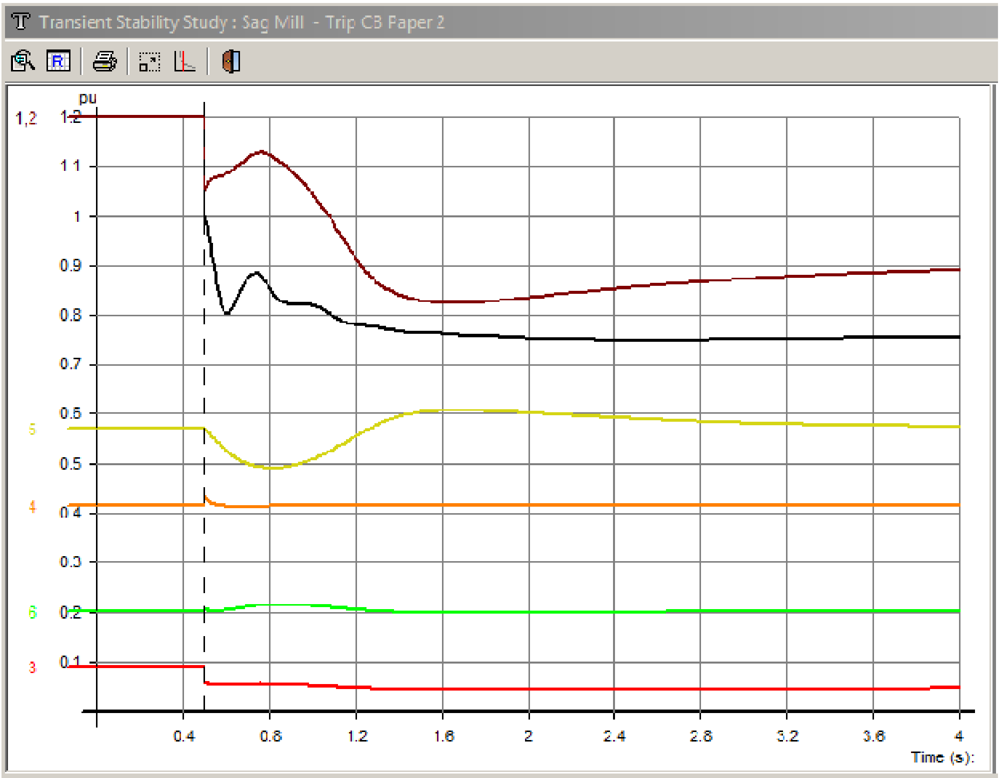
Graph Details

No.	Element	ID	Plot Description	Offset	Mult.
1	Busbar	PS Bus #1	Bus Voltage (kV)	0	10
2	Busbar	PS Bus #1	Bus Frequency (Hz)	40	25
3	Busbar	WGB1B	Bus Voltage (kV)	0	10
4	Synchronous Ge	GS-0011	Absolute Rotor Angle (°	-180	300
5	Synchronous Ge	GS-0011	Relative Rotor Angle (°)	-180	300
6	Synchronous Ge	GS-0012	Absolute Rotor Angle (°	-180	300
7	Synchronous Ge	GS-0012	Relative Rotor Angle (°)	-180	300

Figure 7.9 – Load Rejection Simulation

Figure 7.9 shows the results of a sudden trip of the SAG Mill motor. In this case, the voltage rises on both the power station and DFIG generator buses for a short duration are evident. The most significant change is the frequency increase brought about by the load rejection, which is to be expected due to the loss of nearly 40% of the networks load. At the same time, the Absolute Rotor Angle shifts for a period long enough to allow stability of the generation sets.

Figure 7.10 shows additional information on load rejection that includes the power loss seen by the power station. The wind generation power production remains constant in this case as the power station absorbs most of the loss.



Graph Details

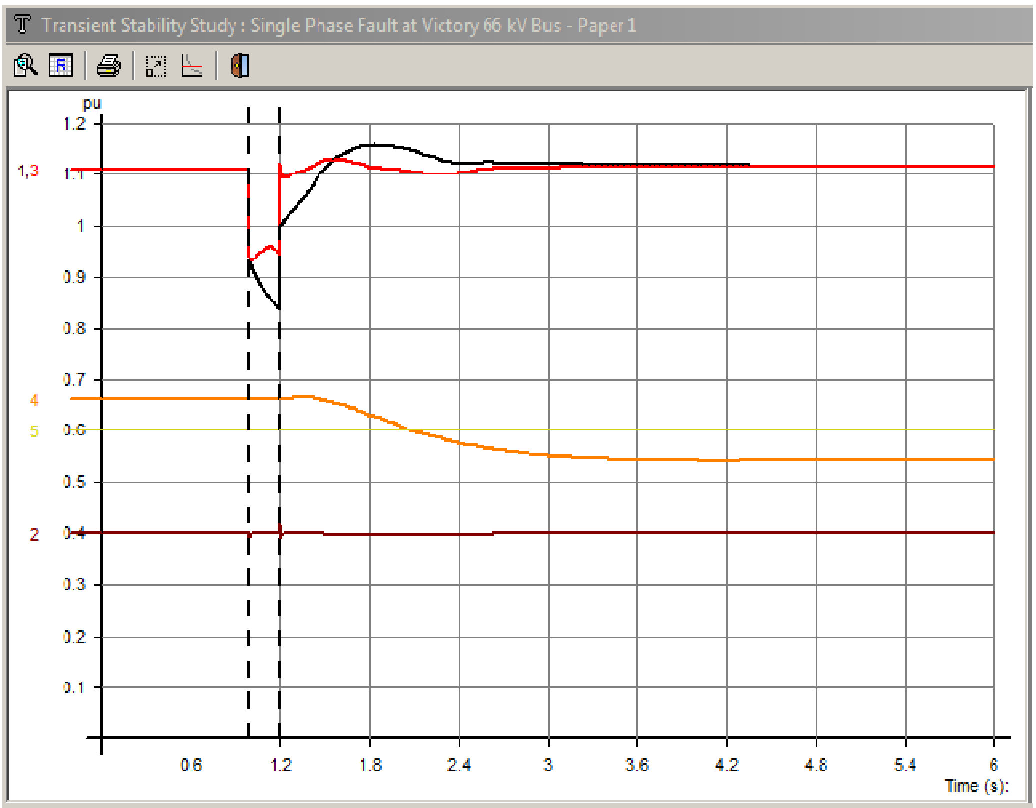
No.	Element	ID	Plot Description	Offset	Mult.
1	Synchronous Ge	GS-0011	Power (MW)	0	3.33
2	Synchronous Ge	GS-0011	Reactive Power (MVAr)	0	4.17
3	Synchronous Ge	GS-0011	Current (kA)	0	5
4	Wind Turbine Ge	WT-0006	Electrical Power (MW)	0	3.33
5	Wind Turbine Ge	WT-0006	Reactive Power (MVAr)	-2.4	3.67
6	Wind Turbine Ge	WT-0006	Current Magnitude (kA)	0	5.83

Figure 7.10 – Additional Information on Load Rejection

7.4.4 Single-Phase Fault Simulation

Figure 7.11 shows an additional simulation that includes a single-phase fault on the sub-transmission lines that form part of the 66 kV network. The single most important concern in this case would be the response of the power station and the wind generation sections. Ride-through capabilities are essential, in particular, when the power station is operating at reduced capacity (one gas turbine is off line).

The fault duration is 200 ms, which is considered typical of such installations.



Graph Details

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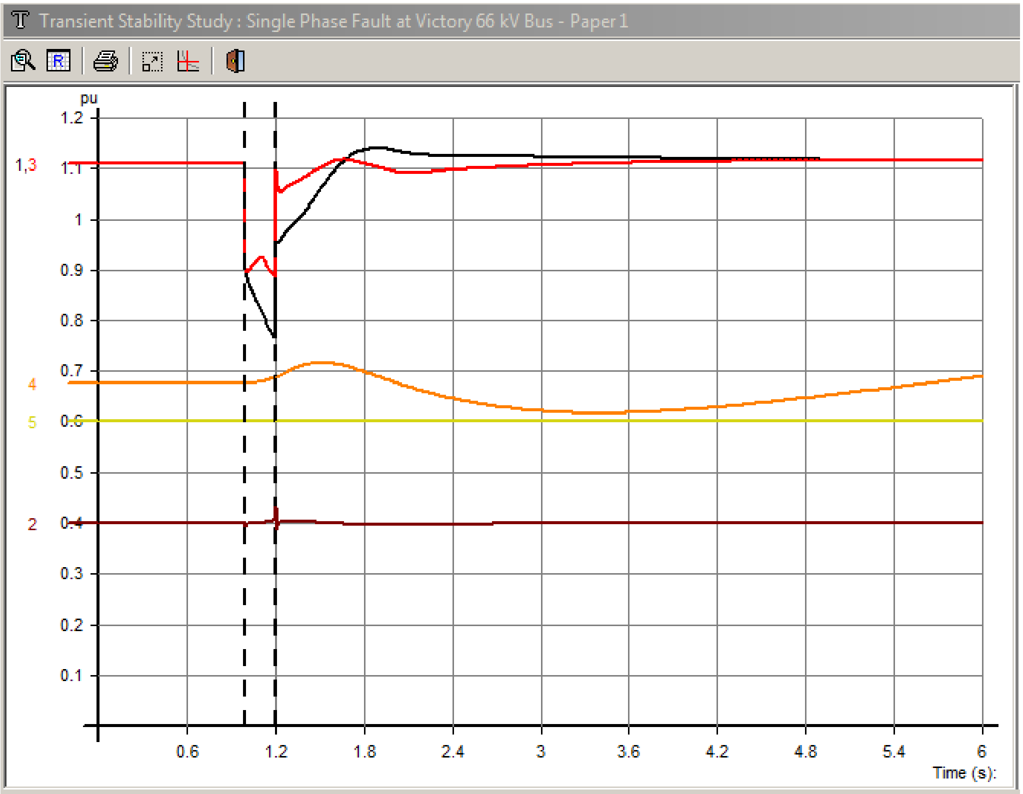
2	Busbar	PS Bus #1	Bus Frequency (Hz)	40	25
3	Busbar	WGB1B	Bus Voltage (kV)	0	10
4	Synchronous Ge	GS-0011	Absolute Rotor Angle (°	-180	300
5	Synchronous Ge	GS-0011	Relative Rotor Angle (°)	-180	300

Figure 7.11 – Single-Phase Fault on 66 kV O/H Line

As Figure 7.11 illustrates, the voltage drops on all busbars, but quickly recovers once the fault is cleared. The recovery is fast considering the large amount of spinning reserve present at the time (all power station turbines and wind turbines are in operation).

Figure 7.12 shows the same simulation with restricted power station generation (one gas turbine disconnected).



Graph Details

No.	Element	ID	Plot Description	Offset	Mult.
1	Busbar	PS Bus #1	Bus Voltage (kV)	0	10
2	Busbar	PS Bus #1	Bus Frequency (Hz)	40	25
3	Busbar	WGB1B	Bus Voltage (kV)	0	10
4	Synchronous Ge	GS-0011	Absolute Rotor Angle (°	-180	300
5	Synchronous Ge	GS-0011	Relative Rotor Angle (°)	-180	300

Figure 7.12 – Single-Phase Fault With reduced Power Station Generation

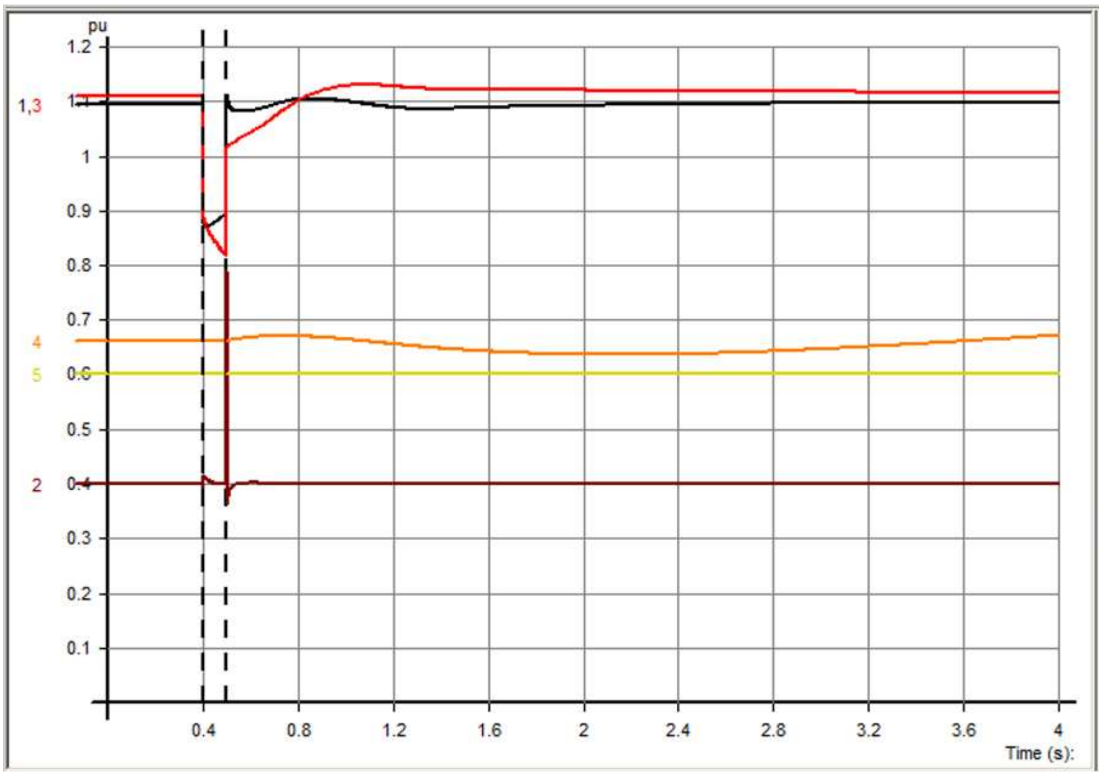
In this case, the voltage drop is slightly larger, although the recovery is fast.

In addition, the rotor angle has the tendency to sightly oscillate brought about by the overcompensation that takes place during the fault period. Irrespective, there is enough inertia in the network to ensure that the frequency does not drift during the period of the fault.

7.4.5 Three-Phase Fault at 11 kV

All local area power distribution has the voltage of 11 kV and it would be of value to establish the overall network response if a three-phase fault on one of these busbars took place. While the fault current on the 11 kV busbar will be limited by the incoming power transformer impedance and the installed inductive motor load, it will still cause a large transient, which will be seen by the generation equipment.

In this case, the fault duration has been limited to 100 ms, which is high for a three-phase fault (worst case). The intent in this case is to review the system response to such a fault and worse case situation. Please refer to Figure 7.13.



Graph Details

No.	Element	ID	Plot Description	Offset	Mult.
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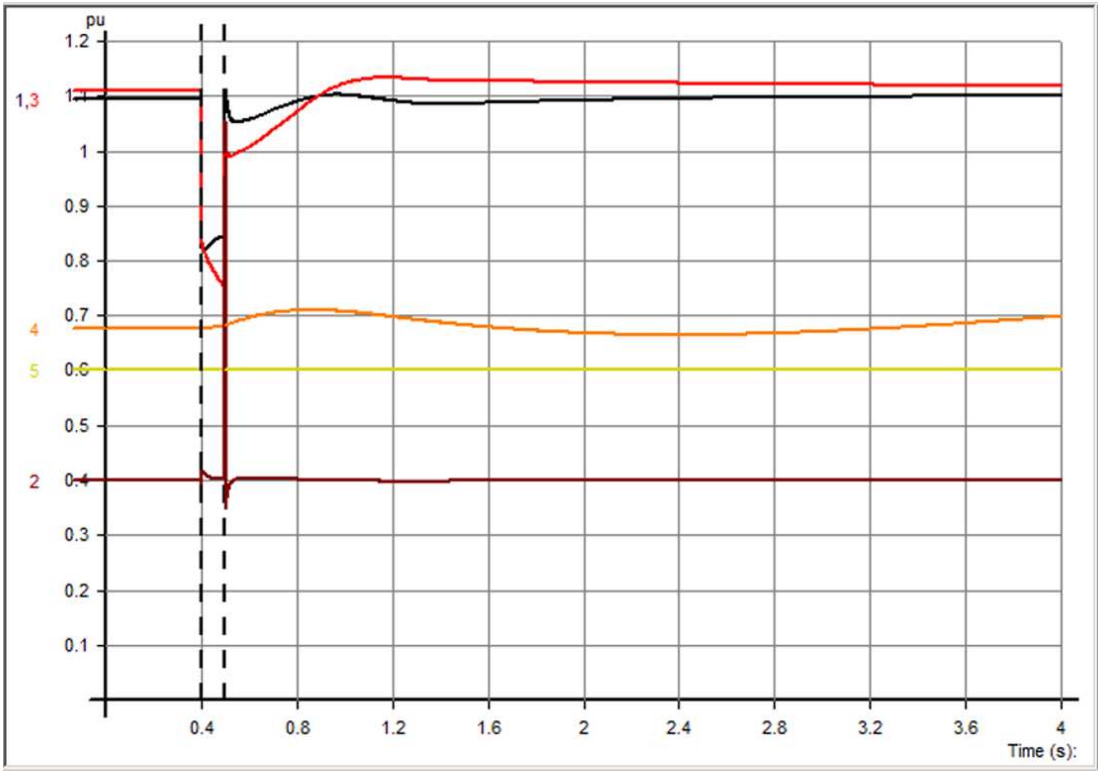
2	Busbar	DFIGMV Bus	Bus Frequency (Hz)	40	25
3	Busbar	PS Bus #1	Bus Voltage (kV)	0	10
4	Synchronous Ge	GS-0011	Absolute Rotor Angle (°	-180	300
5	Synchronous Ge	GS-0011	Relative Rotor Angle (°)	-180	300

Figure 7.13 – Three-Phase Fault at 11 kV

The simulation results are very similar to a single-phase fault on the 66 kV overhead power line as previously presented. The single largest impact of this fault is its effect on the frequency, in particular, once the fault has cleared. This impact is composed of high magnitude and of very short duration and does not seem to affect the networks ability to enhance the fault. Depending on what frequency protection settings are used, it is possible that this could be enough to disconnect the power station from the rest of the network (instantaneous over-frequency or ROCOF), effectively blacking out the area.

Figure 7.14 shows the same fault applied to the busbar with limited power station generation. The outcome of this simulation is quite similar to that of full capacity power station availability, although the voltage drop and frequency spike are significantly more pronounced. In this case, it is possible the generation equipment would not be able to prevent a blackout. Yet, this will depend on the duration of the fault (in many cases three-phase fault duration will be no longer than 80 ms (including the time it takes for a high voltage circuit breaker to open).



Graph Details

No.	Element	ID	Plot Description	Offset	Mult.
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2	Busbar	DFIGMV Bus	Bus Frequency (Hz)	40	25
3	Busbar	PS Bus #1	Bus Voltage (kV)	0	10
4	Synchronous Ge	GS-0011	Absolute Rotor Angle (°	-180	300
5	Synchronous Ge	GS-0011	Relative Rotor Angle (°)	-180	300

Figure 7.14 – Reduced Power Station Output on Three-Phase Fault at 11 kV

7.5 ON THE USE OF GAS RECIPROCATING ENGINES

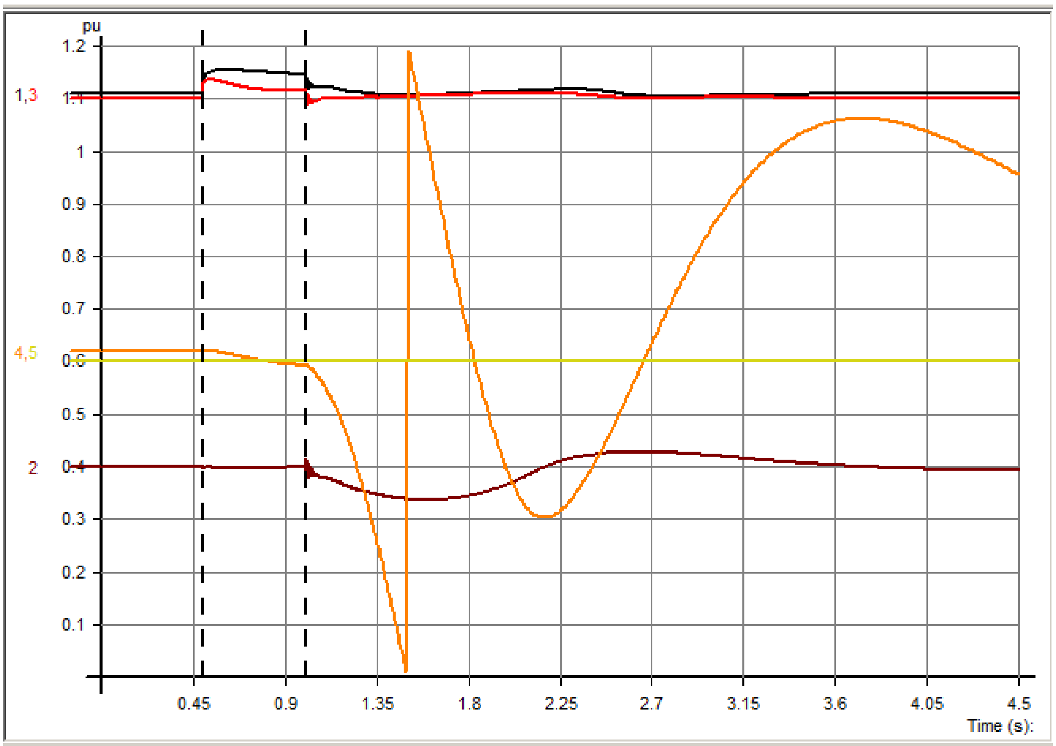
Similar models using gas reciprocating engines in the power station are considered. The use of gas reciprocating engines has become popular in islanded systems (industrial installations) due to the high efficiency such as engines offered by the many suppliers.

The same amount of wind generation is interfaced with the network in order to compare results when under transient events.

The modelling of the gas reciprocating generators has been done using manufacturers data at rating of 8.7 MW at 500 RPM.

7.5.1 Load Acceptance Transient

In the first simulation, Figure 7.15 shows the starting of the SAG Mill (load acceptance).



Graph Details

No.	Element	ID	Plot Description	Offset	Mult.
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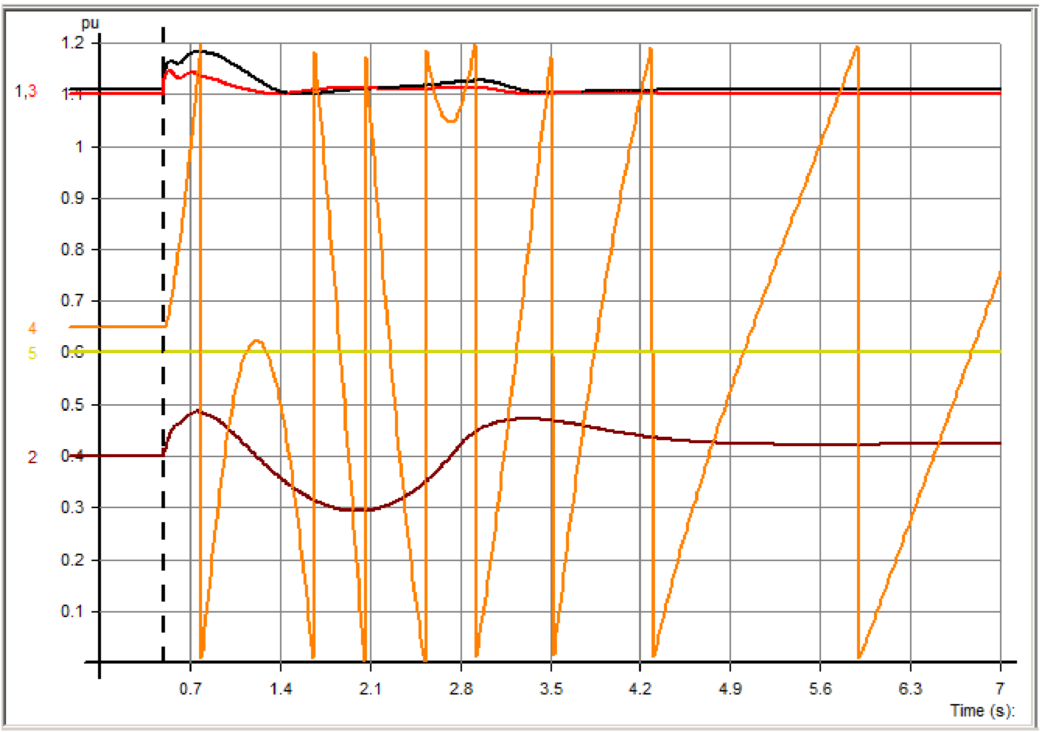
2	Busbar	PS Bus #1	Bus Frequency (Hz)	40	25
3	Busbar	WGC1A	Bus Voltage (kV)	0	10
4	Synchronous Ge	GS-0011	Absolute Rotor Angle (°	-180	300
5	Synchronous Ge	GS-0011	Relative Rotor Angle (°)	-180	300

Figure 7.15 – Load Acceptance SAG Mill Motor

The transient response clearly identifies the severe impact the power station generators experience when starting the Mill. The frequency, in this case, can drop to 48.4 hertz with a large recovery period. Depending on protection arrangements, it is possible that the UFLS relays could activate under this transient load conditions. Indicative of the impact as seen by the power station generators is the Absolute Rotor Angle shift. Given that the relative rotor angle remains rather constant it is possible that loss of synchronism will not take place.

7.5.2 Load Rejection Transient

A similar simulation has been conducted, but with load rejection. That is, tripping of the SAG Mill during a fault event. Please refer to Figure 7.16.



Graph Details

No.	Element	ID	Plot Description	Offset	Mult.
1	Busbar	PS Bus #1	Bus Voltage (kV)	0	10
2	Busbar	PS Bus #1	Bus Frequency (Hz)	40	25
3	Busbar	WGC1A	Bus Voltage (kV)	0	10
4	Synchronous Ge	GS-0011	Absolute Rotor Angle (°	-180	300
5	Synchronous Ge	GS-0011	Relative Rotor Angle (°)	-180	300

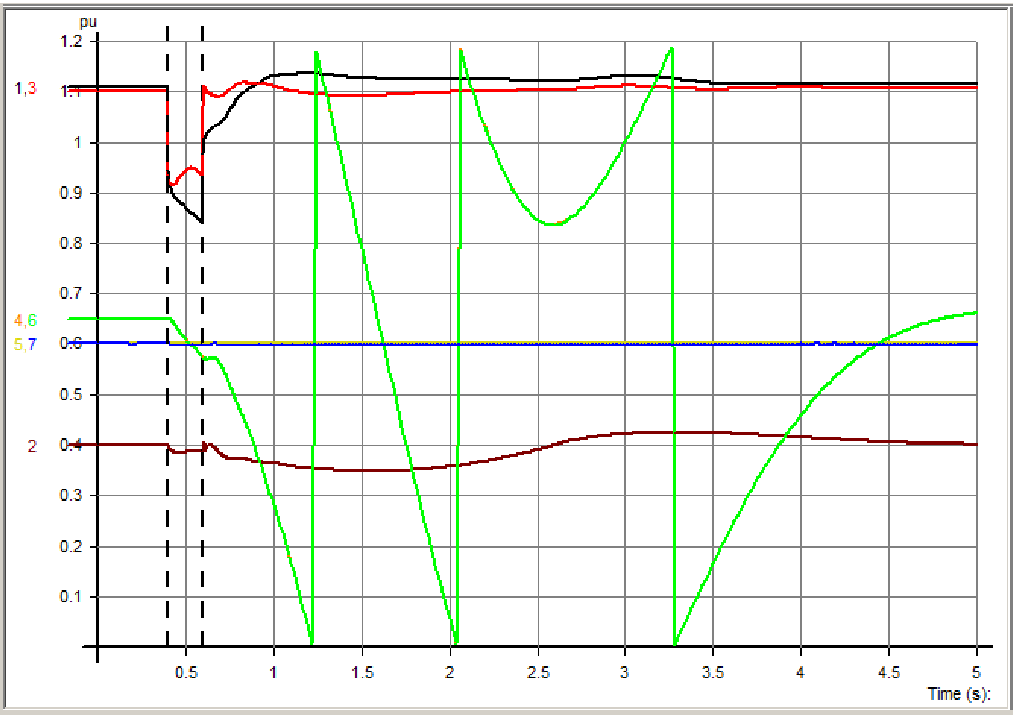
Figure 7.16 – Load Rejection Transient (Trip SAG Mill)

The load rejection case presents a severe enough impact to cause the frequency of the machines to become unstable enough to blackout the station. The rotor angle is also indicative of this potential outcome. This situation presents itself considering the lack of inertia that low speed reciprocating engines experience. They simply do have enough “weight” to manage such changes in the load.

7.5.3 Single-Phase Fault Transient

Figure 7.17 displays the single-phase fault case. In this case, a single-phase fault applied to the 66 kV overhead power line at a location midway from the power station is simulated.

The transient model indicates that the frequency drop reaches 48.7 Hz and the absolute rotor angle experiences a considerable shift. Depending on protection settings, it is possible that the power station will load shed or blackout under this transient event.



Graph Details

No.	Element	ID	Plot Description	Offset	Mult.
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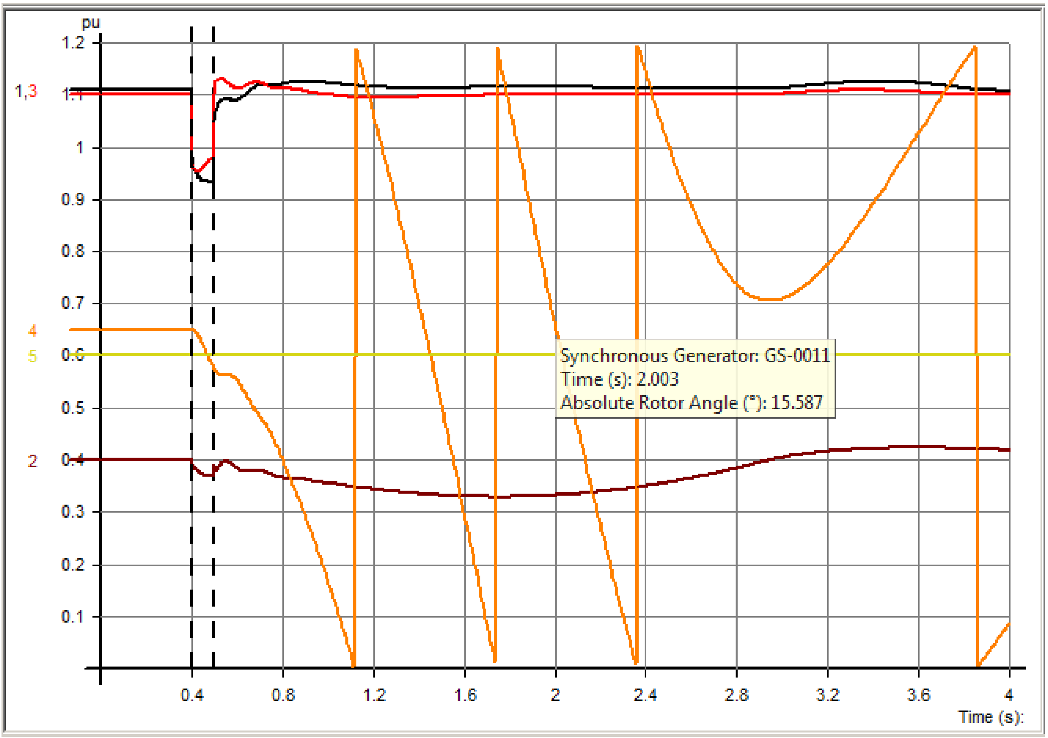
2	Busbar	PS Bus #1	Bus Frequency (Hz)	40	25
3	Busbar	WGC1A	Bus Voltage (kV)	0	10
4	Synchronous Ge	GS-0011	Absolute Rotor Angle (°	-180	300
5	Synchronous Ge	GS-0011	Relative Rotor Angle (°)	-180	300
6	Synchronous Ge	GS-0012	Absolute Rotor Angle (°	-180	300
7	Synchronous Ge	GS-0012	Relative Rotor Angle (°)	-180	300

Figure 7.17 – Single-Phase Fault at 66 kV

7.5.4 Three-Phase Fault at 11 kV Busbar

The simulation of a three-phase fault at 11 kV (distribution voltage) can be seen in Figure 7.18.



Graph Details

No.	Element	ID	Plot Description	Offset	Mult.
1	Busbar	PS Bus #1	Bus Voltage (kV)	0	10
2	Busbar	PS Bus #1	Bus Frequency (Hz)	40	25
3	Busbar	WGC1A	Bus Voltage (kV)	0	10
4	Synchronous Ge	GS-0011	Absolute Rotor Angle (°	-180	300
5	Synchronous Ge	GS-0011	Relative Rotor Angle (°)	-180	300

Figure 7.18 – Three Phase Fault at 11 kV Busbar

Under such a fault, the frequency drops to 48.2 Hz and the voltage levels remain low. With the large impact experienced at the power station, there is little possibility that the network will not undergo a blackout.

7.5.5 Analysis

In considering these simulations (based on “worst transients” that the network could be exposed to) it is essential to consider the following:

a) It must be ensured that the wind generation system interfaced is such that it will assist in stabilizing the network when transients take place. In this case, it has been necessary to split the wind generation equipment into two separate groups installed away from each other (at the end of each section of the network). The power station has been located close to the largest load were the single largest transients can take place. The ability to split the wind generation installations allows for larger wind penetration considering that each connection still limits possible instability of the entire network in the event of a wind generation interface loss.

b) The fault simulations (at 66 kV and 11 kV buses) make use of a maximum duration of 200 ms and 100 ms for a three phase fault. This is based on protection relays settings employed on site, but would need to be re-considered once such an installation is completed. At this stage, this fault duration can be considered to be on the high side. With islanded (or weak) systems CFCT settings can be low and quite restrictive. A relevant protection coordination review would be essential.

c) The power station will, in most cases, absorb most of the transients that could take place (dependent on spinning reserve available at the time of the transient). Yet, the wind generation does assist in stabilizing the network when under fault or large transients occurrence. The wind turbine dynamic model used allows for quick reactive power compensation from all units, thus assisting with network voltage stability. In this thesis, the dynamic model has been thoroughly tested to ensure this reactive power response is present.

d) The ability of the network to provide the necessary power to start large machines such as Sag Mills will be dependent on how fast the drive achieves rated speed and ensuring that sufficient reactive power capacity is available. The installation of wind generation (when fully operational) will assist with this requirement, although the application of a cyclo-converter system with a slow rise time for gaining rated operation limits the reactive compensation required.

   The use of soft starters for large machines (above 132 kW) will always assist in limiting reactive power requirements and would be essential in all islanded installations.

e) The amount of wind generation that will be required to assist the power station and its ability to meet the load or transient events would be dependent on how much spare generation is available in the power station (spinning reserve). This will be reduced when full wind generation is available. It will also depend on the expected magnitude of the transient. In general, wind generation should not be relied on to start large loads without sufficient power station capacity. The wind generation will be more effective in assisting with fault transient events than with load acceptance events.

f) Similar simulations have been completed using reciprocating engines as part of the power station, but the result during transient events are far from acceptable irrespective of wind generation capacity available at the time. The use of low RPM machines in islanded operations with large transient loads will demand a large spinning reserve at the power station in order to manage either load changes or faults. Wind generation equipment will not be viable in this case. Low-speed reciprocating engine based power stations do limit available transient capacity as experience has shown.

g) While the simulations conducted pertain to a specific network, it will be essential to understand that each network of similar characteristics will require its own analysis and determination of where wind generation should be installed. The amount of wind generation shall need to be assessed accordingly as well.

h) The single largest risk to system stability can occur when the wind generation is fully operational and one or more power station generators are disconnected. In the event that a leg of the wind generation interface trips, it could lead to load shedding in the first instance until a power station generator can be synchronized.

7.6 CONCLUSIONS

In the past, the use of wind generation applied to a small-islanded industrial network has not been investigated. This work proves that it is a viable option. It is essential to understand how the power station rotor angles of the generators will respond to transients and how the wind generators will contribute to voltage control. The transient stability models included here show that DFIG wind generators will assist with voltage control, in particular, if the wind generators supply reactive power under transient events.

In each case, realistic fault events and duration form part of the simulations in order to understand how the wind generation would respond to such transients. Considering that the network is a small islanded station with limited reactive capacity, the network can only tolerate small fault events. A three-phase fault would bring the network to a possible blackout depending on power station generator availability and wind resource reactive power availability.

Chapter 8. Protection Coordination of Networks that Make use of Wind Generation

8.1 INTRODUCTION

All power generation and distribution networks make extensive use of protection relays as a primary means of protecting equipment and personnel from abnormal situations. In most cases, protection against common transient occurrences makes use of coordination procedures to ensure that nuisance tripping of healthy sections of the network does not occur.

With the very fast development of renewable generation systems (i.e. wind generation) it has become evident that the need to understand the dynamics of the interconnection of this equipment to weak networks is paramount. Research into the application of wind generation system into small, islanded networks has identified key issues associated with network response to the loss of embedded generation including fault based system losses.

It has been quite traditional in the past to make use of limited protection arrangements that included protection at the LV level of the wind generator and in some cases, some protection on the HV side of the interface to a feeder arrangement. Over the past year or so new relays have been offering some ring main unit (RMU) arrangement protection to the feeder interface legs. While in some cases this might be considered adequate it is not necessarily the case with installations such as islanded networks.

8.2 GENERAL PROTECTION SCHEMES

Installation of wind generation equipment interfaced with large network transmission lines is common practice. In general, wind generation farms include the use of a large number of units (in excess of 200 in some cases) and grouped into radial sections/legs. Each leg will then interface to the transmission system via a number of step-up transformers.

Protection of each leg has been minimal and has primarily been arranged to rely on the LV protection (solid-state circuit breakers) side connection. Lately, some degree of protection achieved via protection relays on RMU units that offer a greater variety of functions including communications interface is available. Many of the older installation have very little protection on the HV side.

Normal protection schemes may offer simple overload and earth fault protection as a rule with very little additional protection options considered.

The requirements that could be expected from a weak power system would differ from any standard network interconnected power distribution system. Such an installation must consider what levels of rotor angle changes the generation units would tolerate prior to loss of synchronism (this could effectively cause a total blackout) [7, 8, 14]. This will have a large impact into the selected equipment that can be used throughout industrial operations as well as the load changes which are normal operating practices [9, 10]. Transient stability studies conducted on power stations designed with gas turbines versus reciprocating engines have shown that their response will be quite different, thus demanding slightly different protection schemes or settings [14].

In most cases generator manufacturers will allow a generous leeway in protection settings for each machine when under transient events. This limit will represent the starting point for the protection settings for the rest of the network.

In general, the networks used as part of a weak system will be radial in design and specifically designed to meet the expected load (equipment designed for load requirements with minor growth expectations and some spinning reserve) with a small amount of redundancy. Various protection methods to secure network stability can be implemented (outside standard protection techniques) including:

- Under Frequency Load Shed (UFLS).
- Advanced Power Level Detection (APLD Relay).
- Blocking Mechanisms (via communications links).

The wind generation protection system can only be considered as a low voltage arrangement (specifically if the DFIG units operate at below 1000 Vac) and make use of step-up transformers prior to network connection. Low voltage circuit breakers rely on standard solid state protection relays, although the employment of more sophisticated arrangements is possible.

Installation of wind generators make use of a step-up transformer (generally at the base of each unit) which is then connected to the network via an RMU. Protection on the RMU can vary according to the needs of each installation. The latest protection relays offer features such as (but not limited to):

- Overload protection
- Earth fault protection
- Negative Sequence protection
- Breaker Failure protection

In most cases the installation of under voltage protection would not be widely applied considering the need to allow Ride-Through capabilities when the network is operating under a transient fault.

In designing a protection scheme for an islanded system with wind generation it will be necessary to consider the fault levels for each area of the operation and it will be essential to understand the transients that can be expected from the heavy machinery used (load acceptance and load rejection) on site.

The installation of wind generation interconnected to an islanded system calls for careful consideration of the location where the wind generators are to be interfaced. Having the ability to limit any potential instability to the network if there is total or partial loss of wind generation will establish how flexible the protection system will need to be. In this thesis the wind generation system has been split into two areas of the network, both having the same number of wind generators. Consider the following:

a. In all cases the use of standard protection schemes will be applicable (i.e. overload and earth fault protection coordination schemes etc...).

b. Directional protection schemes could be considered in order to accommodate shifting loads vs. wind generation availability (or fault level changes). For some circuits ride-through will be required and directional schemes can assist.

c. Relay blocking schemes would also need to be considered with these networks in order to ensure that any major trip of the wind generation system limits stability of the network.

d. Auto-reclosing schemes, while popular with distribution systems, would have to take into consideration synchronizing requirements, frequency control issues and potentially, total loss of wind generation. This could prove to bring instability to the network. Note that in some industries this option is not possible due to statutory requirements.

e. Under-voltage schemes are not to be considered due to the systems need to manage ride-through requirements. Under-voltage schemes could compound stability issues.

f. CFCT limitations will limit the network’s ability to ride-through and will have a large impact on network design and response to fault events.

g. Each wind turbine, assuming they generate at low voltage levels, would include its own solid-state circuit breaker with electronic protection. This unit can be coordinated with the HV connection leg of the RMU, but will need to consider coordination requirements with the other legs of the RMU (this could prove to be difficult due to the fault current contributions expected of each wind turbine vs. network connection).

There are various options when considering an appropriate protection scheme for such a network and this would include:

i. The installation of some degree of protection on the wind generator connecting leg of a RMU only. This option has been widely used and relies on a protection relay at the point of connection of each leg of a wind farm. As the fault on any part of the leg will trip all wind generation units in the downcast faulted section, this option is not considered adequate for islanded or weak networks due to the unnecessary loss of ride-through capability.

ii. The use of simple bi-directional protection relays on each of the two legs of the interconnecting RMU. This is a good option as it offers some back up to each relay when a fault occurs. The bi-directional capability of these relays limits their application to directional faults considering the differing fault level contributions from each side of the RMU.

iii. The deployment of directional relays on each interconnecting leg of the RMU. The benefits of this option are discussed in Section 8.4.

Each option has merit and would need to be considered at the design stage of the wind farm connection.

8.3 NEW PROTECTION COORDINATION SCHEME

In view of the more stringent requirements that can be expected from the integration of wind generation into weak networks it has been essential to consider more effective means of protection on wind generation installations. The need to assist with voltage stability under faulted conditions has become essential in order to provide better and more effective protection schemes. This can ensure selective tripping, a condition essential to limit wind generation system interruption and voltage stability assistance.

In the case of a wind generation installation connected to a weak (or islanded) network it will be necessary to consider that:

- ⇨ The wind generation units might not be connected at one single location (as has been the case in this research).
- ⇨ Given the smaller number of wind generation units per leg it is possible to consider the application of a ringed system. The protection scheme in this case will be different.
- ⇨ It is necessary to consider that the ride-through capability of the wind system can become an embedded generation issue and the protection scheme needs to consider this.
- ⇨ The use of RMU arrangements to interface wind generation units do not necessarily include protection relays on the three legs. This needs to be considered at the design stages.

The use of directional protection relays is one specific option worthy of additional investigation when an RMU interface is required.

A proposed protection arrangement for wind turbines on radial installation would have installed directional relays on both feeder legs as seen in Figure 8.1.

In this case, the wind turbine LV protection would coordinate with the HV protection arrangement (feeder leg of RMU). The two interface legs of the RMU would include the directional relays and these would coordinate with other wind generators (standard discrimination IDMT arrangements).

Figure 8.2 shows the way the interface legs would coordinate with each other. By using directional relays in these cases, it is possible to obtain a more effective way of protection when faults take place.

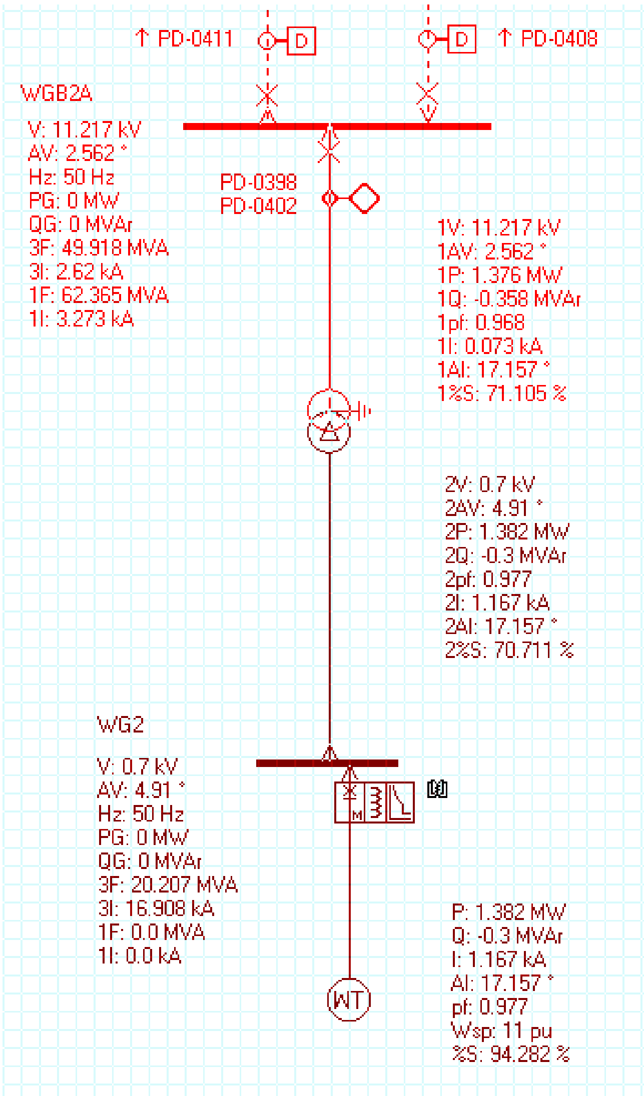


Figure 8.1 – Protection Scheme for Wind Generation Interface

Assuming that a fault takes place between busbars of the RMU units or the cables that interface these, it s possible to discriminate the protection arrangement so that both ends of the interface will trip. In this case, the fault contributions from each busbar will be different (forward or reverse currents) and the directional relays can be programmed to recognise these currents. The use of directional protection will be very effective in tripping both ends of the HV cables thus limiting any ride-through embedded generation from the wind turbines.

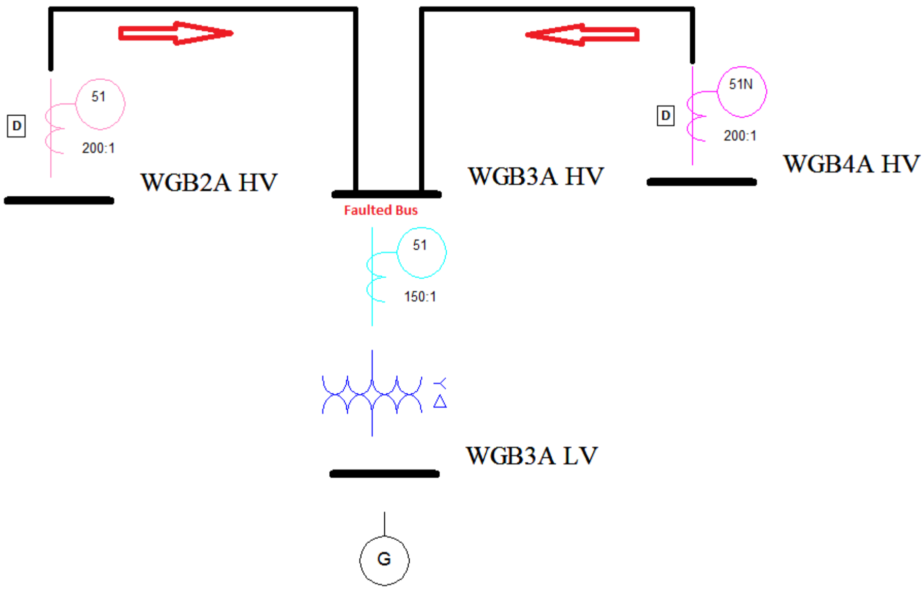


Figure 8.2 – Directional Relay Protection Scheme

Figures 8.3 and 8.4 show typical protection coordination that can be achieved in both directions for a radial wind generation connection.

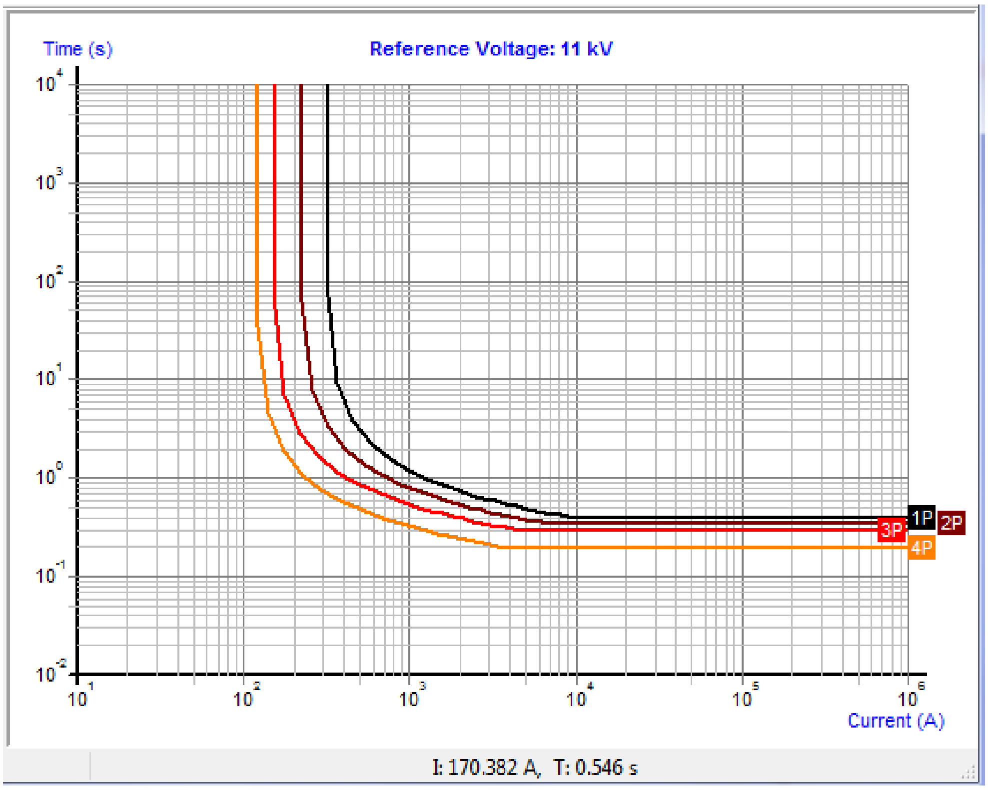


Figure 8.3 – Forward Directional Coordination Settings

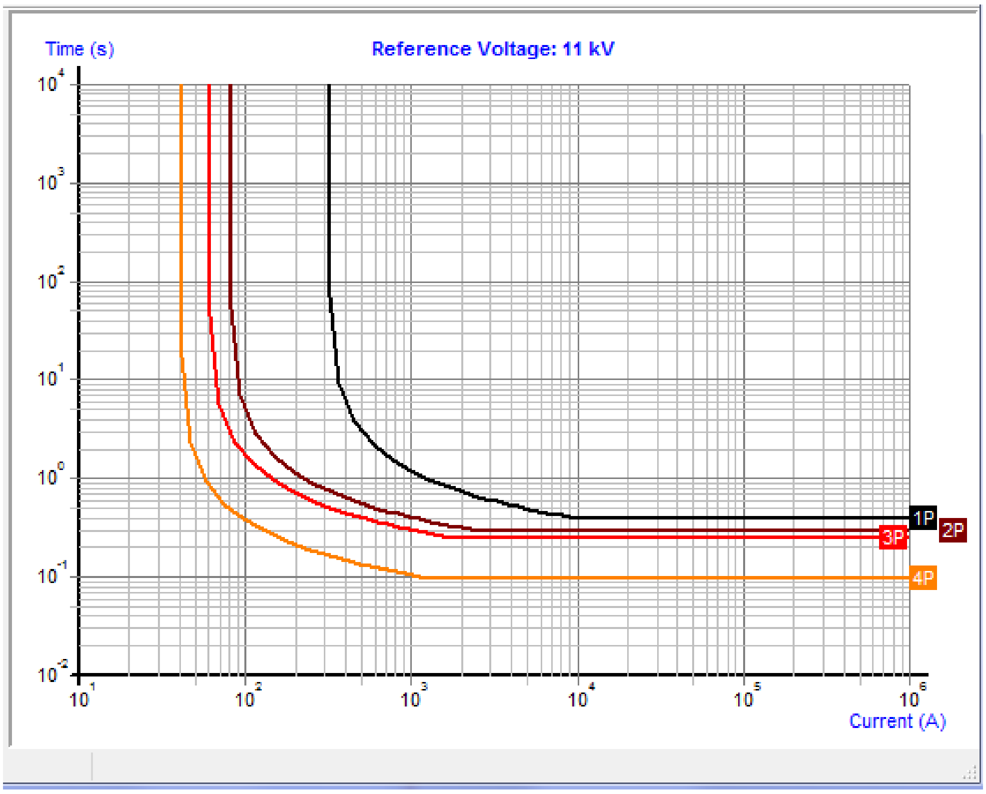


Figure 8.4 – Reverse Directional Coordination Settings

Additional protection requirements for an islanded system would include:

a) The continued use of distance protection for the transmission lines if these are present. Consideration for load reduction when the wind generation system is operational must be included in this scheme. Distance protection settings associated with the nearest transmission line (to the wind generation system) will have a large influence on other protection settings.

b) All transformers and busbars would continue to rely on differential and zone protection schemes. The operation of any of these systems would island the relevant leg of the wind generators with loss of this generation capacity. This situation, as previously stated, can limit transients on the network depending on the number of wind generation legs installed.

c) Standard overload and earth fault protection would continue its operation, only with alternate settings, which would be activated in the event that the wind generation equipment in each leg is not under use (i.e. no wind). The scheme would consider:

- If the wind generation system is not operational, the radial network would operate as per normal protection scheme.
- If the wind generation system is operating then directional relays are to be installed to allow limited ride-through capability.

8.4 SIMULATION RESULTS

The proposed directional protection scheme has been included in the main model and tested accordingly.

Figure 8.5 shows a typical arrangement that makes use of 4 x 1.5 MW DFIG wind generation units. The proposed directional protection scheme has been included on each leg of each RMU. The selected values for the protection relays are typical for such an installation. Table 8.1 shows the results of such a protection scheme. .

Two separate interconnections form part of the wind generator connection (in order to limit transients on the network in the event of a fault and total loss of wind generation) each relying on a slightly separate cabling scheme. The first has a single radial connection and the second has a ringed system. Both are viable options considering the small number of DFIG wind generators used.

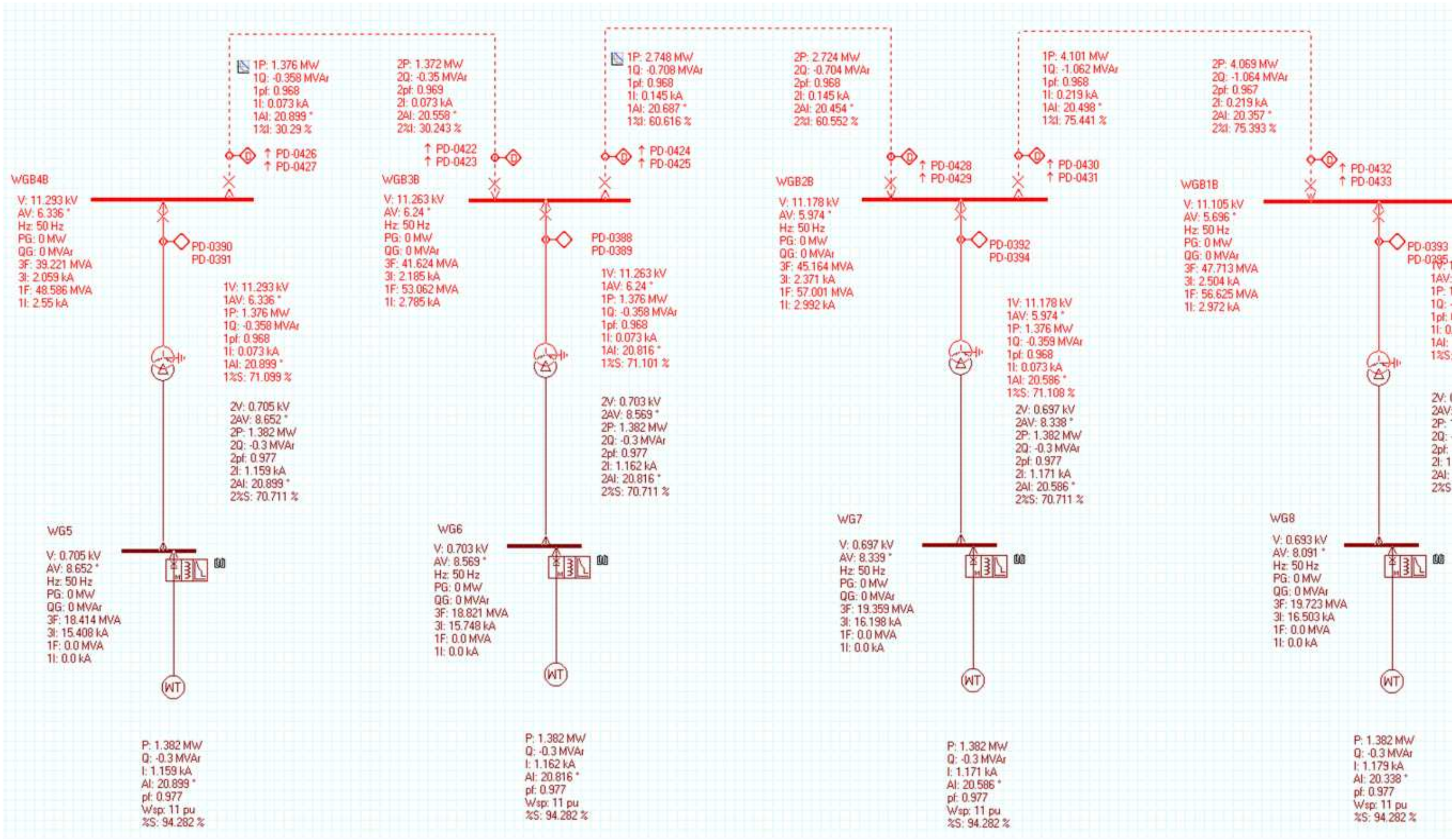


Figure 8.5 – Full Wind Generation Arrangement

Table 8.1 – Protection Scheme Test Results

Faulted Bus	Relay Bus	Trip	Pickup (s)	Trip (s)
Three Phase Fault				
WGB4A	WGB3A	Yes	0.228	0.258
WGB3A	WGB2A	Yes	0.364	0.394
WGB2A	WGB1A	Yes	0.481	0.511
Single Phase to Earth Fault				
WGB4A	WGB3A	Yes	0.138	0.168
WGB3A	WGB4A	Yes	0.128	0.158
	WGB2A	Yes	0.158	0.188
WGB2A	WGB3A	Yes	0.188	0.197
	WGB1A	Yes	0.197	0.227

By establishing a clear protection coordination program it is possible to trip only those two units installed between the locations of the fault (i.e. busbar), limiting disconnection of wind generation units to a minimum. When HV protection relays are not used on the interface cables, it would be evident that under any fault the complete leg would be disconnected from the network.

8.5 CONCLUSIONS

The addition of wind generation to a weak network does not represent a significant issue, yet needs consideration as a design issue when the possibility of instability may exist. Many options are available for the successful protection arrangement of such installations. The most effective is that which quickly isolates a faulted section with minimal wind generator interruption that implies improved stability under faulted condition.

The use of directional protection scheme on the interconnecting legs of an RMU offers a solid option that ensures fast action and isolation from both ends of the connection. The need for ride-through on such installation can cause embedded generation. In addition, the installation of bi-directional relays cannot be used to clear faults effectively as the fault contribution from each side of an RMU will be different.

When the number of wind generators forming a connection leg is small the use of a ringed system can be most useful. In this case, the protection scheme would follow the standard directional protection arrangement.

Installation of other protection functions must also form part of a dedicated protection scheme, as this will assist in further ensuring a quick course of action under faults. Blocking facilities are possibly the most essential of these.

Chapter 9. Conclusions

The application of small size wind generation installations interconnected to weak networks has been investigated in this thesis. Emphasis has been placed on networks that are very similar to existing installation found in Western Australia remote areas used to supply large industrial installations (i.e. Mining and Mineral processing Plants).

Two specific networks have been investigated, one interconnected to a utility network (remote location) and one based on an islanded power station arrangement. Each network has been carefully modeled to include accurate representation of networks and loads and wind generation has been added to establish the basis of this work.

While this work has concentrated on the installation of DFIG turbines any other type can be used, although the specifics in this case has been the ability of this particular DFIG unit to generate reactive power when under no wind condition.

The DFIG used has been dynamically modeled to meet the supplier's specifications and to provide identical results when tested. Dynamically modeling this DFIG has been the most time consuming task as it was necessary to ensure accurate performance when under transient simulations. All other parts composing the networks have been modeled as per the ERACS software data entry requirements (typical load flow modeling).

Having as a main objective the ability to predict the overall response of the addition of wind generators to such networks, it has been necessary to rely on very well established networks and to implement very accurate data to model these networks.

The restrictions imposed by weak networks can be significantly greater than those wind generation systems applied to robust networks which offer solid interface arrangements and some degree of redundancy. Weak networks do not have excess capacity, especially reactive power, and cannot tolerate significant transient events without having major interruptions to the network. Much of these issues have been reviewed in Chapter 1 of this thesis.

Chapter 2 outlines the more critical aspects of the computer model used to simulate the networks and the wind generation unit. The selected wind generator (1.5 MW GE DFIG) has been carefully modeled and tested in order to achieve accurate results.

Chapter 3 includes the existing definitions of a weak network as this has not been clearly established in the literature. With weak networks there are many variables that will contribute to the weak behavior and these need to be identified. A simple definition has been offered of what a weak network is.

In order to understand the foundations of transient stability analysis it has been necessary to include a chapter on the Swing equation and EAC; this has been used as part of the weak network analysis with wind generation. Chapter 4 covers this information and the equations which stem from Kimbark [18]. Mathematical development of the swing equation as applied to a standard network and one with wind generators only has been included in this chapter. The combination of these equations assists in determining the type of response that can be expected when transient analysis is modeled. The inertia constant for wind generators has been approximated from an equation developed by Gonzalez – Rodriguez et.al. [37]. This initial work has demonstrated the type of response that can be expected when such a combination of wind generation and fossil fuel based generation and network are combined and analyzed.

A comparison between the use of gas turbines and reciprocating engines power stations on one side and the DFIG wind generators on the opposite side has shown excellent results when analyzing transient events in weak network arrangements.

In order to establish the maximum quantity of wind generation that a weak network could accommodate it has been necessary to simulate a variety of scenarios. These can be seen in Chapter 5. The most important parameter used to determine the suitability of wind generation has been the rotor angle of the network generators as this clearly identifies the degree of instability brought about by the addition of wind generators. The maximum number of wind generators developed in this chapter is part of the computer models for both networks under consideration (weak connected and weak islanded). The results have shown that the addition of wind generators can have a positive effect under transient events (i.e. faults) within a limit of wind generation units installed. The conclusion in this case is that eight 1.5 MW wind generators would be the limit.

The first analysis with respect to the use of DFIG in weak networks is found in Chapter 6. The results obtained in Chapter 5 have been included in the network model that is interconnected to a major utility. Each of the eight wind generators has been included in the model. Initially all eight were connected to a single bus, but this proved to cause significant instability when the wind generator interface was tripped at full load. An initial conclusion of the simulations has been the need to separate the wind generation equipment into different sections. Thus, half of machines would be interconnected to the network at a different location to the rest of the wind generators in order to limit any transient events brought about by a fault at the interconnection point. The total loss of the wind generation leg would cause a significantly large impact on the network to cause instability throughout most of the local and main network. In this case, the loss of the 220 kV interconnecting transmission line (main to remote section of the system) due to remote instability would cause instability on the main network. This situation could not be acceptable under any circumstances.

Simulations have been carried out to cover the most critical events that could take place, such as fault incidents on transmission lines and fault events on distribution lines and substations. The most important aspect of this research is the overall response that could be expected of other gas turbines installed in the weak section of the network to transient events using wind generation assistance (ride-through issues) for voltage stability. Various small power generation gas turbines have been included in sections of the weak network and understanding their response when faults take place at some distance have shown that rotor angle and frequency fluctuations can be prohibitive.

Of greater importance to this research has been the application of DFIG units to islanded networks, the results of which can be seen in Chapter 7. This research has not been previously undertaken and has proven that wind generators can be used with such networks as long as the network limitations are understood and controlled.

In this case, the power station has been designed with typical generators used in the region and with the typical spinning reserves installed at these sites. The loads are highly inductive with large drives which can bring instability during load acceptance and load rejection. The maximum amount of wind generation will never exceed the load minus the capacity of one power station generator as there will always be the need for voltage and frequency control. As the addition of wind generation is established the need to repalce power station machines is evident (this is the main reason for wind generation addition to these sites – to reduce kWh costs). The results of the simulations prove that there is an effective combination possible between the inclusion of wind generation and the use of power station generators. The wind generation units quite effectively contribute to voltage control (ride-through) for operations under abnormal conditions.

9.1 CONTRIBUTIONS

The primary contributions of this research include:

a. Research work to establish a mathematical foundation for the determination of what represents a weak network by performing fault calculations; network reduction forms an integral part of this investigation. The use of fault contributions, whilst briefly mentioned in the literature, was not previously mathematically developed. This process has been included in this research work. Considering that all networks are unique, this process can simplify such a determination and thus, establishes a process to follow when adding wind generation.

b. While the use of the swing equation and EAC analysis has been employed for many years, this research has extended this analysis to include wind generation equipment. The results of this work have identified a simple and quite effective way of obtaining preliminary results into stability analysis (rotor angle and frequency calculations) when wind generators are installed in weak networks.

c. This research has demonstrated that relying wind generation can be effective on weak networks as long as a good understanding of the limitations of the interfacing network form part of the design. Installing wind generation at the far end of the network (worst possible location) has helped in proving that the wind generators will reduce the load on the radial transmission line and assist with network stability under transient events as they can comply with good ride-through capabilities.

   In some cases the need of splitting the wind generation installations will limit transient swings when interruptions takes place (total loss of the wind generation feeder is avoided this way).

   The use of rotor angle and frequency parameters to analyse transient events proves to be quite effective in understanding the possible limitations brought about by the addition of wind generators to a weak network. In particular, this research work shows that as the rotor angle fluctuates so does the current of the relevant feeders and this will have a large impact on protection system design.

d. The application of wind generation interfaced to a small, islanded network with large transient events due to machine load acceptance/load rejection and fault incidents has been simulated and computationally tested. This type of research, which has not been previously undertaken, has proven to offer a very viable alternative to remote power generation with wind generation installations. This research work has demonstrated that large wind generation equipment can operate in unison with small networks that include large industrial loads even under limited power station spinning reserve.

e. In conducting this research work, it became apparent that a revision of the protection relay practices presently used was necessary to incorporate wind generation to weak networks. Having a limited number of wind generators interfaced to weak or islanded networks presented a different problem as compared to large installations. As part of this research, a proposal that makes use of directional protection scheme is included in the two interconnecting legs of an RMU in order to limit any cases of embedded generation while maintaining as much wind generation operational during fault incidents. The need for ride-through capabilities is essential and the directional scheme can assist.

f. At all times the intent of this research has been to apply wind generation to weak networks, but interfaced to large industrial installations. A large number of islanded power systems used by industrial installations are common in remote locations and wind generation can assist in limiting energy costs. The foundations of this research have been those operations with large power swings, limited reactive power capacity and limited spinning reserve. The use of wind generation is technically viable as has been demonstrated.

9.2 FUTURE WORK

The application of wind generators will continue to be viable for many years to come given the large amount of development work currently undertaken by academia and industry. As the utility industry saturates viable locations for wind generation there can only be an increase in the application of such wind generation systems to weaker networks (remote locations or interfaced to radial transmission and distribution lines).

The following topics are suggested for future research as a continuation of this work:

a) Further research work should be pursued in the area of the application of other than DFIG wind generators. Technologies such as synchronous wind generators, new and improved induction wind generators and other such technologies should be applied to weak networks and compare performances of these under transient events.

b) In applying wind generation to weak networks further research should be encouraged on the application of FACTS devices. While wind generation with reactive power compensation facilities has been included in this case, the use of FACTS would be a possible solution when reactive capacity is not present with the wind generation technology such as induction generators.

c) Additional mathematical modeling of wind generation in weak networks should be researched in order to develop a simple-equation based method to establish an approximation of the maximum amount of wind generation that can be installed to limit instability under faulted conditions.

d) A research program could be established to understand and improve a protection scheme using blocking functions or relay communications control system. Interfacing all wind generators and the power station (for an islanded systems) to control output would be very effective in controlling capacities (real and reactive).

e) Having a dynamic model of the GE 1.5 MW DFIG wind generator it is now possible to conduct additional research on possible ways to improve the performance characteristics of DFIG wind generators when interfaced to weak networks.

Further research option should include:

f) Investigate the control of DFIG based wind farms for compensating voltage unbalance in weak networks. A DFIG system model containing the generator and its back-to-back converters suitable for analyzing system operation under unbalanced conditions can be developed. A control strategy for compensating grid voltage unbalance using DFIG systems can be proposed.

g) In order to focus on how different types of wind power facilities affect a network's dynamic stability when exposed to small disturbances, dynamic simulations for typical wind series and systematically use of leaner analysis (eigenvalues, sensitivities, etc.) to identify critical variables should be undertaken. Analyses can be carried out for wind power facilities based on both constant speed wind turbines and variable speed wind turbines. Dynamic models of SVC and traditional condenser batteries can be used if found necessary.

h) To provide voltage stability support in weak transmission networks for the ability of DFIG can be analyzed to find out the response of wind turbines to voltage dips at the point of common coupling and its effects on system stability. Also, in order to support the grid voltage by injecting reactive power during and after grid fault events, a control strategy can be developed for operation of the grid and rotor side of the converters.

i) For low-voltage-ride-through (LVRT) capability of wind turbines (WT) and in particular those driven by DFIG the biggest challenges facing massive deployment of wind farms is the increasing penetration of WT's in the grid. The grid connection codes in most countries require that WT's should remain connected to the grid to maintain the reliability during and after a short-term fault. This results in LVRT with only 15% remaining voltage at the point of common coupling (PCC), possibly even less. In addition, it s required for WT's to contribute to system stability during and after fault clearance. To fulfill the LVRT requirement for DFIG-based WT's, there are two problems to be addressed, namely, rotor inrush current that may exceed the converter limit and the dc-link overvoltage.

j) Consider larger size, say, 100 MW DFIG wind power plant to a weak transmission system. The effects of various wind plant load factors (100, 60 and 25% of nameplate rating) can be investigated. System performance can then be compared to a 100 MW conventional synchronous generator interconnected at the same location, and when the conventional generator is installed some distance away.

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Every reasonable effort has been made to acknowledge the owners of copyright material. I would be pleased to hear from any copyright owner who has been omitted or incorrectly acknowledged.

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Appendix A – GE 1.5 MW DFIG Wind Generation Unit Dynamic Model

The General Electric 1.5 MW Double Fed Induction Generator (DFIG) unit which has been used in the computer models has been described in detail in a paper issued by GE [35]. The information supplied in this paper includes a detailed description of each section that make up a wind generation unit in mathematical or dynamic model. Each section has been used to form a final model employed as part of the overall computer model established to analyze weak networks making use of DFIG units.

The dynamic model can be broken down into various sections including:

i. Wind model

ii. Mechanical model including blade arrangement, gear box and other minor parts composing the overall mechanical arrangement.

iii. Electrical generator system that includes real and reactive power generation.

Each section of the dynamic model has been modeled and later integrated to the overall system model. Each section has computationally been tested to ensure that correct results are obtained by comparing results with those outlined in the GE paper. The results have then been further tested to ensure that load flow models and transient stability models produced the correct and expected results and then it was possible to proceed with the research.

These three relevant sections that form the dynamic model have been relied on in the computer simulations. The following Figures outline the various major sections of the dynamic model of the GE 1.5 MW DFIG.

Figure A1 shows the dynamic model for Reactive Power Control which is critical for voltage control of the DFIG, in particular, when under transient events. This outlines the reactive power control for the GE DFIG unit. This particular model is critical as it allows reactive power to flow into the grid connection irrespective of wind speed. The GE unit can provide reactive compensation when real power is not present.

Figure A2 outlines the generator/converter model. This is the section of the model that interfaces with the grid arrangement. Each wind generation unit used as part of the model interfaces as per this arrangement.

Figure A3 provides an electrical interface module between the reactive power module and the generator.

Figure A4 outlines various aspects of the dynamic module. In this figure there is the need to take not account the wind power model that includes the curves forming part of Figure A8. This information is key for the conversion of wind to mechanical power. In addition, the modules include the blade angle control and the conversion dynamic model from mechanical power to real power.

Figure A5 outlines the pitch control and pitch compensation dynamic models.

Figure A6 shows the Two-Mass rotor model which effectively represents the mechanical arrangement for the wind generator including blade interface, gear box and shaft dynamics.

All this information has been employed to create a dynamic model using the Universal Dynamic Modeler (UDM) from the ERACS software and has been interfaced with the complete computer model of the network models used. The model was thoroughly tested in order to ensure that the results were accurate.

Although, the main objective of this research program was not to include a DFIG wind generation model it was necessary to have this completed to fit the network models that already existed (client based requirement).

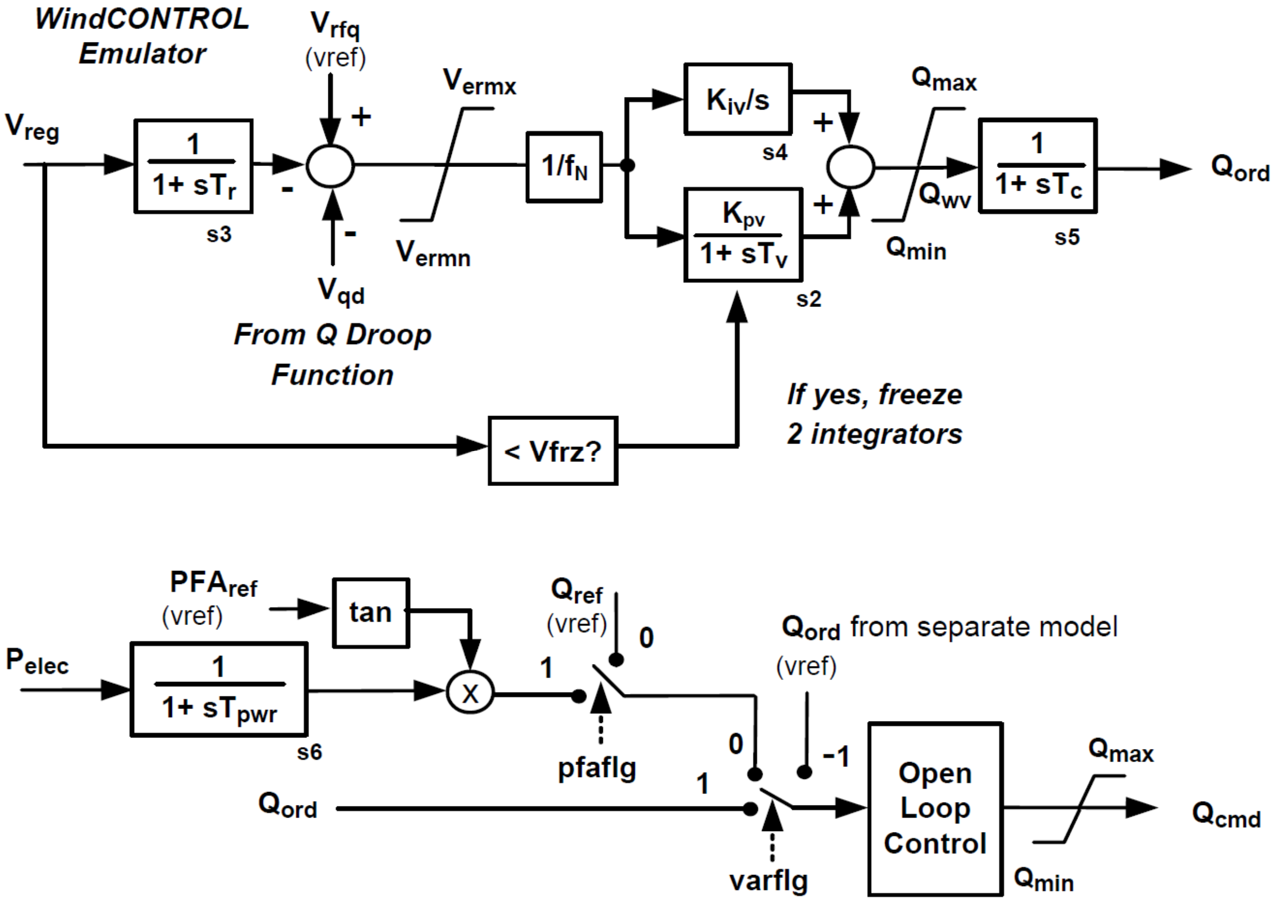

Figure A1 – Reactive Power Control Model

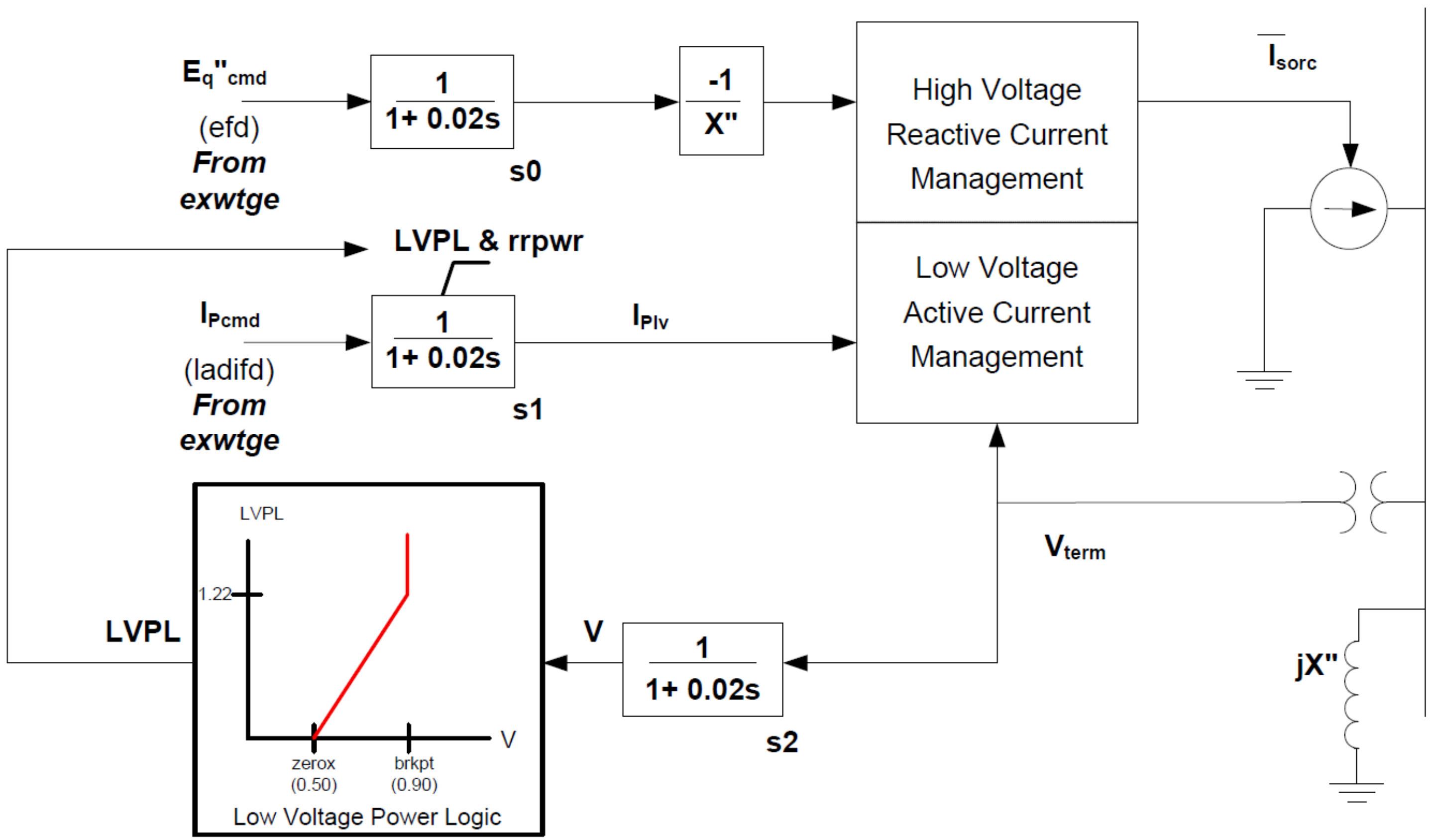

Figure A2 – DFIG Generator/Converter Model

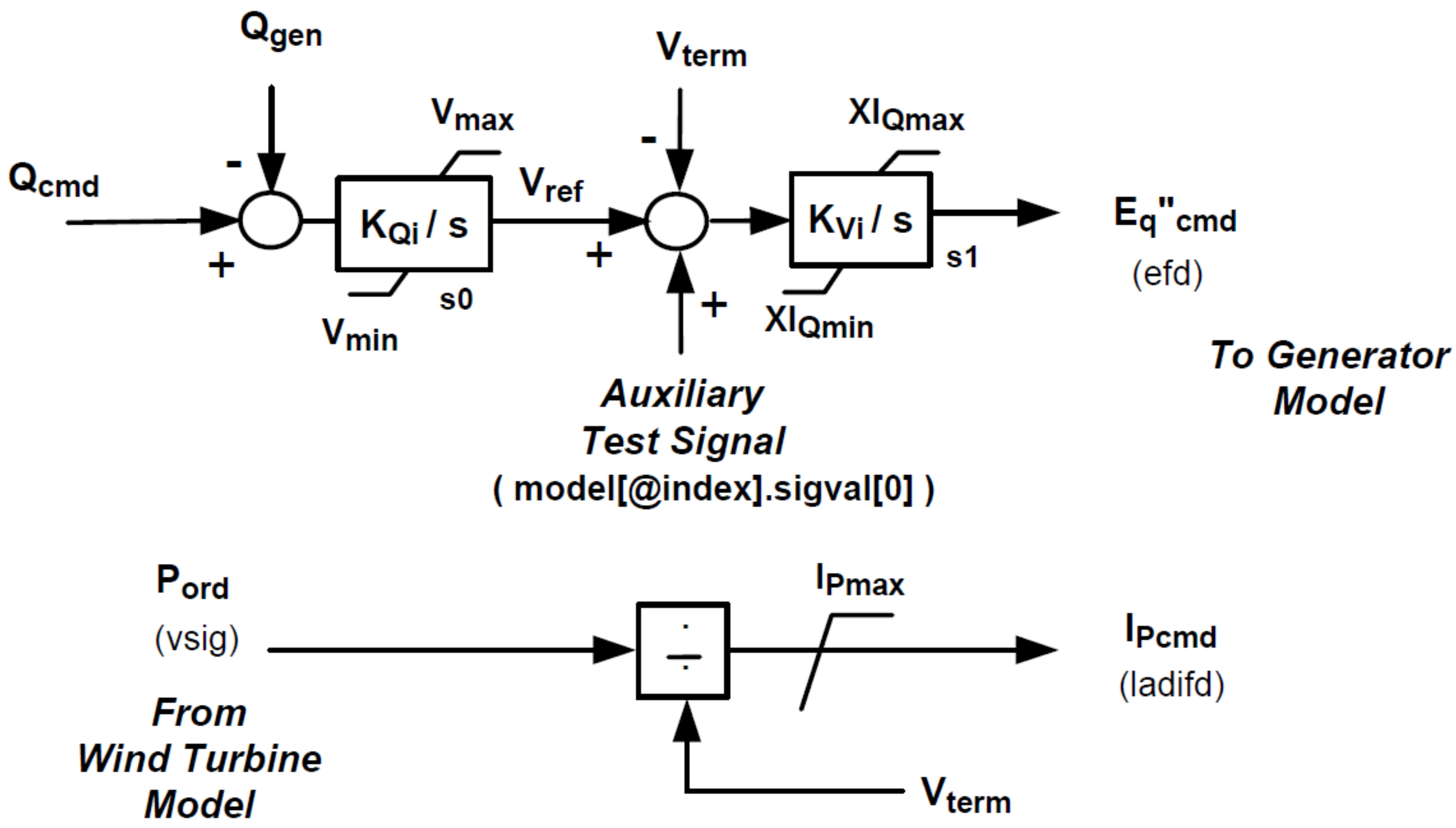

Figure A3 – DFIG Electrical Control Module

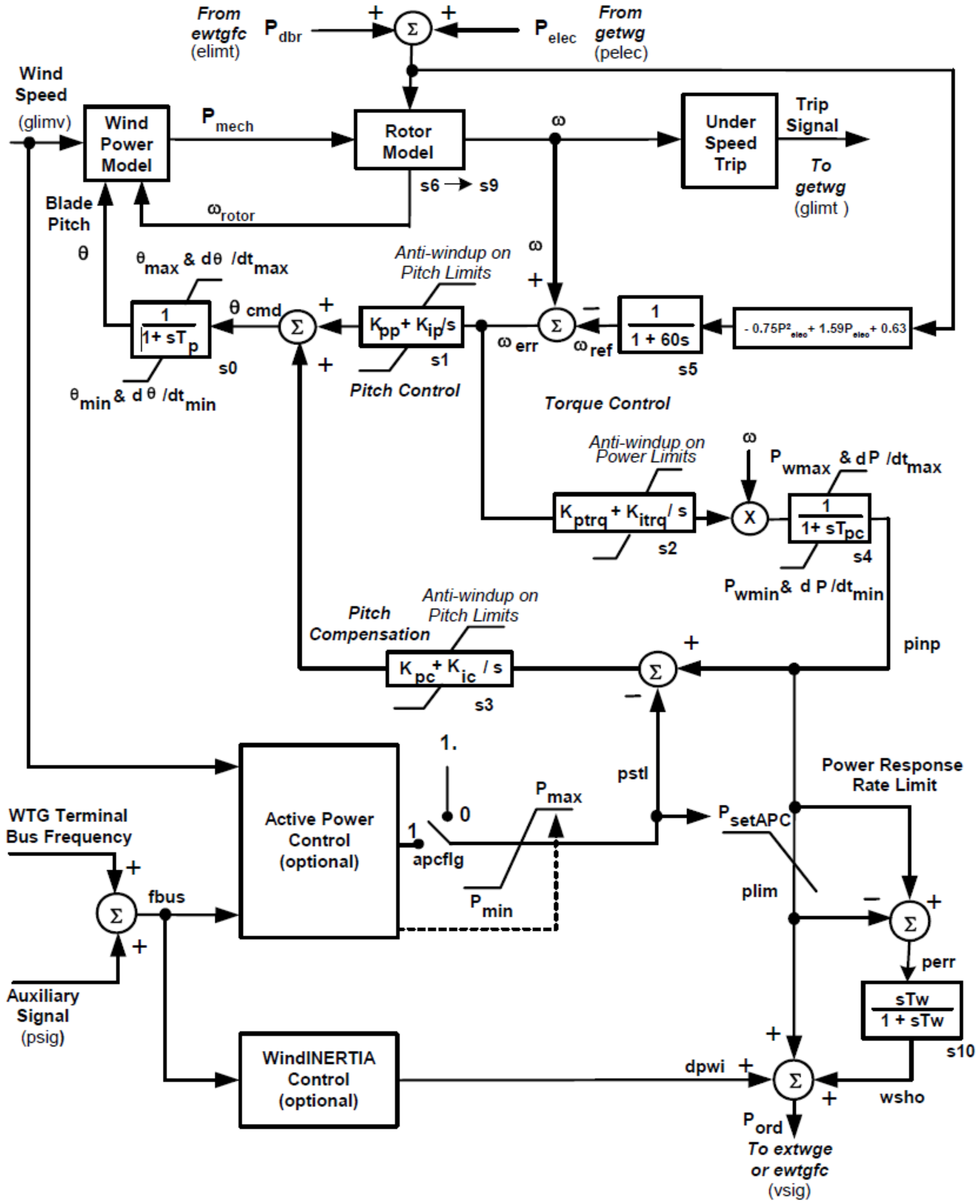

Figure A4 – Wind Turbine Block Model

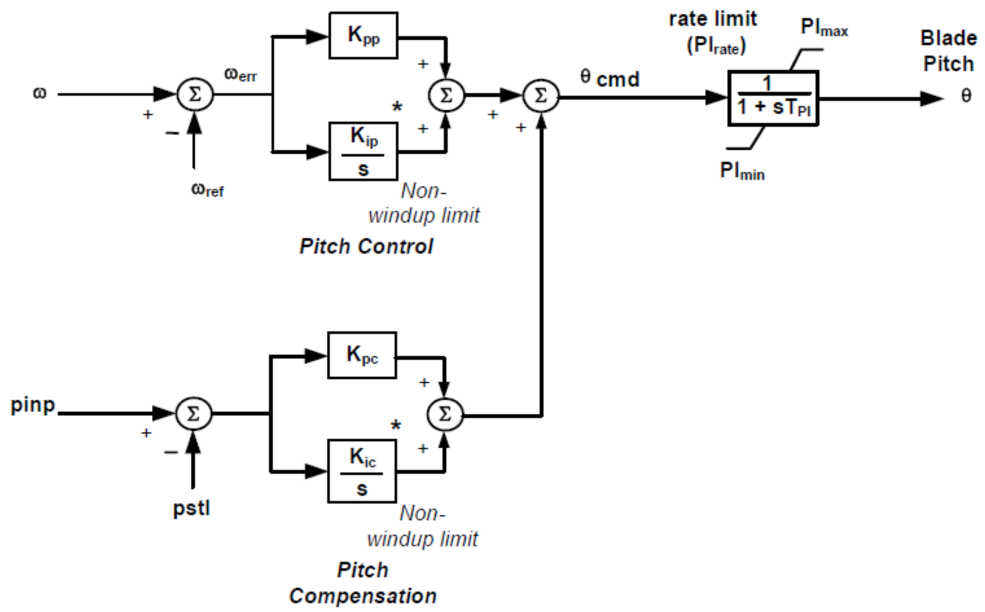

Figure A5 – Pitch Control and Pitch Compensation Block Diagram

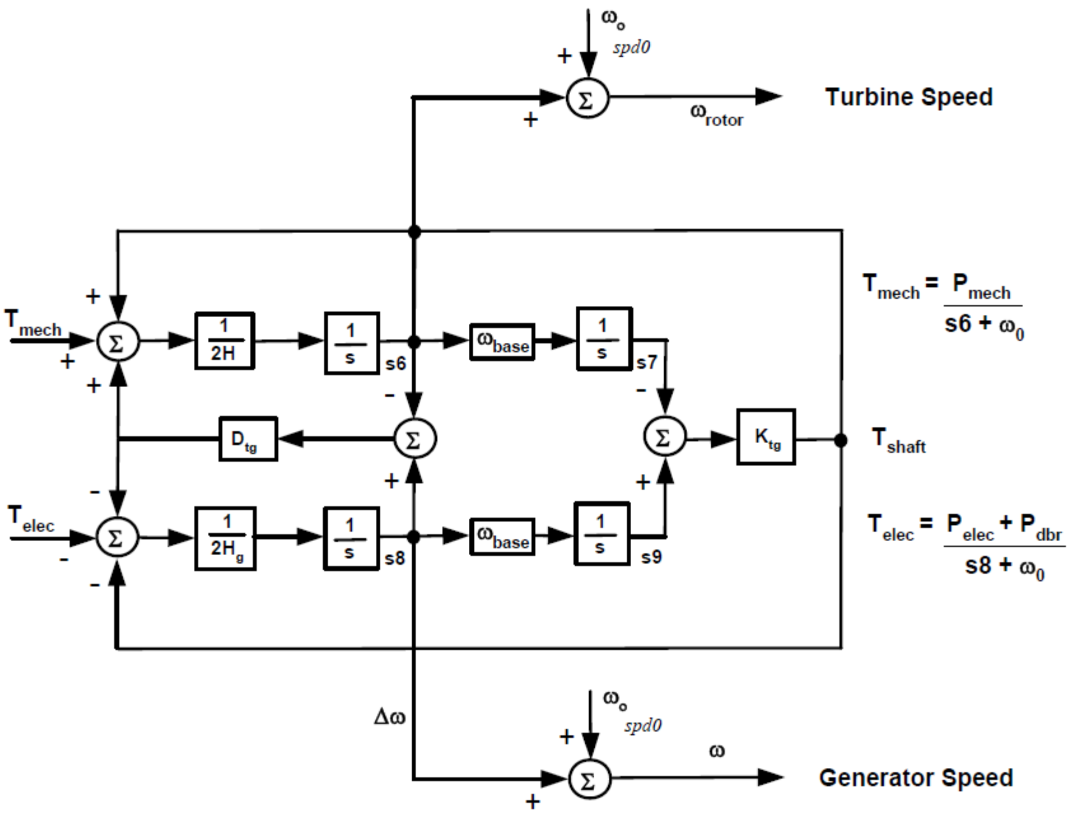

Figure A6 – Two-Mass Rotor Model

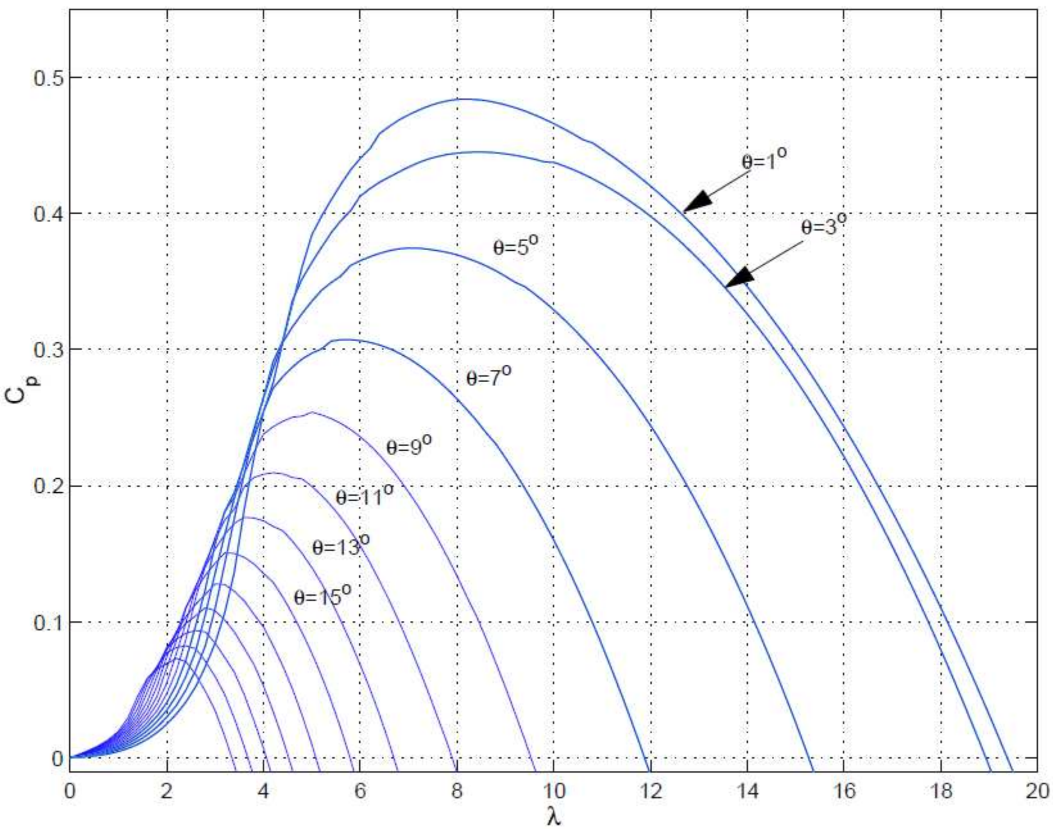

Figure A7 – Wind Power Cp Curves

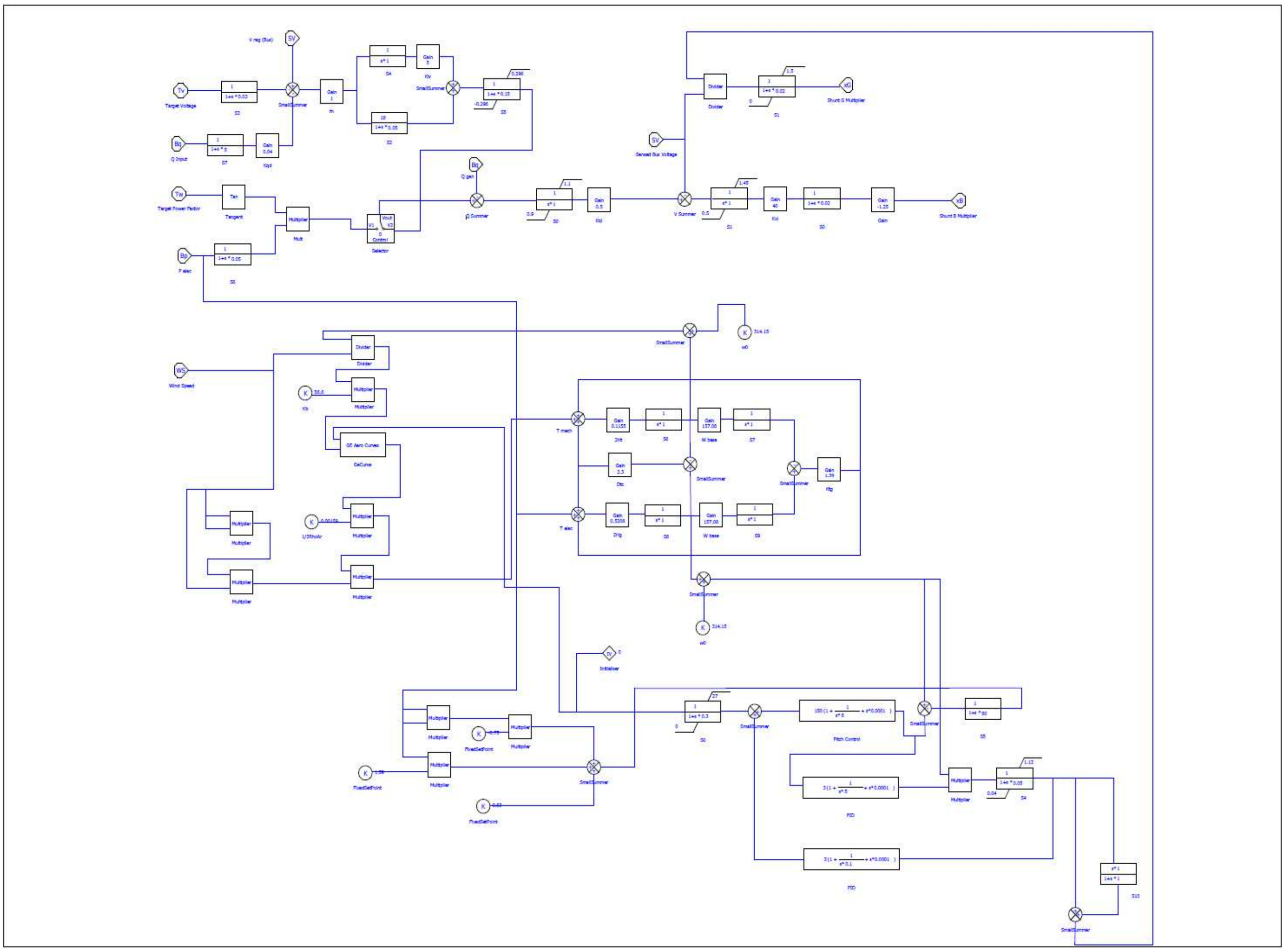

Figure A8 – ERACS Dynamic Model of GE 1.5 MW DFIG Wind Generator

Figure A9 is the complete ERACS model that has been completed based on the information supplied by GE. On completion of the model this has been thoroughly tested in order to ensure that it meets the expected performance. The performance of the testing as conducted in this thesis has been compared with the results GE has obtained with their own dynamic model testing. The results obtained are equal and some of the results have been verified by simple hand calculations.

Appendix B – Swing Equation Used for Maximum Wind Generation

The swing equation can be used to establish what amount of wind generation could be installed in a weak network by considering the rotor angle shift of generators installed in the weak section of the network under consideration.

If we consider that a network can be reduced to include a weak section of the network and the wind generation inclusion via a small network that is reduced to a simple reactive impedance we can calculate rotor angles that can be expected from a transient event.

Consider the reduced network in Figure B1. This represents the two machinery equivalences connected by a reactive impedance.

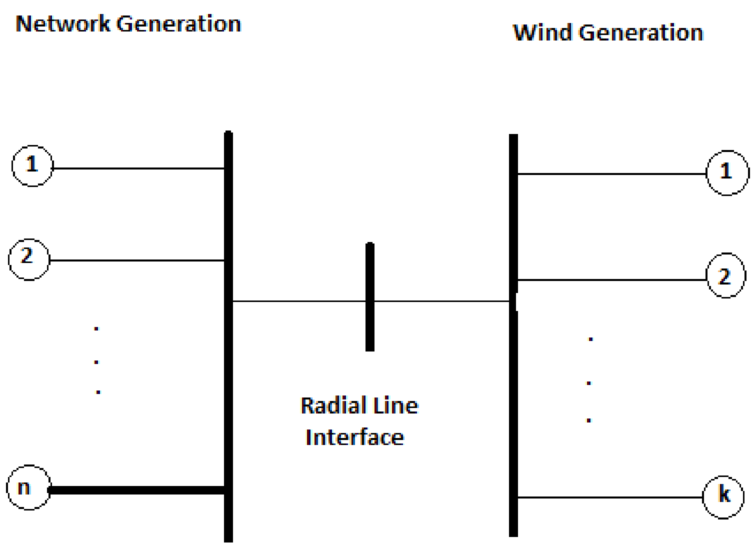

Figure B1 – Reduced Network

On the left side we have a representation of a weak network and on the right side we have an equivalent wind generation installation. Each side is represented by a swing equation that includes each of the generators.

$$\frac{H_n}{\pi f_0}\frac{d^2\delta_n}{dt^2} = P_{M_n} - \sum_{j=1}^{m} |E_n^{'}||E_j^{'}|\,|Y_{nj}|\cos(\theta_{nj} - \delta_n + \delta_j) \qquad (B-1)$$

where

$$\frac{H_n}{\pi f_0}\frac{d^2\delta_1}{dt^2} = P_{M_n} - P_{e_n} \qquad (B-2)$$

and

$$\frac{H_k}{\pi f_0}\frac{d^2\delta_k}{dt^2} = P_{M_k} - \sum_{j=1}^{m} |E_k^{'}||E_j^{'}|\,|Y_{kj}|\cos(\theta_{kj} - \delta_k + \delta_j) \qquad (B-3)$$

where

$$\frac{H_k}{\pi f_0}\frac{d^2\delta_2}{dt^2} = P_{M_k} - P_{e_k} \qquad (B-4)$$

Equation B-1 represents all machinery installed in the network and B-3 represents all the wind generators installed.

In this case the following information is relevant:

$$|E_k^{'}| = |E_k^{'}| \llcorner \delta_k \qquad \text{(B - 5)}$$

$$|E_j^{'}| = |E_j^{'}| \llcorner \delta_j \qquad \text{(B - 6)}$$

$$|Y_{kj}| = |Y_{kj}| \llcorner \theta_{kj} \qquad \text{(B - 7)}$$

These equations represent the network voltages (sending and receiving ends) and the network impedance that interconnect the generators.

If we apply the following abbreviations:

$$M_n = \frac{H_n}{\pi f_0} \qquad (B-8)$$

$$M_k = \frac{H_k}{\pi f_0} \qquad (B-9)$$

$$\delta = \delta_n - \delta_k \qquad (B-10)$$

We the obtain a combined swing equation for the two machine problem [12]:

$$\frac{M_n M_k}{M_n + M_k} * \frac{d^2\delta}{dt^2} = \frac{(M_k P_{M_n} - M_n P_{M_k}) - (M_k P_{e_n} - M_n P_{e_k})}{M_n + M_k} \qquad (B-11)$$

In this case we have two clearly defined entities [12]:

$$P_i = \frac{(M_k P_{M_n} - M_n P_{M_k})}{M_n + M_k} \qquad (B-12)$$

$$P_u = \frac{(M_k P_{e_n} - M_n P_{e_k})}{M_n + M_k} \qquad (B-13)$$

Equation (B-11) represents the swing equation for the complete network including the wind generators.

If we then add a small disturbance to the network on the wind generation side, we would have:

$$\frac{M_n M_k}{M_n + M_k} * \frac{d^2(\delta_T + \Delta\delta)}{dt^2}$$
$$= \frac{(M_k P_{M_n} - M_n P_{M_k}) - (M_k P_{e_n} - M_n P_{Max} \sin(\delta_k + \Delta\delta)}{M_n + M_k} \qquad (B-14)$$

Expanding the small disturbance side by making use of the equivalence

$$\sin(\delta_k + \Delta\delta) = (\sin\delta_k \cos\Delta\delta + \cos\delta_k \sin\Delta\delta) \qquad (B-15)$$

And considering that $\cos\Delta\delta \approx 1$ and that $\sin\Delta\delta \approx \Delta\delta$ then we can reduce this to:

$$\frac{M_n M_k}{M_n + M_k} * \frac{d^2(\delta_T + \Delta\delta)}{dt^2}$$
$$= \frac{(M_k P_{M_n} - M_n P_{M_k}) - (M_k P_{e_n} - M_n P_{Max} (\sin\delta_k + \cos\delta_k * \Delta\delta)}{M_n + M_k} \qquad (B-16)$$

The term $\mathrm{P_{max}} \cos\delta_k * \Delta\delta = P_s$ is the synchronising power coefficient and this determines the level of stability of the network.

If we consider that

$$P'_{ek} = \sum_{L=1}^{m} |E'_n||E'_k||Y_{nk}| \sin(\theta_{nk} - \delta_n - \delta_k) * \Delta\delta \qquad (B-17)$$

by reducing:

$$|E'_n||E'_k||Y_{nk}| = P'_{ma} \qquad = Amplitude$$

and

$$\beta = \theta_{nk} - \delta_n - \delta_k \qquad (B-18)$$

We obtain for L generators

$$P'_{ek} = \sum_{L=1}^{m} P'_{ma} \sin(\beta) * \Delta \qquad (B-19)$$

Substituting into (B-14)

$$\frac{d^2\Delta\delta}{dt^2} = \frac{(M_k P'_{ek} - M_k * \sum_{L=1}^{m} P'_{ma} \sin(\beta) * \Delta\delta}{M_n M_k} \qquad (B-20)$$

$$\frac{d^2\Delta\delta}{dt^2} = P'_{mT} - \left\{ \frac{P'_e}{M_k} + \frac{1}{M_n} \sum_{L=1}^{m} P'_{ma} \sin(\beta) * \Delta\delta \right\} \qquad (B-21)$$

and

$$P'_{mT} = \frac{(M_k P_{M_n} - M_n P_{M_k})}{M_n * M_k} \qquad (B-22)$$

Equation (19) is the swing equation for an equivalent group of machines including the wind generators for Figure B1 and it includes a transient event $\Delta\delta$. When we solve this equation, we find the solution for δ as:

$$\delta = \delta_0 + \frac{\Delta\delta}{\sqrt{1-\vartheta^2}} * e^{-\vartheta\omega_n t} \sin(\omega_d t + \theta) \qquad (B-23)$$

where:

δ_0 = Initial Rotor Angle

$$\omega_d = \omega_n \sqrt{1-\vartheta^2} \qquad (B-24)$$

$$\vartheta = \frac{D}{2}\sqrt{\frac{\pi f_0}{HP_s}} \qquad (B-25)$$

In this case, H (the inertia constant) will be that which has been calculated for the two generators system.