Wind Generation Investigation Project

Investigation 9

Effect of wind generation on reactive power contribution and dynamic voltage responses

WGIP: INV9

March 2008

TRANSPOWER

SYSTEM OPERATOR

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Transpower New Zealand Ltd • The National Grid

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Executive Summary

Introduction

The Electricity Commission has initiated the Wind Generation Investigation Project (WGIP) to determine what changes to the Electricity Governance Rules and Regulations (EGRs) and industry arrangements will be necessary to accommodate the connection of large scale wind generation. The 'Implications' phase of the project is an investigation of the impacts of wind generation on the operation of the New Zealand power system and electricity market, for a specified set of wind generation development scenarios.

Nine areas where the variability of wind generation output or the technical capability of wind generation may adversely impact on the operation of the New Zealand power system and electricity market were identified. Each of these areas has been investigated to determine the likely impact under the defined scenarios and whether further analysis is required for the Options stage of the Project.

Figure 1 shows the nine areas of investigation.

Variability of wind generation output	Scheduling and dispatch	Investigation 1 Effect of unpredictability of wind generation output on pre-dispatch processes	Investigation 2 Effect of variability of wind generation output on dispatch of generation	Investigation 3 Effect of variability of wind generation output on asset loading
Wind generation technical capability	Voltage and frequency management	Investigation 4 Effect of wind generation capability on steady state voltage management	Investigation 5 Effect of wind generation capability on management of frequency excursions	Investigation 6 Effect of wind generation capability on small disturbance voltage stability
	Power system stability	Investigation 7 Effect of wind generation capability on power system transient stability	Investigation 8 Effect of wind generation capability on oscillatory stability	Investigation 9 Effect of wind generation capability on dynamic voltage performance

Figure 1:- WGIP investigation areas

This report documents Investigation 9 which is concerned with the effects of wind generation on power system dynamic voltage responses and its impact on wind farm operation. Power flow and time domain simulation technique are used to identify power system voltage operation issues which will eventually lead to recommendation for further works to formulate guidelines and standards for new wind farm installation in New Zealand power system.

Related investigations are Investigation 6 (the effect of wind generation on steady state voltage stability, analysed using transient analysis of the power system), and Investigation 4 (the effect of wind generation capability on the System Operator's ability to manage steady state voltages).

Issues related to large scale wind generation development that are found to be significant will be advanced to the next phase of the WGIP which considers options for addressing these issues.

Voltage Quality

Voltage quality from the utility perspective can be defined as the characteristics of voltage waveform presented at a particular point of interest. A sufficient deviation of voltage parameters from a pure 50 Hz sinusoidal voltage waveform can distort voltage quality received by end users to the extent that operation of equipment connected to the power system is affected. Voltage magnitude deviation is usually initiated by system events such as short circuit fault and switching of system components causing system voltage to sag or swell. The ability of the power system to manage this disturbance to within the voltage quality limits is of interest in this study as this will affect the operation of the wind farm and possibly jeopardise system security. Dynamic Voltage performance is critical to wind farm operation especially for wind farm utilising induction generator as an energy conversion medium.

The System Operator has two obligations under the EGRs with regard to voltage[1]:

- Manage steady state system voltages within quality targets under normal conditions and post contingency, and
- Avoid cascade failure resulting from voltage instability.

The effects of wind generation on the management of steady state voltages have been considered in Investigation 4. This investigation considers the effects of wind generation on dynamic power system voltage response.

The displacement of other generation by wind generation will lead to changes in power system performance. For example, the displacement of synchronous generating plant in a region by wind generation outside the region will significantly change short circuits levels within the region. Likewise the displacement of synchronous generating plant in a region by FSIG technology wind generation will have a significant effect on post fault voltage recovery. Investigation 9 examines the effect of displacing other generation and the influence of different types of wind generation technologies on the dynamic system voltage performance.

Purpose

The aim of this investigation is to study the effects on power system dynamic voltage performance arising from:

- the displacement of other generation by wind generation; and
- the interaction of wind generation technologies with the power system during short circuit faults and immediately after the fault is removed. Wind generation technologies under consideration are Fixed Speed Induction Generator

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[1] Section II, Part C of the Electricity Governance Rules.

(FSIG), Doubly-Fed Induction Generator (DFIG) and Full Scale Frequency Converter (FSFC).

The results of this study can be used to as a basis for further works to determine if any changes to voltage support and Low Voltage Ride Through (LVRT) requirements for wind farm installations should be incorporated in the EGRs.

Assumptions and approach

New Zealand power system

The New Zealand power system consists of two island power systems (North Island and South Island) connected by an HVDC link. Figure 2 and Figure 3 show the North Island and South Island power systems respectively.

For the purposes of analysis used in this investigation, it was assumed that the present capability and configuration of the grid will apply and that committed new generating plant and committed grid upgrades have been commissioned.

It was assumed that there are no major upgrades to transmission capacity, and no new generating plant is commissioned beyond what is currently committed during the ten year period considered by the wind generation development scenarios. It is noted that upgrades of the transmission system (particularly into the Auckland region and the HVDC link) are likely to occur within the next ten years. These upgrades are likely to improve steady state voltage management capability. Basing the analysis on the existing power system will produce a more conservative result in terms of the effects of wind generation on steady state voltage management.

Wind Generation Development Scenarios

The Electricity Commission has developed four possible wind generation scenarios [1] (A, B, C and D) which have been used in the nine investigations analyses. Wind generation development as in Scenario C was modelled in the base case for the voltage studies. Scenario C has the maximum amounts of installed wind generation capacity in aggregate as well as in the most relevant regions in both the North and South Islands, and will therefore be the most extreme case for examining impacts on voltage stability.

The wind generation development scenarios developed by the Commission assume the connection of new wind generation on a regional basis but do not specify where in a region the new wind farms will be located. Future wind generation was assumed to connect into key regional nodes (e.g. Bunnythorpe in the Manawatu region) as shown in Table 1. It was also assumed that transmission upgrades have been undertaken where necessary to enable the new wind generation to connect to the power system at the major node.

Table 1 shows the major nodes and the amount of new wind generation expected to connect into the major node for each region.

Island	Region	Grid Connection (for modelling purposes)	Scenario C (very high penetration, diversified across the country)
North Island	Northland	Marsden 220KV	150 MW
	Auckland	Otahuhu 220 KV	300 MW
	Waikato	Huntly 220 KV	100 MW
	Hawkes Bay	Redclyffe 220 kV	300 MW
	Wairarapa	Masterton 110 KV	0 MW
	Manawatu[2]	Bunnythorpe 220 kV	450 MW
	Wellington	Wilton 220 KV	300 MW
TOTAL NI MW			**1600 MW**
South Island	Marlborough-Nelson	Blenheim 110KV	50 MW
	Canterbury	Timaru 220 kV	300 MW
	Southland	Invercargill 220 kV	300 MW
TOTAL SI MW			**650 MW**

Table 1: New wind generation and major node for connection under Scenario C

The other wind generation development scenarios would be expected to show a lesser impact on voltage stability, and the results of studies based on Scenario C for varying levels of wind generation penetration can be extended to the other scenarios. Separate studies for Scenarios A, B and D were not conducted for assessing the power limits due to voltage instability.

Wind generation assumptions

The Wind Generation Investigation Project has identified nine areas for investigation. The potential impact in each area has been assessed through preliminary analysis.

The approach taken during the preliminary analysis was to determine, for a situation where the impact of wind generation would most noticeable, if the effects would result in significant problems for operation of the power system or electricity market during the next ten years. If this case shows no material effects then no further study is required.

The following assumptions were made for this investigation:

- Generic wind turbine models are used in this investigation to illustrate the effect of various wind generation technologies on both static and dynamic voltage responses.
- Wind generation development scenario C will have the greatest potential effect and hence was chosen as the basis of the assessment.
- The displacement by wind generation by other generation will result in the greatest size of effects (if any) from wind generation in the area under investigation. This investigation assumes that regional generation providing voltage support will be displaced by wind generation that does not.

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[2] This figure includes the existing 250 MW of wind generation (Te Apiti, Tararua I, II and III) located near Bunnythorpe.

Wind generation dispatch

The New Zealand wholesale market design includes offer-based merit order dispatch using locational marginal pricing (nodal pricing) to arrive at the overall lowest cost secure dispatch solution. Nodal pricing includes both losses and congestion. The model co-optimises the dispatch of energy and reserves. Reserves are procured sufficiently to cover the loss of the single largest generating unit.

The current electricity market arrangements in New Zealand require wind generators to offer their output at a price of $0 or $0.01 per MWh,[3] which effectively results in wind generation being dispatched ahead of most other forms of generation.

Displaced generation could provide ancillary services (for example, hydro units could operate in tail water depressed mode to provide voltage support). This has not been considered in the analysis as it is by no means certain that any particular hydro unit is capable of operating in tail water depressed mode or that the owners of the plant would wish to provide the service.

Methodology

This investigation assesses the changing of system short-circuit levels as the result of displacing synchronous generating units with wind generation. Two analytical methods are used:

- Steady state analysis is used to analyse the changes in short-circuit level and the effect on voltage sag for a bolted three phase short circuit fault. This will provide the initial screening to identify regions which are most affected by the wind farm integration.
- Dynamic studies are carried out to analyse the dynamic voltage performance and its impact on the operation of different wind generation technologies under consideration in this study. The effects of additional reactive power compensation device at wind farms are considered.

Findings and recommendations

Wind generation technology has an important influence on voltage sag performance. Certain technologies can enhance performance in regions where there is little other generation and other technologies can significantly degrade performance in regions where synchronous generation is displaced by wind generation.

The analysis indicated that high amounts of wind generation using FSIG technology could cause voltage collapse following severe power system faults at times of light loading. The risk of voltage collapse can be reduced by installed dynamic reactive support devices at the wind farms or by limiting the amount of FSIG wind generation at times of light load.

Issues with new wind farms around lack of low voltage ride capability or poorly performing plant threatening power system security will be identified at the planning stage of the wind farm development. The developer can then decide whether to proceed taking into account the operational costs (e.g. instantaneous reserves costs and event fees and operational constraints) against the costs of providing mitigating measures (e.g. using different technology or providing additional plant).

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[3] Rules for offering and dispatch of wind generation were developed in 2004 in order to enable New Zealand's first grid-connected wind generator to be dispatched.

It is recommended that issues around low voltage ride through capability requirements be given a medium priority for future work and should be combined with any review of dynamic voltage support requirements for all types of generation. It is recommended that any such review of requirements for low voltage ride though and dynamic support capability for all generation considers protection system performance design and the low voltage ride through requirements for load.

1 Introduction

1.1 The Wind Generation Investigation Project

The Electricity Commission of New Zealand has initiated the Wind Generation Investigation Project (WGIP) [2] to determine what changes will need to be made to the Electricity Governance Rules and Regulations (EGRs) and industry arrangements to accommodate the integration of a large volume of wind generation into the New Zealand power system.

The project has four phases:

1. Development of potential wind generation development scenarios for New Zealand.
2. Assessment of the effects of the potential scenarios on the operation of the power system and electricity market.
3. Development of options to mitigate these effects.
4. Recommendation of changes to the rules and industry arrangements to accommodate the connection of large scale wind generation to the New Zealand power system.

The current phase of the project (phase 2) was an investigation of the impacts on the operation of the New Zealand power system and electricity market for a specific set of wind generation development scenarios determined in phase 1 of the project.

Transpower has been engaged by the Electricity Commission to undertake investigations into areas where the connection of large scale wind generation may affect operation of the power system and electricity market.

Investigations into nine areas are being carried out, and include issues related to both variability of wind generation output and technical capability of wind generation.

Significant issues related to large scale wind generation integration identified within any of the investigations will be put forward to the next phase of the WGIP which considers options for addressing these issues.

1.2 Effects of wind generation on power system dynamic voltage responses

The System Operator has two obligations in regard of voltage:

- Manage steady state system voltages within quality targets under normal conditions and post contingency, and
- Avoid cascade failure during voltage excursions.

The effects of wind generation on the management of steady state voltages have been considered in Investigation 4. This investigation considers the effects of wind generation on dynamic power system voltage response.

The displacement of other generation by wind generation will lead to changes in power system performance. For example, the displacement of synchronous generating plant in a region by wind generation outside the region will significantly change short circuit levels within the region. Likewise, the displacement of synchronous generating plant in a region by FSIG technology wind generation will have a significant effect on post fault voltage recovery. Investigation 9 examines the effect of displacing other generation and the influence of different types of wind generation technologies on the dynamic system voltage performance.

The management of voltage on the New Zealand power system relies mainly on synchronous generating units providing voltage support and other reactive power compensation devices such as capacitor banks, Static Var Compensator (SVC) and HVDC filter banks to regulate system voltage within the voltage quality targets. Unlike real or active power, reactive power does not accomplish any useful work but is required to support system voltage to maintain a continuous flow of active power. Consumption of reactive power lowers system voltage while supplying reactive power increases voltage magnitude.

The occurrence of short circuit faults is a common event in power systems. Such faults can be caused by lightning strikes on transmission plant, insulator breakdown, or transmission circuits sagging under heavy loading and contacting trees. Such faults need to be detected and the faulted assets removed from the power system in a short time. Delays in clearing system faults can cause the disconnection of sensitive loads or generating units and in a worst case scenario, power system collapse.

During short circuit faults, it is critical to supply enough short circuit reactive power to reduce the magnitude of voltage sag and provide sufficient short circuit current to allow protection relays to detect and isolate the fault. Power systems are designed to operate under short circuit conditions for short periods of time without damaging any equipment or de-stabilizing power system operation. Protection relays are employed to detect short circuit faults and act to isolate faults in an effective and responsive manner to reduce impact of the fault. The occurrence and removal of short circuit faults will result in momentary voltage sag experienced across the entire power system.

The ability of a power system to supply enough reactive power to reduce the magnitude of voltage sag and supply enough short circuit current to allow protection relays to operate correctly can be measured by the availability of short circuit power at the point of fault.

Most short circuit power is supplied by synchronous generating units connected to the power system. The consequence of introducing wind generation into the power system is that some synchronous generating units will be displaced and this can potentially affect power system operation in three distinct ways.

1. The displacing wind generation technologies may provide less short circuit power capability than synchronous generating units. Reduced system short circuit power reduces the power system’s ability to support system voltage during short circuit faults. More severe system voltage sags are expected.
2. The displacing wind generation may be in an area that is remote from the displaced synchronous generation. This will further reduce system short circuit power and the power system’s ability to support system voltage during short circuit faults.
3. The intrinsic characteristic of wind generation technologies such as Fixed Speed Induction Generators may worsen voltage sag by absorbing large amounts of reactive power from the grid after the fault is removed prolonging system voltage recovery time. This may result in instability in power system operation.

Delays in removing faulted assets can result in generating units disconnecting from the power system as a result of losing synchronism or through the action of protective systems. A long persisting severe fault could result in the disconnection of large amounts of generation and result in system collapse.

The deterioration of dynamic voltage performance as a direct result of wind generation can severely affect the ability of generation (including wind generation) to remain connected to the power system. The New Zealand power system is not tightly meshed and does not have very high short circuit levels.

Improvements in wind generation technologies led to the development of Doubly Fed Induction Generator (DFIG) and Full Scale Frequency Converter (FSFC) technologies that have a better dynamic voltage performance as compared to the FSIG technology. The faster and more agile power electronic control with inbuilt low voltage ride through capability enable DFIG and FSFC wind generation technologies to be less susceptible to system faults.

1.3 Wind generation investigation project approach

The timeframe of the WGIP requires that the analysis of the impacts of wind generation on the operation of the power system and electricity market be conducted over a short period. The analysis must therefore be limited in scope and focused on determining the answers required.

The analytical approach was to identify which of the nine areas where wind generation may affect the operation of the New Zealand power system and electricity market warrants detailed investigation. The approach was to take a situation (e.g. assume highest amounts of wind generation penetration, most limited capability of wind generation) where the effects of wind generation are likely to be most noticeable and determine if the impacts of wind generation are material. If the impacts are not material then no further investigation was required.

If the impacts are material then further investigation may be needed. It is anticipated that further investigation would be combined with consideration of options to mitigate the impacts in the next stage of the project.

The size and urgency of the impacts of wind generation determined during the preliminary analysis will allow the issues to be prioritised for attention in the next phase of the WGIP. For example, an issue that will have major impacts on the operation of the power system and electricity market for relatively low penetration levels of wind generation will be given high priority whereas an issue that has no significant impacts can be assigned a low priority.

The assumptions specific to this investigation have been made so as to be consistent with the approach for the WGIP.

1.4 This investigation

The scope of work covered in this report was limited to assess the dynamic voltage response during short circuit faults as wind generation displaces other generation and the effects of different wind generation technologies. Light system load scenarios present the most onerous test case. This is when the fewest generating units are dispatched, which lowers the system short-circuit level. Under these situations the power system is at its most vulnerable stage during system short circuit faults.

In general, regions in the New Zealand power system can be classified into two categories:

Regions with significant generation

- Regions with surplus generation where power is exported to other load centres within the power system. These are regions such as Auckland, Hamilton (thermal), Taranaki (thermal), Edgecumbe (hydro), Otago (hydro) and Southland (hydro).

Regions with little generation

- Regions with little or no local power generation that rely on imported power to satisfy local load demand. These are regions such as North Isthmus, Hawkes Bay, Wellington, Nelson and Canterbury.

2 Assumptions

2.1 New Zealand power system

The New Zealand power system consists of two island power systems (North Island and South Island) connected by an HVDC link. The North Island power system is dominated by fossil fuel power generation whereas hydro generation supplies the majority of the load demands in South Island power system. Figure 2 and Figure 3 show the North Island and South Island power systems respectively.

For the purposes of analysis used in this investigation, it was assumed that the present capability and configuration of the grid will apply and that committed new assets (e.g. the Huntly E3P generating station) and committed grid upgrades have been commissioned.

It was assumed that there are no major upgrades to transmission capacity, and no new generating plant is commissioned beyond what is currently committed, during the ten year period considered by the wind generation development scenarios.

Note

This is construction voltage. Operating voltage may be less. System as at 1 July 2004.

Figure 2:- North Island power system

Figure 3:- South Island power system

The wind generation development scenarios assume the connection of new wind generation on a regional basis but do not specify where in a region the new wind farms will be located. It was assumed that all wind generation in a region will connect into a major node in the region (e.g. Bunnythorpe in the Manawatu region) and that the necessary transmission upgrades have been made to enable the new wind generation to connect to the power system.

2.2 Reactive capability of wind generation

The Electricity Governance Rules in New Zealand require grid connected generators to support voltage by:

- having adjustable reactive power output (export reactive power at least equal to 50% of Maximum Continuous MW rating, import reactive power at least equal to 33% of Maximum Continuous MW rating) over the HV grid voltage range (e.g. 0.9 pu to 1.1 pu);
- continuously operating (when connected) in a manner that supports voltage and voltage stability on the grid; and
- having an excitation and voltage control system with a voltage set point that is adjustable over the grid voltage range and always operating in voltage control mode when connected.

At present, grid connected wind generation is expected to meet the same asset owner performance obligations (AOPOs) and technical codes (of the EGRs) for voltage support that other types of generating plant must meet. There are no such requirements on embedded wind generation. Individual wind turbines installed in grid connected wind farms to date have not been able to meet these requirements and additional reactive devices (e.g. static compensators and switched capacitors) have been required to ensure that the wind farm, as a whole, can meet the requirements.

It was assumed, for the purposes of this investigation, that future wind generation provides no steady state voltage support for FSIG technology or limited support as for DFIG and FSFC technologies. The requirements for voltage support to be provided by wind farms will be considered in the Options analyses in the next phase of the WGIP.

The new wind generation in a region was assumed to be connected (via new transmission assets) to a major transmission node in the region. It was assumed that the combination of new transmission assets and new wind generation was equivalent to a generating unit operating at unity power factor connected at the major node.

2.3 Generation dispatch scenarios

The New Zealand wholesale market design includes offer-based merit order dispatch using locational marginal pricing (nodal pricing) to arrive at the overall lowest cost secure dispatch solution. Nodal pricing includes both losses and congestion. The model co-optimises the dispatch of energy and reserves. Reserves are procured sufficiently to cover the loss of the single largest generating unit.

Dispatch occurs every five minutes through formal dispatch instructions sent electronically. In New Zealand there is no Automatic Governor Control (AGC). All generation offered under the trading rules in Part G of the EGRs is dispatched through the offer process in real time.

The current electricity market arrangements in New Zealand require wind generators to offer their output at a price of $0 or $0.01 per MWh. This effectively results in wind generation being dispatched ahead of most other forms of generation, such that generation plant providing reactive support is displaced by minimum capability wind generation plant.

2.4 Wind generation scenarios

The Electricity Commission has developed four possible wind generation scenarios, which are inputs to the analyses [1]. Wind generation development as in Scenario C was modelled in the base case for these studies. Scenario C has the maximum wind penetration in aggregate as well as in the selected regions in both the North and South Islands and will be the most extreme case for impacts on voltage stability.

The other wind generation development scenarios are expected to show a lesser impact on voltage stability. The results of studies for Scenario C for varying levels of wind generation penetration can be extended to the other scenarios. Separate studies for Scenarios A, B, and D have not been conducted for assessing the power limits due to voltage instability.

Table 2 shows a summary of the wind generation development scenarios developed by the Electricity Commission, together with the assumed grid connection nodes.

Island	Region	Grid Connection (for modelling purposes)	Scenario A (high penetration, concentrated in the North Island)	Scenario B (high penetration, diversified across the country)	Scenario C (very high penetration, diversified across the country)	Scenario D (low penetration, diversified across the country)
North Island	Northland	Marsden 220 kV		100 MW	150 MW	
	Auckland	Otahuhu 220 kV		100 MW	300 MW	30 MW
	Waikato	Huntly 220 kV	100 MW	50 MW	100 MW	30 MW
	Hawkes Bay	Redclyffe 220 kV	300 MW	150 MW	300 MW	30 MW
	Wairarapa	Masterton 110 kV		50 MW		
	Manawatu[4]	Bunnythorpe 220 kV	450 MW	350 MW	450 MW	250 MW
	Wellington	Wilton 220 kV	300 MW	150 MW	300 MW	30 MW
TOTAL NI MW			**1150 MW**	**950 MW**	**1600 MW**	**370 MW**
South Island	Marlborough-Nelson	Blenheim 110 kV		50 MW	50 MW	
	Canterbury	Timaru 220 kV		150 MW	300 MW	
	Southland	Invercargill 220 kV	100 MW	100 MW	300 MW	50 MW
TOTAL SI MW			**100 MW**	**300 MW**	**650 MW**	**50 MW**

Table 2: Summary of scenarios developed by the Electricity Commission

2.5 Wind generation technologies

2.5.1 *Fixed Speed Induction Generator (FSIG)*

The most basic form of wind generation technology is a conventional squirrel-cage induction (asynchronous) generating unit directly connected to the grid through a transformer deriving its mechanical power from stall-regulated (fixed pitch) blades connected to a hub via gear and soft-start mechanism. Figure 4 shows an FSIG topology. Induction generating units are basically an induction motor operating at a

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[4] This includes the existing 250 MW of wind generation (Te Apiti, Tararua I, II and III) located near Bunnythorpe.

speed slightly higher than the synchronous speed and are mainly used in the wind generation technology as an energy conversion medium due to its robustness in construction and low investment cost.

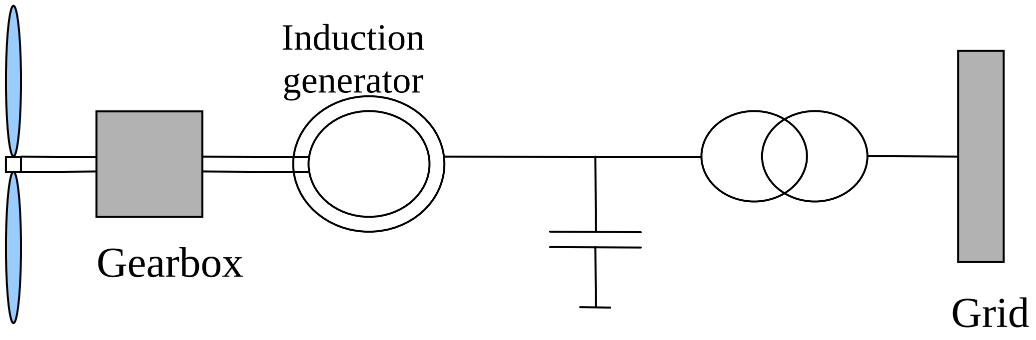


Figure 4:- Fixed Speed Induction Generation (FSIG) Wind Generation Technology Topology

The FSIG wind generation technology operates by drawing reactive power from the external grid via the stator to flux the rotor circuits. This results in the unit demonstrating a low full load power factor. Switched capacitor banks or power electronic controlled reactive power compensation devices (SVC or STATCOM) are installed to compensate for the reactive power consumed in order to reduce the intake of reactive power from the grid hence reducing transmission losses and in some instances improving grid stability. The main concern for utilising FSIG in wind generation is the absorption of excessive reactive power from the power system to magnetise the generator rotor circuit during voltage sag conditions arising from switching-in or system short circuit fault events. This effect is more pronounced in a weak power system where reactive power reserve is scarce.

2.5.2 Doubly-Fed Induction Generator (DFIG)

The Doubly-Fed Induction Generator (DFIG) technology uses a similar configuration as the FSIG except that a more sophisticated rotor winding control system is employed. The rotor winding control system consists of two bidirectional IGBT voltage source converters arranged in a “back-to-back” configuration with dc-link capacitor placed between the two converters acting as an energy storage device to reduce dc voltage ripple magnitude.

The DFIG topology is shown in Figure 5.

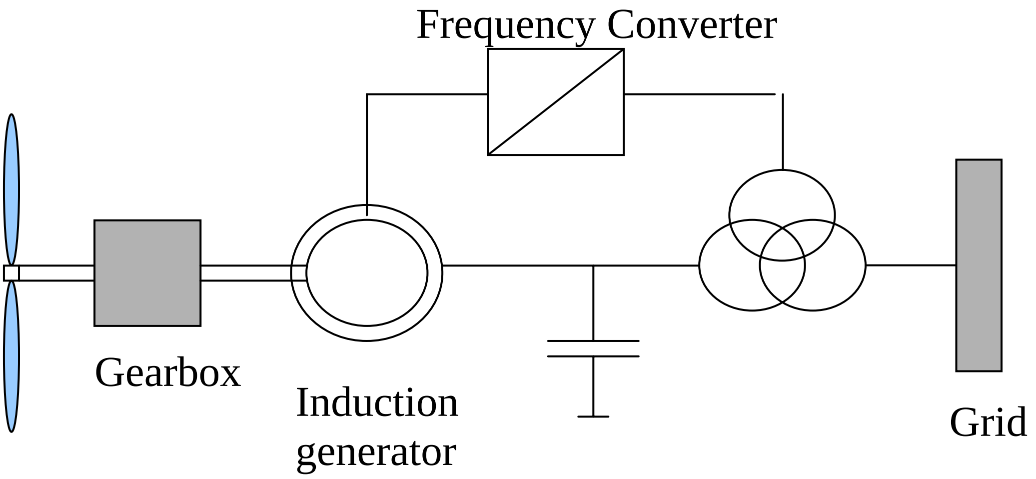


Figure 5:- Doubly-Fed Induction Generation (DFIG) Wind Generation Technology Topology

The rotor side converter is configured to control the magnitude and phase of rotor current thus controlling the values of electromagnetic torque production of the induction generator. The ability to control these rotor quantities enable the stator active and reactive power flow to be controlled. The grid side converter is configured to maintain a steady dc voltage and at the same instant, can absorb or provide real power to the grid depending on the operating speed of the generator. The converter can deliver about 20-30% of the total generator output thus reducing losses in the power electronic converters.

With DFIG configuration, the rotor frequency is effectively decoupled from the grid permitting a wider slip range than FSIG wind generation technology, thus reducing the impact of wind speed variation and maintaining a more efficient operating point for a range of wind speed. The ability of DFIG to control reactive power helps in power system operation. This feature is particularly useful for weak power systems to manage voltage fluctuations.

Under electrical transient conditions such as system short circuit faults, the DFIG unit exhibits similar characteristic as the FSIG unit in terms of fault current contribution but DFIG has a better performance during the fault recovery period. The converter requires a protection mechanism, such as “crowbar protection”, to activate to prevent thermal damage to the converter to avoid damage from high rotor currents during severe system faults.

2.5.3 Full Scale Frequency Converter (FSFC)

The Full Scale Frequency Converter (FSFC) wind generation technology has a power converter connected between the grid and the wind turbine. All the power generated by the wind turbine is processed by the converter before being transmitted to the grid system. This effectively isolates the wind dynamic and generator characteristics from the grid system. Any forms of energy conversion medium (induction, synchronous, permanent magnet etc) can be adapted to convert wind energy to electrical power. An example of FSFC configuration can be shown in Figure 6.

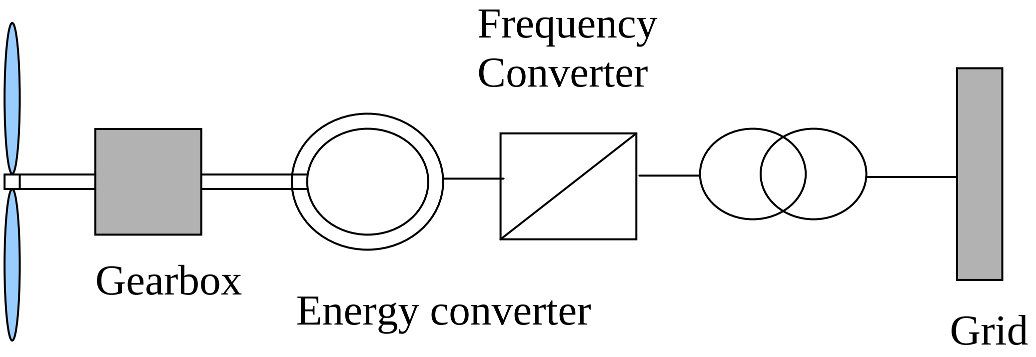


Figure 6:- Full Scale Frequency Converter Wind Generation Technology Topology

With modern power converter technology and advanced control systems, it is possible for the FSFC to control both active and reactive power precisely. The flexibility in controlling speed, active and reactive power whether during normal or disturbed grid conditions makes this technology attractive. Due to the need to transmit all the generated power, the converter is sized to at least the same rating as the generator. Fault current support is limited to the rating of the converter and the converter has to be disconnected/blocked to protect it from thermal damage under severe close-up faults.

2.6 Wind generation modelling

Table 1 shows the Electricity Commission's wind generation development scenarios. Each scenario has an amount of wind generation development assumed for each region of the country. The location and size of new wind farms in each region are not specified. The manner in which the new wind farms are connected (e.g. direct connection to the grid or embedded in a distribution network) was not specified.

In this study, the new wind farms connected to the system are modelled with a generic medium voltage and low voltage distribution system. Figure 7 is an example of a wind farm connected to the grid. This connection is for a wind farm at Marsden. The wind farm is assumed to be located some distance away from the Marsden 220 kV bus and is connected via 110 kV circuits. This is assumed to be a connection arrangement which will produce conservative results from the analysis.

New wind farms were modelled using the following principles:

- Where the point of common coupling (PCC) is a 220 kV bus, a step down 220/110 kV (10% impedance) transformer has been created with a MVA rating according to the nominal output of the wind-farm at 0.9 power factor. For example, a 300 MW wind farm will require a 334 MVA transformer (300/0.9).

- Transmission circuits (rated at 114 MVA) connect the new 110 kV bus to the wind farm (assumed to be 10 km away from the PCC). The transmission circuits are based on nitrogen conductor type which has a thermal capacity of 600 Amps. The number of transmission circuits is determined by the installed capacity of the new wind farm (e.g. 300 MW installed capacity will require three 114 MVA circuits).

- From the far end of the new 110 kV circuits, a step down 110/33 kV transformer is added. This has an impedance and rating identical to the 220/110 kV transformer;
- Wind turbines are assumed to be generic fixed speed asynchronous machines, double fed induction generators, or full converter synchronous generators as appropriate.
  - FSIG: It is assumed that these units have no built in fault ride through capability and no additional fast reactive power compensation. Each unit has a rating of 1805 kVA at 690V with a fixed capacitor to compensate for the reactive power absorption of the asynchronous generator.
  - DFIG: A doubly-fed Induction generator (DFIG) is a wound-rotor induction machine with a frequency-converter connected to the slip-rings of the rotor. Typically, the frequency converter consists of two back-to-back voltage-source converters with an intermediate dc bus [4].
  - FSFC: A Full Scale Frequency Converter is a generating unit (either synchronous or induction) connected to the grid through a variable frequency power converter system, which completely decouples the generator speed from the grid frequency. The power converter system consists of the grid-side and the generator-side converters connected back-to-back through a DC link. Because of the almost perfect decoupling of electrical machine dynamics from the grid by the fully rated converter, it is appropriate to highly reduce the model for grid impact studies and to use highly reduced machine models [5].
  - The Wind Turbine Models used in this study are generic models which did not refer to any makes or manufacturers. Hence, the models have not been validated by field measurement data.
- In addition to the unit capacitors a small fixed capacitor has been added to the 33 kV bus to offset reactive losses in the distribution system – in accordance with the typical practice for modern wind-farms.

Any reactive power compensation devices associated with particular wind generation technology will be modelled to produce a more accurate dynamic voltage response from the model.

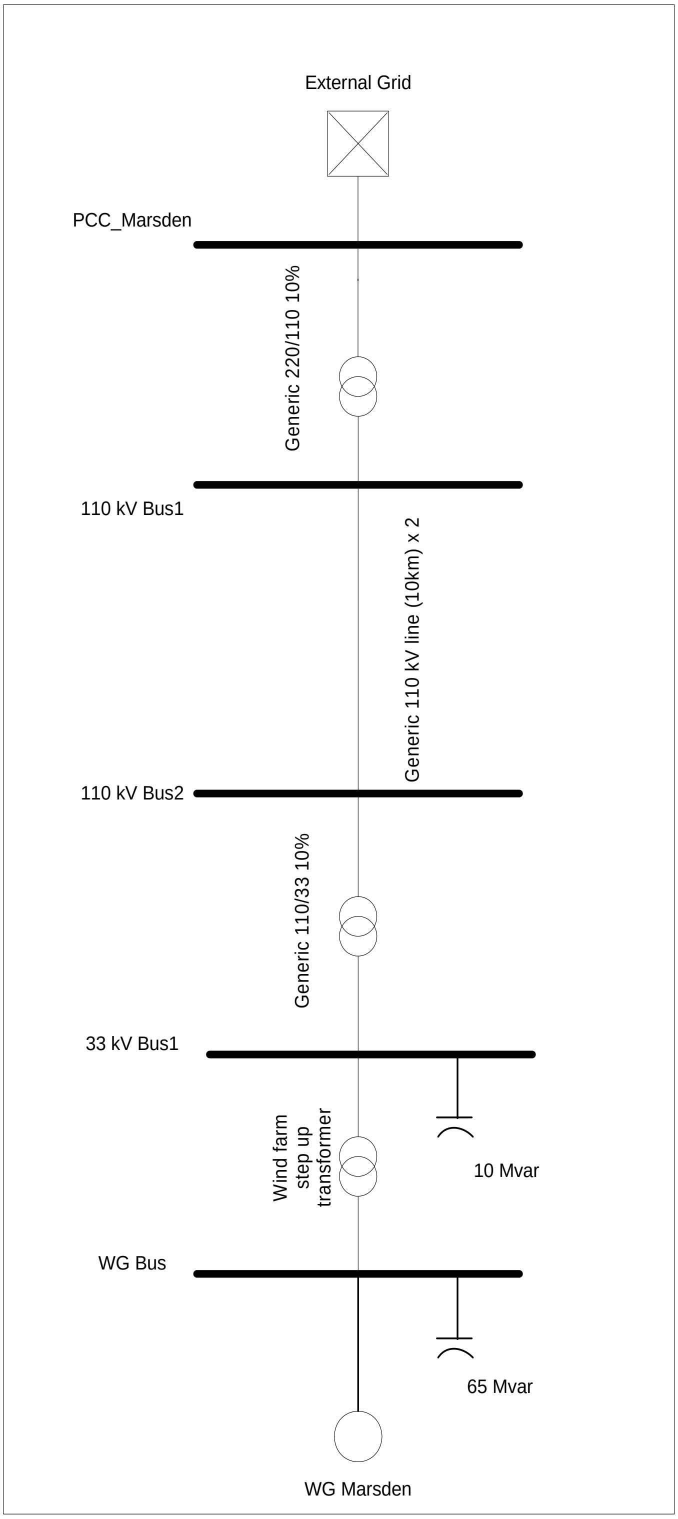


Figure 7:- Assumed Wind Farm Configuration

2.7 Planning criteria for performance analysis

The performance analysis is based on Transpower's Main Transmission Planning criteria [3]. The requirements are the same as the Asset Owner Performance

Obligations (AOPOs) and technical standards concerning voltage contained in the EGRs.

2.8 Power system operation

The operation of tap changers on transformers with on load tap changing capability was modelled in the analysis. It should be noted that not all transformers have on load tap changers. These transformers are modelled with a fixed tap position consistent with what would be typically applied under the different power system conditions.

The shunt capacitors connected to the grid are operated to meet set grid voltage profiles. These profiles are designed to maintain pre and post contingency voltages within the voltage range, as far as possible.

2.9 Planned outages

Planned transmission outages have not been specifically considered in these studies. Such outages only go ahead under satisfactory system conditions. Planned outages do not go ahead at times of system peak loading or at times of lightest system loading (e.g. early on Christmas morning). Outages tend to go ahead at times of lower loading. It is possible that there may be issues with steady state voltage management during some outages.

Outage planning considers how power system security will be maintained during outages, in particular where concurrent outages are requested. Some outages will not be able to go ahead at the same time as other outages. Operational measures will be required during some outages to maintain power system security. These measures, such as load management and constraints on the dispatch of generation, are arranged with the affected parties prior to the outage taking place. Some outages may require generation to be shut down for the duration.

It was assumed that issues associated with steady state voltage management during outages will be managed according to current outage planning processes. Planned generation maintenance was not explicitly considered in the studies. The effects of such outages can be estimated from the effects of displacement of generation in a region.

2.10 Power System Interaction during short circuit fault

The FSIG unit is basically an induction generator with its stator windings directly coupled to the grid. Magnetic excitation required for torque production is drawn from the grid via the stator winding. At the inception of the fault, stator current can build up to a value several times the rated current depending on the sub-transient reactance of the generator and the reactance of the equivalent network at the location of fault. The fault current contribution decays over time due to the decay of main flux of the machine as the rotor voltage collapses during fault. After the fault is removed, voltage recovery is hampered by the re-magnetizing of the iron core drawing large amounts of reactive power from the grid system.

With fast response power converters and controllers employed in the DFIG technology, it is possible to control the stator current continuously and precisely for the duration of the fault event. At the instant of system short circuit fault, the stator and rotor current increase dramatically and to prevent the converters from thermal damage, crowbar protection is usually employed. The activation of crowbar protection effectively reverts from DFIG to FSIG configuration. Hence, DFIG behaves similarly to the FSIG except that DFIG can regain control of the rotor current faster after fault has been removed, thus improving the voltage recovery process.

The FSFC unit has a power converter that decouples the generator from the grid. With modern power semiconductor devices capable of fast turn-on and turn-off characteristics, it is possible to control active and reactive power flow into the grid, regardless of grid system conditions. The dynamic voltage behaviour of the FSFC during short circuit fault is therefore not governed by the intrinsic characteristics of the generator, but the embedded control algorithms of the power converter. In this study, FSFC is considered to contribute fault current up to its full load current rating during short circuit fault and will regain its ability to control active and reactive power flow after fault is removed.

2.11 Methodology for analysing dynamic voltage performance

Both static and dynamic analysis methods can be employed to assess the impact of wind generation on dynamic voltage performance. Static methods are generally used to analyse short-circuit power contribution. This can be used to assess effects on:

- Management of steady state voltages;
- Voltage sag magnitude for short circuit faults; and
- Protection setting calculation and coordination.

These static studies are carried out by calculating short circuit levels at system buses or calculating fault currents and voltage sag for different fault types and locations.

Dynamic studies are performed to analyse voltage deviation due to many power system events. Such studies involve using power system dynamic models and applying a fault to determine how the power system reacts during and following the removal of the faulted asset. This investigation uses two methods to assess the effects of wind generation on power system voltage performance.

2.11.1 Effect on power system short circuit levels and voltage sag during faults

Short circuit levels at a number of buses around the power system are calculated for different system conditions:

- With no wind generation and with different levels of wind generation output displacing synchronous generating plant; and
- With different types of wind generation technology.

Fault voltages at key buses are calculated for three phase faults at varying locations and for varying amounts of wind generation. The effects of different wind generation technologies are examined.

2.11.2 Effect on dynamic voltage sag performance

Studies using dynamic models of the power system are carried out to determine voltages at key buses during, and following, faults at varying locations on the power system.

Figure 8 shows example voltage sag waveforms. The minimum voltage reached and the time required for the voltage to recover to 0.9 pu for each type of wind generation technology are shown for each voltage sag waveform.

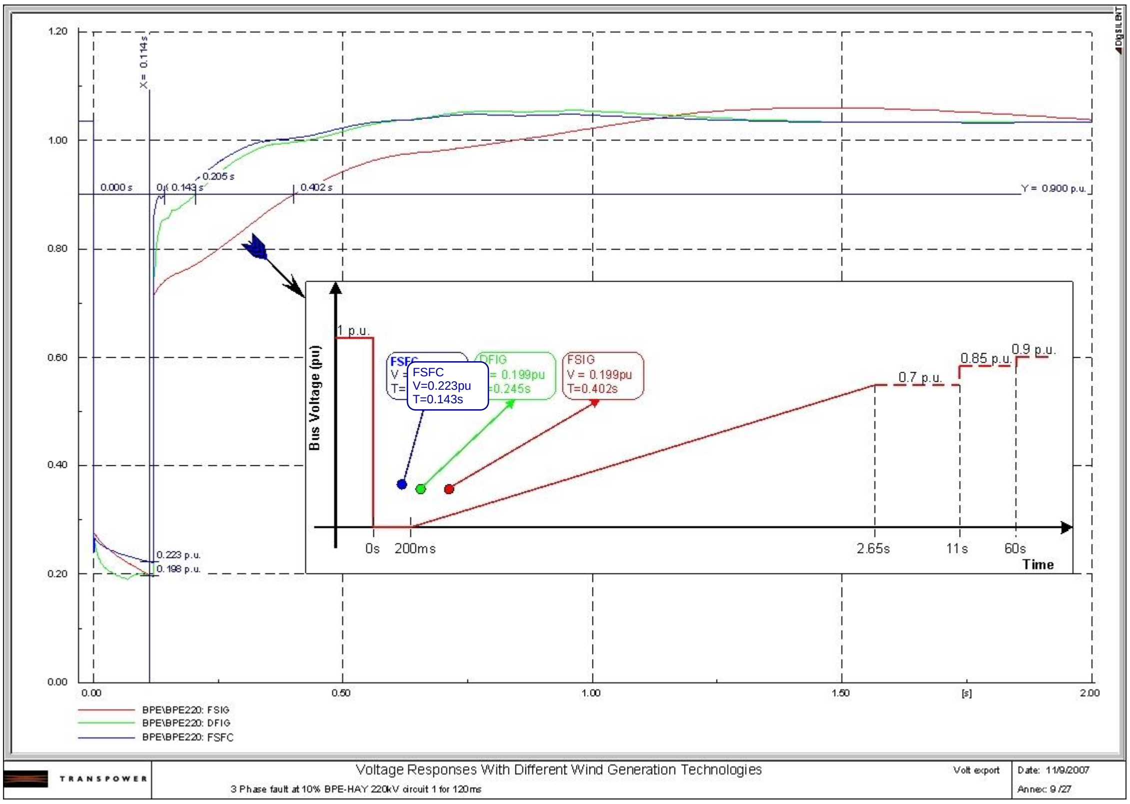


Figure 8:- Example of voltage sag waveforms showing minimum voltage and time required to recover to 0.9 pu.

The minimum voltage (V) reached in *Figure 8* for the FSIG technology is 0.199 pu and the recovery time to 0.9 pu (T) is 0.402s.

The overall approach is:

- A bolted three phase short circuit fault is applied to the power system and is cleared in 120 milliseconds by a main protection element.
- A voltage sag waveform at the bus of interest is obtained through dynamic studies.
- The minimum voltage reached and the time required for the voltage to recover to 0.9 pu are recorded from each voltage sag waveform.

3 Study Results and Analysis

3.1 Short circuit level Analysis

3.1.1 Generation and short-circuit level distribution

The amount of wind generation capacity envisaged in wind generation development scenario C (2250 MW) is significant in comparison to system load under light load conditions (around 3000 MW). The effects of wind generation displacing other generation will be most pronounced under light load conditions.

The introduction of new wind generation significantly changes the generation dispatch patterns for both North and South island power systems under light load conditions. Under the light load scenario, a considerable amount of hydro generation in the Waikato region is assumed to be displaced by the wind generation. Minimum thermal generation is kept in Auckland, Hamilton, and Taranaki regions to maintain a satisfactory voltage profile and to maintain power system stability.

Figure 9 and Figure 10 show the changes in generation dispatch for no wind generation, wind generation output at 50% of installed capacity, and wind generation at 100% of installed capacity for times of light load, for the North Island and South Island respectively. The Bay of Plenty and Waikato regions are most affected by the introduction of wind generation as regional generation is being displaced by wind generation elsewhere, as illustrated in Figure 9. Some regions, such as North Isthmus, Hawkes Bay, and Wellington, may see increases in short circuit levels with the introduction of new wind generation in these regions with limited other generation.

In the South Island power system (see Figure 10), the Otago region is most affected by the envisaged new wind generation at Timaru 220 kV bus. The installed capacity of power generation in the Otago region increases from 10 MW to 300 MW which should improve local voltage support capability. As for the Southland region, the displacement of a generating unit in Manapouri Power station by 300MW of installed wind generation capacity at Invercargill considerably reduces local short-circuit levels, hence affecting voltage sag magnitude during short circuit faults.

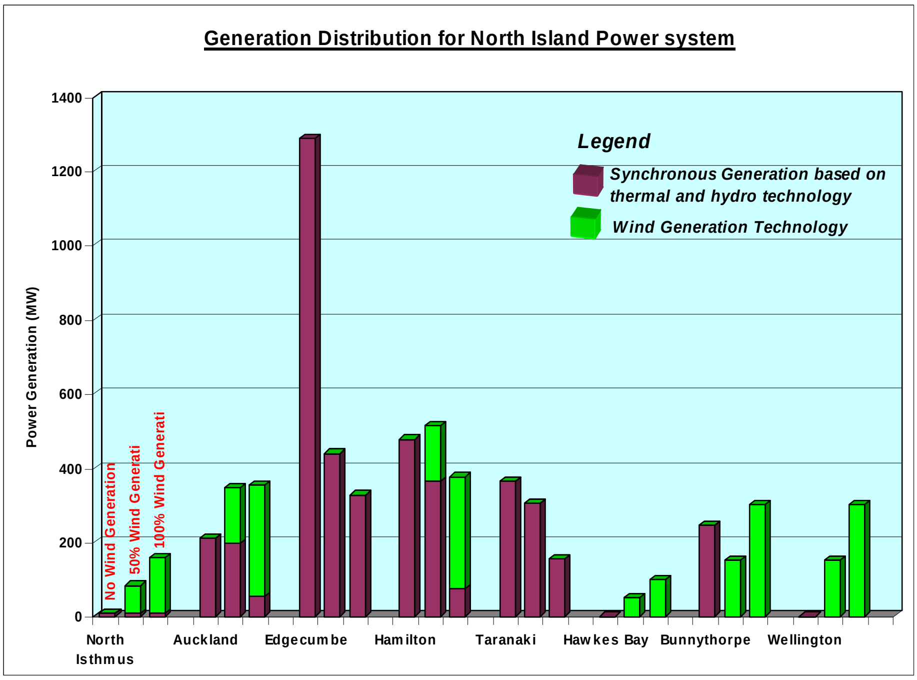


Figure 9:- North Island Power System – Generation Dispatch Pattern

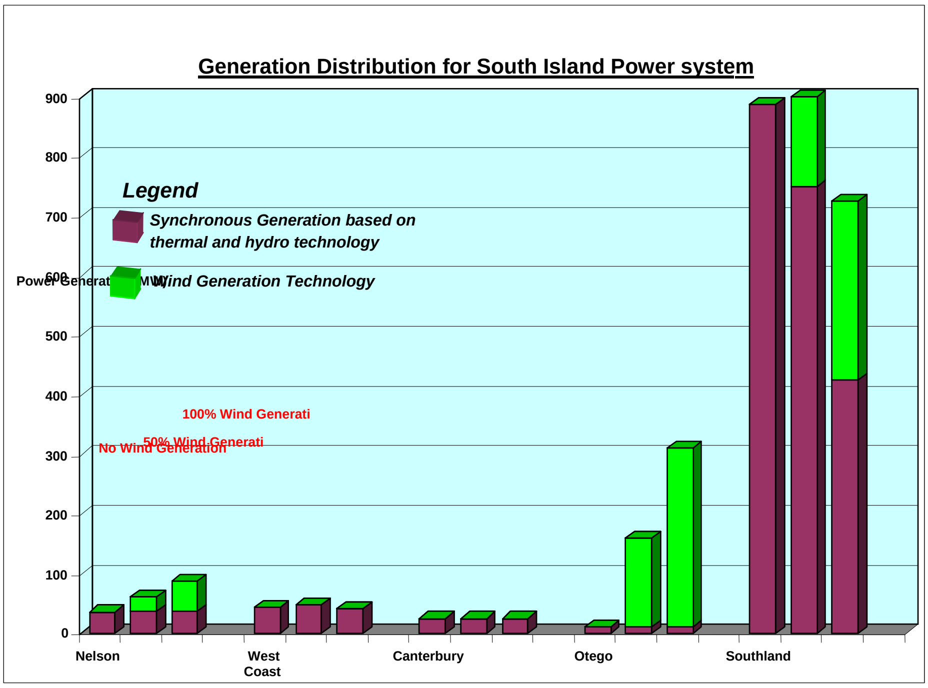


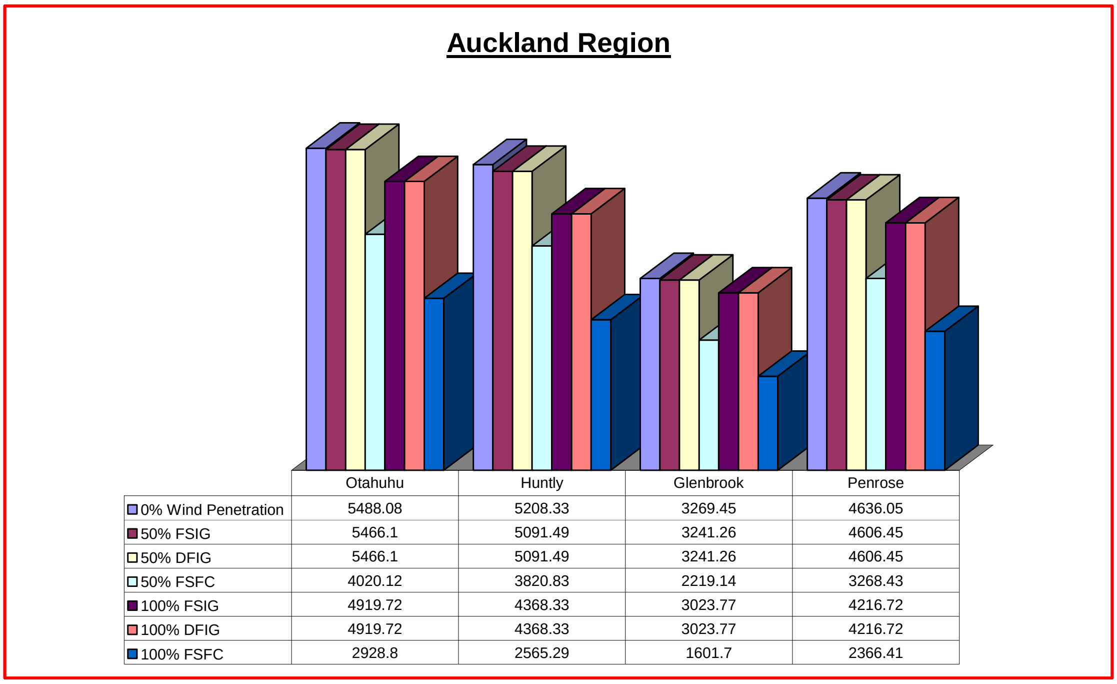
Figure 10:- South Island Power System – Generation Dispatch Pattern

3.1.2 North and South Islands short-circuit level analysis

The changes in dispatch pattern have not only altered the power flow but also the distribution of system short-circuit levels. Reducing short-circuit level has a direct effect on the ability for power system to maintain voltage during short circuit faults.

From Figure 11, the Auckland and Waikato regions are the most affected, as at least 50% of the local generation is being displaced by wind generation elsewhere. There is a reduction of nearly 50% of short-circuit levels on major 220 kV buses if wind generation output level reaches 100% of installed capacity with FSFC wind generation technology. The Huntly 220 kV substation short-circuit level is reduced from 5208 MVA to 2565 MVA which should result in more severe voltage sag during short circuit faults.

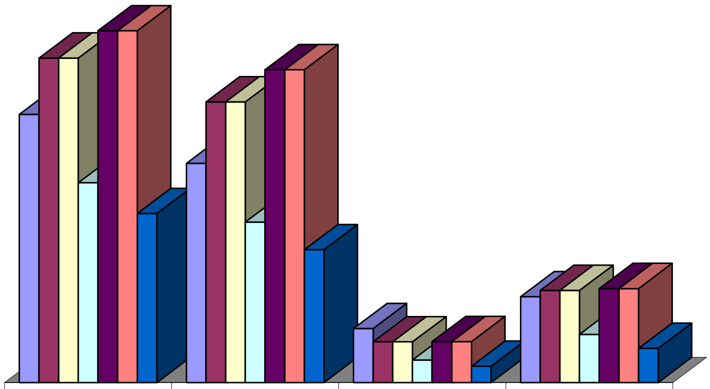
Connecting wind generation in regions with little other generation such as Wellington, North Isthmus, Nelson, and Otago regions has a reverse effect (see Figure 12 and Figure 13). Regional wind generation increases short-circuit level locally and this should improve voltage sag performance during short circuit faults.


Auckland Region

	Otahuhu	Huntly	Glenbrook	Penrose
0% Wind Penetration	5488.08	5208.33	3269.45	4636.05
50% FSIG	5466.1	5091.49	3241.26	4606.45
50% DFIG	5466.1	5091.49	3241.26	4606.45
50% FSFC	4020.12	3820.83	2219.14	3268.43
100% FSIG	4919.72	4368.33	3023.77	4216.72
100% DFIG	4919.72	4368.33	3023.77	4216.72
100% FSFC	2928.8	2565.29	1601.7	2366.41

Figure 11:- Short-circuit level at major 220 kV buses in Auckland/Hamilton Region with different wind generation technologies and wind generation output (as % of installed capacity)

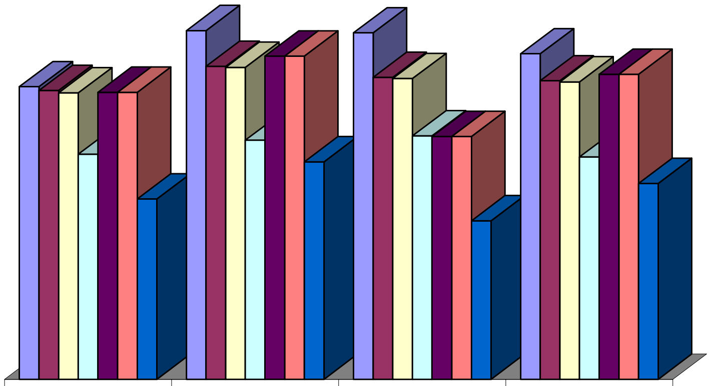
Wellington Region



	Haywards	Wilton	Mangahao	Masterton
0% Wind Penetration	2285.89	1869.05	461.08	732.94
50% FSIG	2765.97	2391.97	347.61	786.02
50% DFIG	2765.97	2391.97	347.61	786.02
50% FSFC	1703.34	1367.99	192.47	412.38
100% FSIG	2999.11	2666.51	349.55	802.28
100% DFIG	2999.11	2666.51	349.55	802.28
100% FSFC	1441.16	1133.64	139.59	292.78

Figure 12:- Short-circuit level at major 220 kV buses in Wellington Region with different wind generation technologies and output (as % of installed capacity)

Southland Region



	Invercargill	Clyde	Manapouri	Roxburgh
0% Wind Penetration	2913.28	3472.71	3449.74	3241.31
50% FSIG	2875.93	3117.51	3006.64	2973.09
50% DFIG	2853.26	3106.83	2995.05	2961.34
50% FSFC	2242.15	2380.89	2424.57	2213.86
100% FSIG	2858.02	3218.54	2418.22	3038.11
100% DFIG	2858.02	3218.54	2418.22	3038.11
100% FSFC	1796.75	2165.93	1579.21	1949.84

Figure 13:- Short-circuit level at major 220 kV buses in Southland Region with different wind generation technologies and output (as % of installed capacity)

Figure 14 illustrates graphically the changes in short-circuit level for the North Island power system as a result of incorporating wind generation into the system that exhibits distinctly different short circuit performance compared to synchronous generating units. In summary, introducing wind generation in load centres such as the North

Isthmus and Wellington regions, where local generation is sparse, increases short circuit levels locally whereas the regions with significant other generation, such as Hamilton and Edgecumbe, have their short-circuit level capacity reduced by, in some cases, more than 50% to its base case values.

Figure 15 showed an identical trend for the South Island power system. FSFC wind generation technology has a more significant impact on short-circuit level than FSIG and DFIG as FSFC fault current contribution is limited by the power converter rating. Manapouri 220 kV bus is most affected as shown by the reduction of 50% in short circuit capacity when a bolted three phase short circuit is applied to the bus.

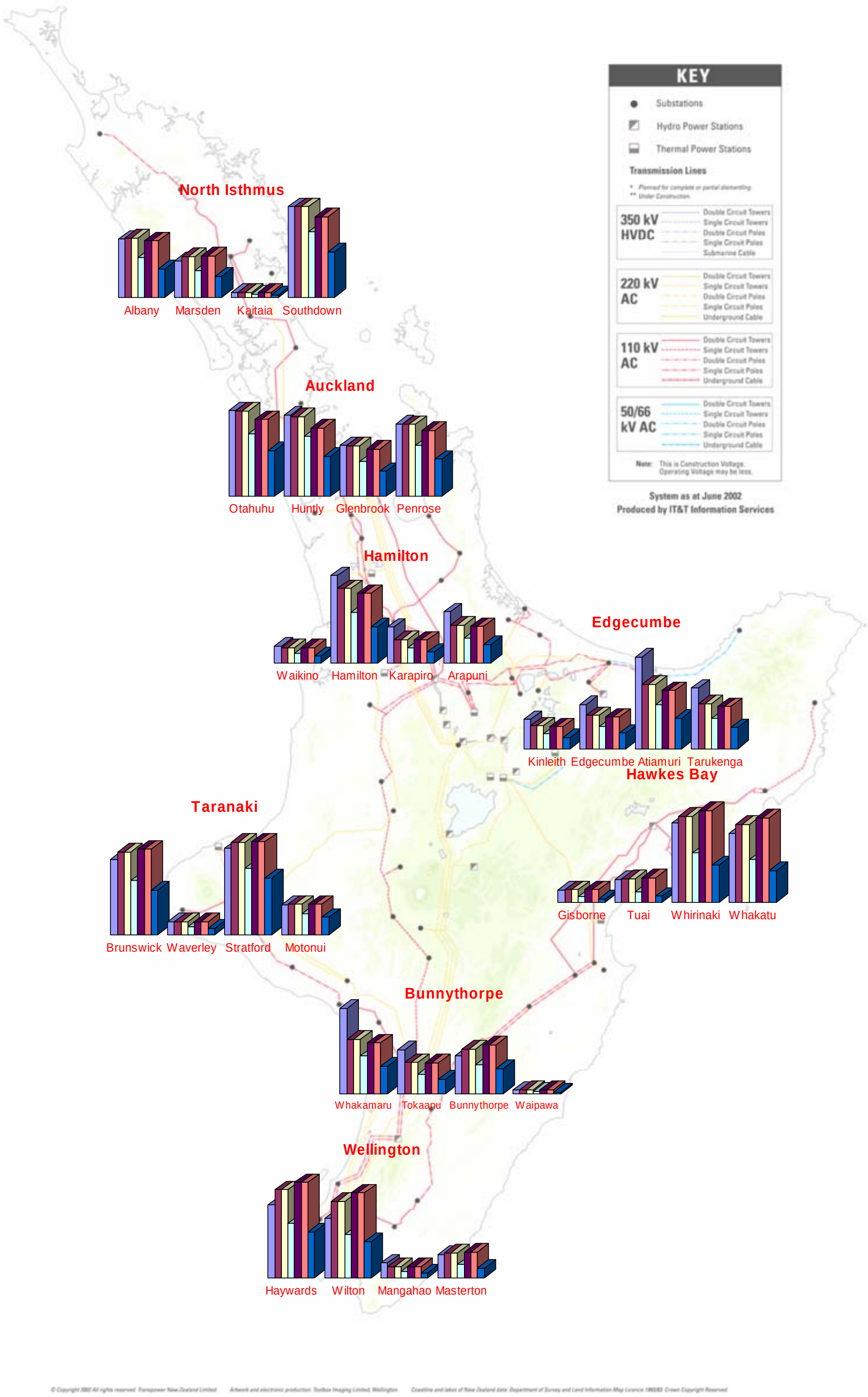


Figure 14:- Short-circuit level distribution for North Island Power system

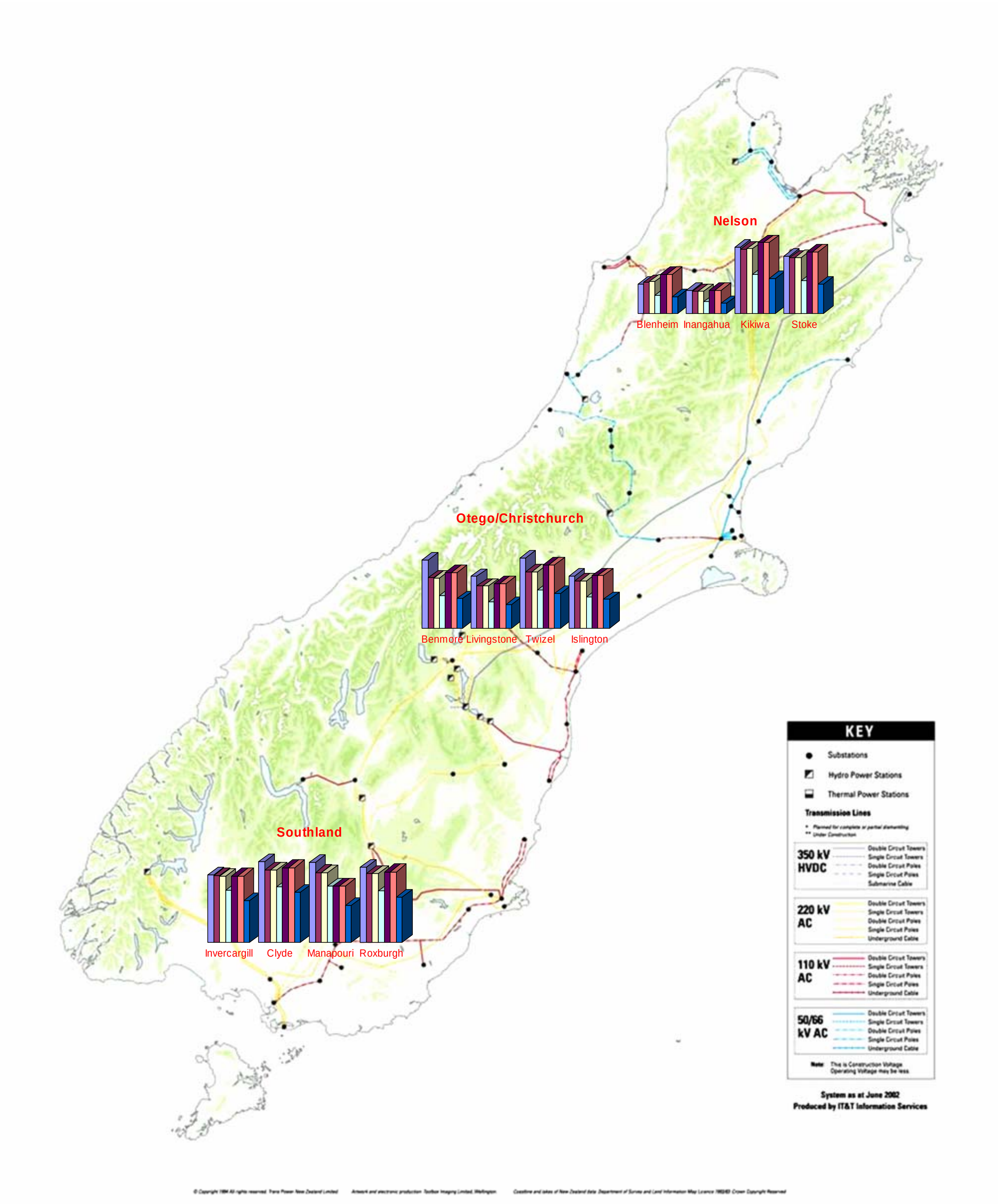


Figure 15:- Short-circuit level distribution for South Island Power system

3.2 Effect on short-circuit level and voltage sag performance

For a region with a significant amount of other generation such as Auckland, the displacement of thermal generation at Huntly by wind generation elsewhere reduces local short-circuit levels considerably. Voltage sag performance during short circuit faults is affected as a direct result of this reduction in short-circuit level. Figure 16 shows that with no wind generation dispatched in the system, a bolted three phase fault has to be applied within a 4 km radius (drawing is not to scale) of Huntly 220 kV bus to cause a voltage sag greater than 85% of nominal value at Huntly 220 kV bus. For the purposes of this investigation, this radius is referred as the 85% voltage sag radius. A bolted three phase fault occurring in the 85% voltage sag radius of a nominated bus will cause voltage at the nominated bus to fall below 85% of nominal. The 85% voltage sag radius for the Huntly 220 kV buses increases to 4.6 km with a wind generation output of 50% of installed capacity with FSIG technology.

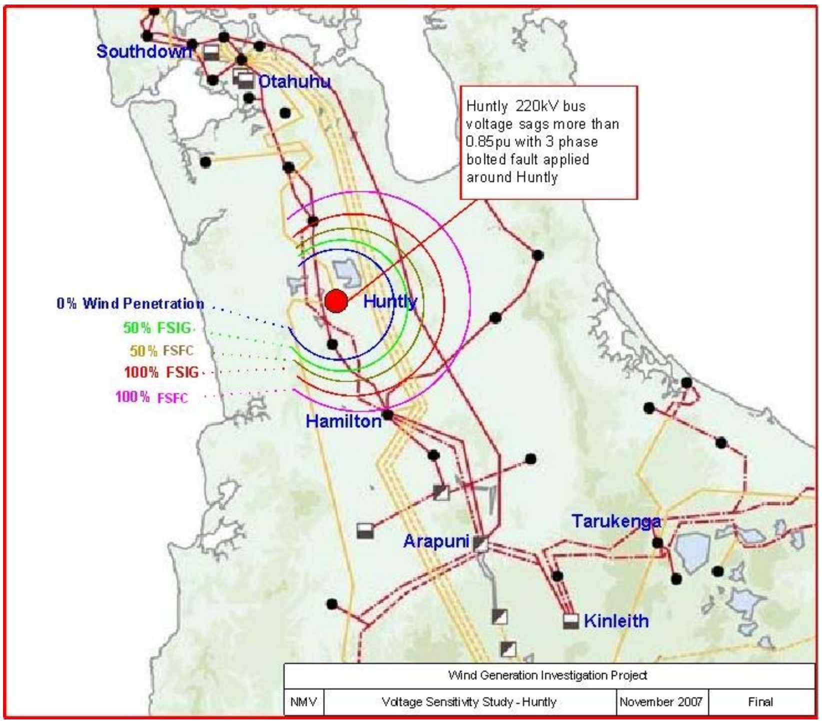


Figure 16:- Voltage sensitivity result for Huntly 220 kV Bus system

As for regions with little or no generation locally, new wind generation installed locally can improve the voltage sag performance as illustrated in Figure 17. At Bunnythorpe, the connection of new induction generator based wind generation improved voltage sag performance at the Bunnythorpe 220 kV bus (as shown by the decrease in 85% voltage sag radius) whereas FSFC technology has the opposite effect as the fault current contribution by this technology is limited by the converter MVA rating, which effectively reduced the net short circuit capacity in the region.

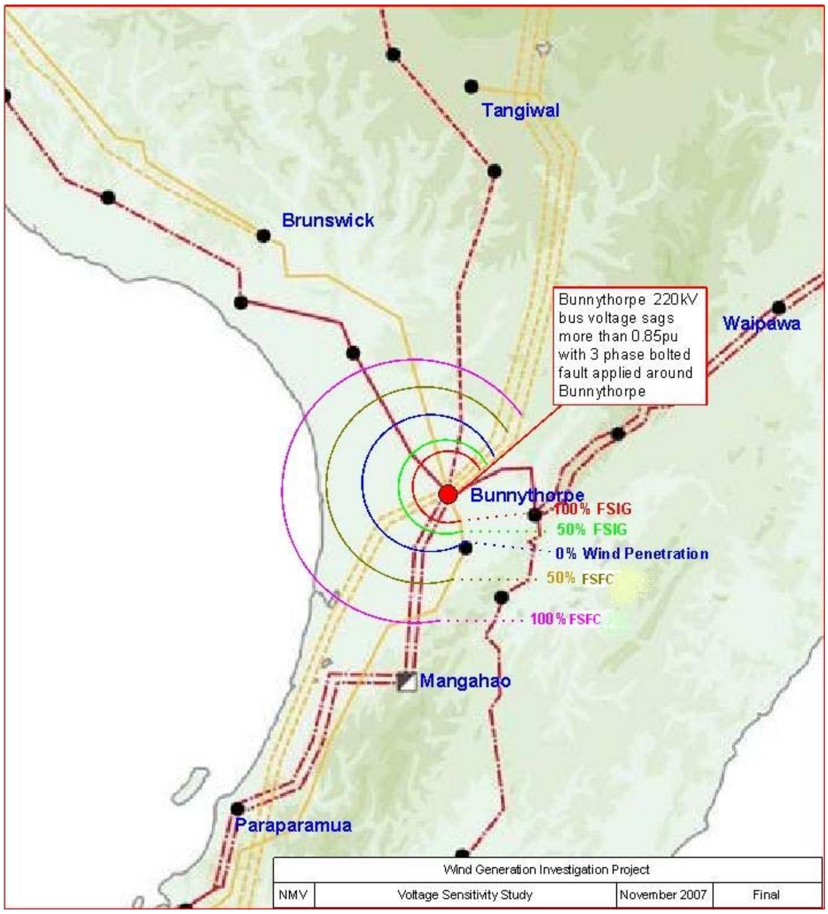


Figure 17:- Voltage sensitivity result for Bunnythorpe 220 kV Bus

3.3 Dynamic voltage response study

The results of the previous section showed a significant change in short circuit levels as wind generation displaced other generation. The effects of wind generation technology on voltage sag were significantly different.

This analysis did not take into account the induction generator stator/rotor flux dynamic during a transient fault, which is particularly important for FSIG as this technology depended on system voltage to magnetise the rotor circuit for torque production, hence affecting the voltage recovery process.

Dynamic studies are carried out to study power system dynamic voltage performance and to account for stator/rotor flux dynamics. The intrinsic electromagnetic property of induction generation and its voltage control ability have a significant influence in the level of dynamic voltage performance that a wind farm presents to the power system. The effects of reactive power compensation devices such as STATCOM on wind farm performance are examined.

Figure 18 and Figure 19 shows the dynamic voltage performance at the Whakamaru and Bunnythorpe 220 kV buses respectively where wind generation output is 50% of installed capacity. Figure 20 and Figure 21 show the voltage sag waveforms for wind generation output at the Whakamaru and Bunnythorpe 220 kV buses respectively where wind generation output is 100% of installed capacity.

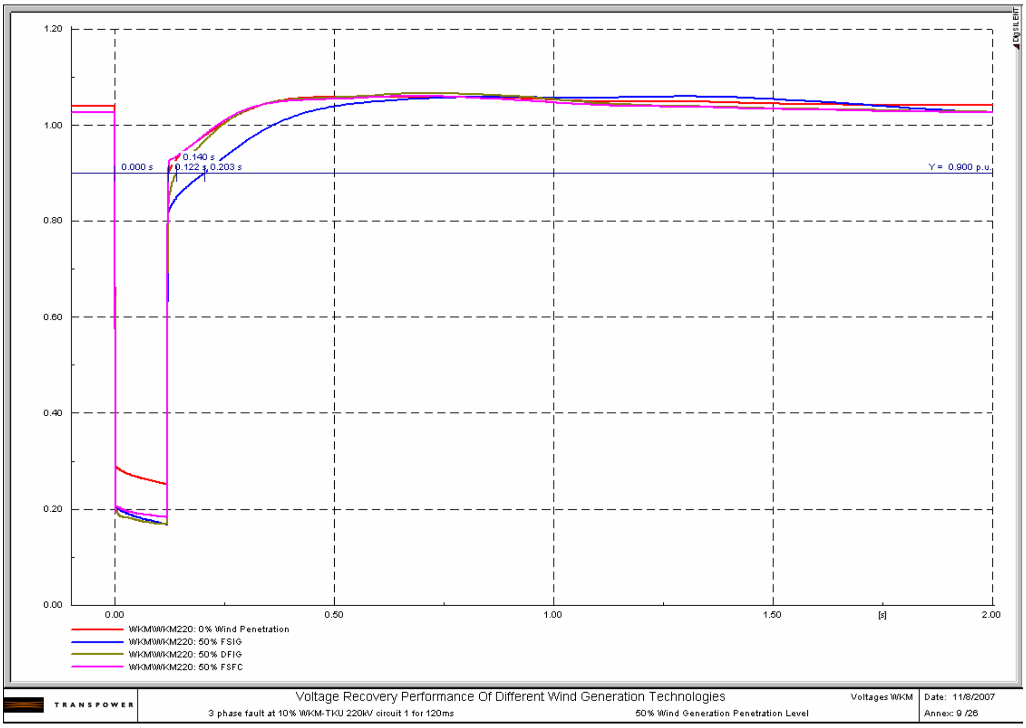


Figure 18:- Voltage sag waveform for Whakamaru 220 kV Bus with wind generation output at 50% of installed capacity

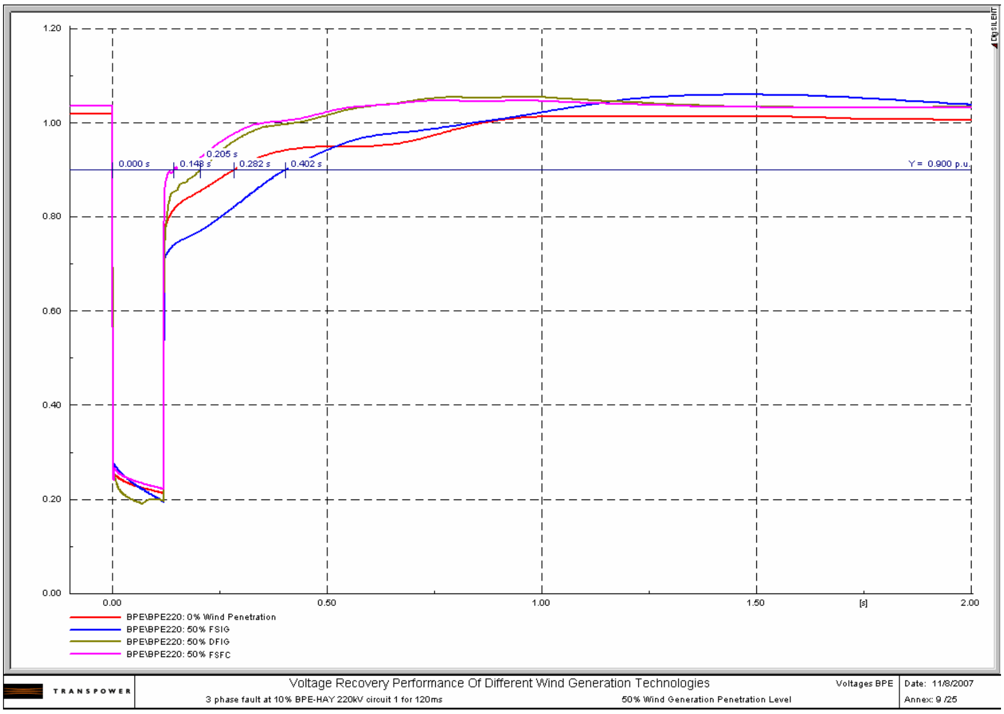


Figure 19:- Voltage sag waveform for Bunnythorpe 220 kV Bus with wind generation at 50% of installed capacity

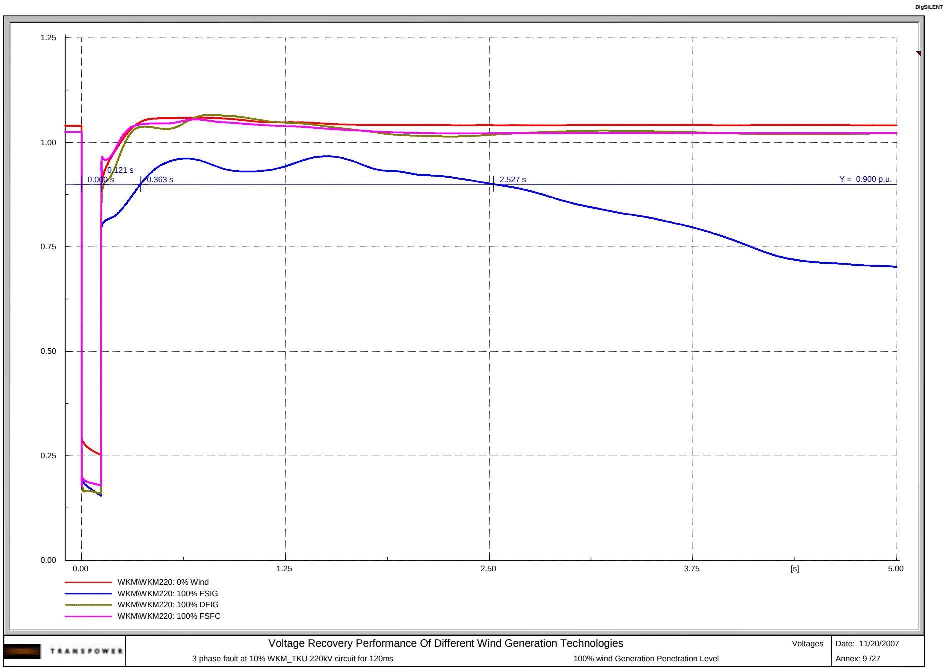


Figure 20:- Voltage sag waveform for Whakamaru 220 kV Bus with wind generation at 100% of installed capacity

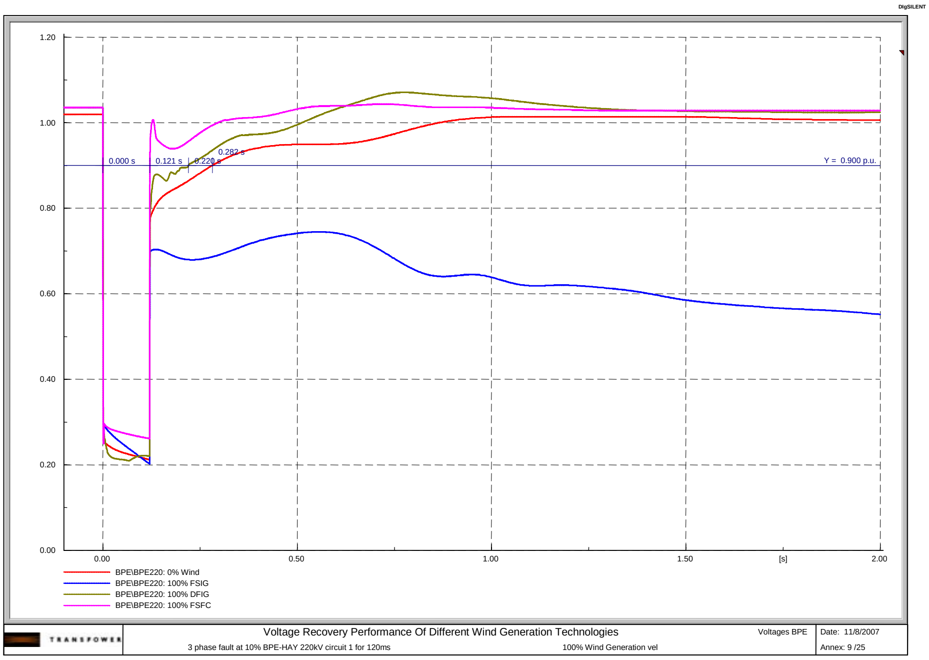


Figure 21:- Voltage sag waveform for Bunnythorpe 220 kV Bus with wind generation at 100% of installed capacity

The blue traces in Figure 18 and Figure 19 show the delay in voltage recovery for FSIG technology. In Figure 20 and Figure 21, voltage collapse is observed for the case with FSIG technology.

The FSIG unit derives its excitation directly from the power system to magnetise the iron core. During short circuit faults, the total or partial collapse of generator terminal voltage causes the main flux field to vary with the terminal voltage which influences the magnitude of generator fault current contribution during the fault. A close-up fault represents the worst scenario in which the terminal voltage sags to a low value causing the flux field to collapse. Considerable amounts of reactive power will be drawn from the power system to magnetise the iron core after the fault is removed. This phenomenon prolongs the voltage recovery process and, if excessive reactive power is drawn from the power system, may cause the power system to collapse.

With DFIG technology, the initial response to a short circuit fault is similar to FSIG technology. During short circuit faults, magnetic coupling between stator and rotor circuits can generate high voltage at the power converter terminal. Crowbar protection is usually employed to clamp down high voltage, protecting the converter from damage. After the fault is cleared, generator terminal voltage recovers close to its nominal value. The rotor side power converter has the ability to regain control of the rotor control quickly which minimises the requirement of reactive power from the power system. This is indicated by the fast voltage recovery for the DFIG after the fault is cleared. Different manufacturers employ different protection algorithms to protect power converter during transient faults.

For FSFC technology, the converter interface to the power system governs the dynamic voltage response for this topology. Fault current contribution is limited to a value slightly higher than nominal full load current. During transient faults, excessive power produced by the generator is controlled by the chopper action to control the DC voltage within the operation limits. The fast converter control action contributed to responsive voltage control after fault is removed. In conclusion, FSFC demonstrates a better dynamic voltage response as compared to FSIG and DFIG.

Figure 22 shows V (minimum voltage reached) and T (time to recover to 0.9 pu voltage) for voltage sag waveforms calculated for faults located at varying distances from Whakamaru 220 kV bus on 220 kV transmission circuits terminating at Whakamaru. In general, the voltage sag waveforms with FSIG technology tend to have lower minimum voltages and longer recovery times. DFIG technology gives similar, but somewhat inferior, performance to FSFC technology for higher levels of wind generation output as a percentage of installed capacity. In regions with significant amounts of synchronous generation, the introduction of significant amounts of wind generation tends to increase voltage sag, with the FSIG technology having the greatest impact.

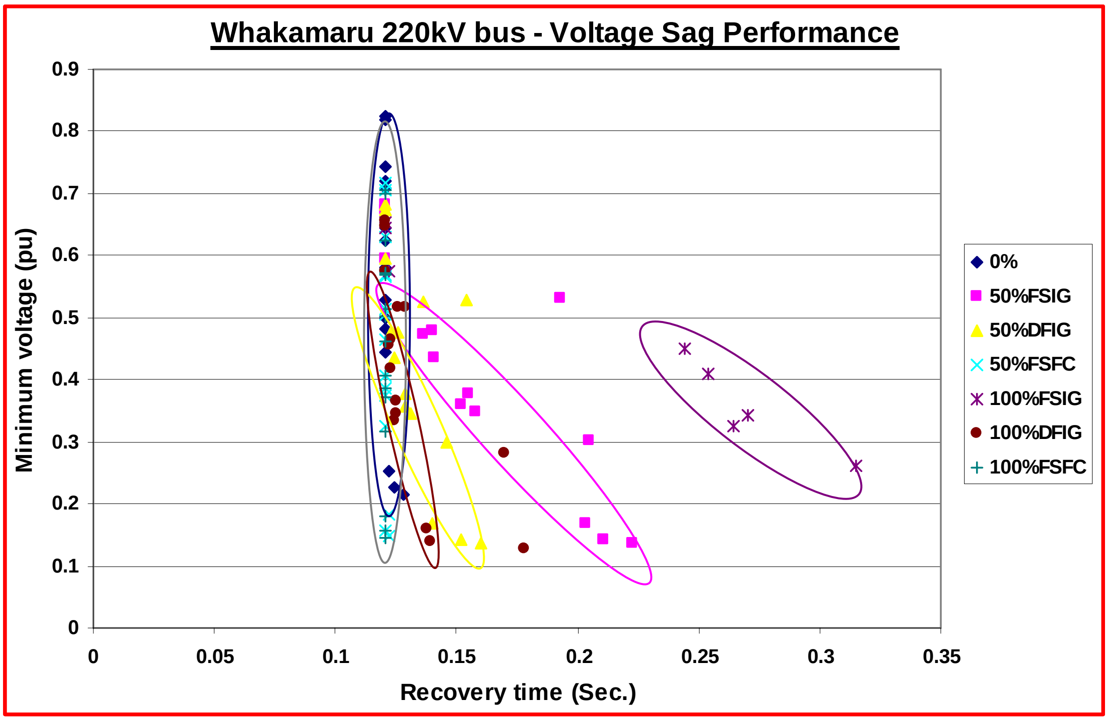


Figure 22:- Voltage sag performance plot for Whakamaru 220 kV Bus

Figure 23 shows V (minimum voltage reached) and T (time to recover to 0.9 pu voltage) for voltage sag waveforms calculated for faults located at varying distances from Bunnythorpe 220 kV bus on 220 kV transmission circuits terminating at Bunnythorpe.

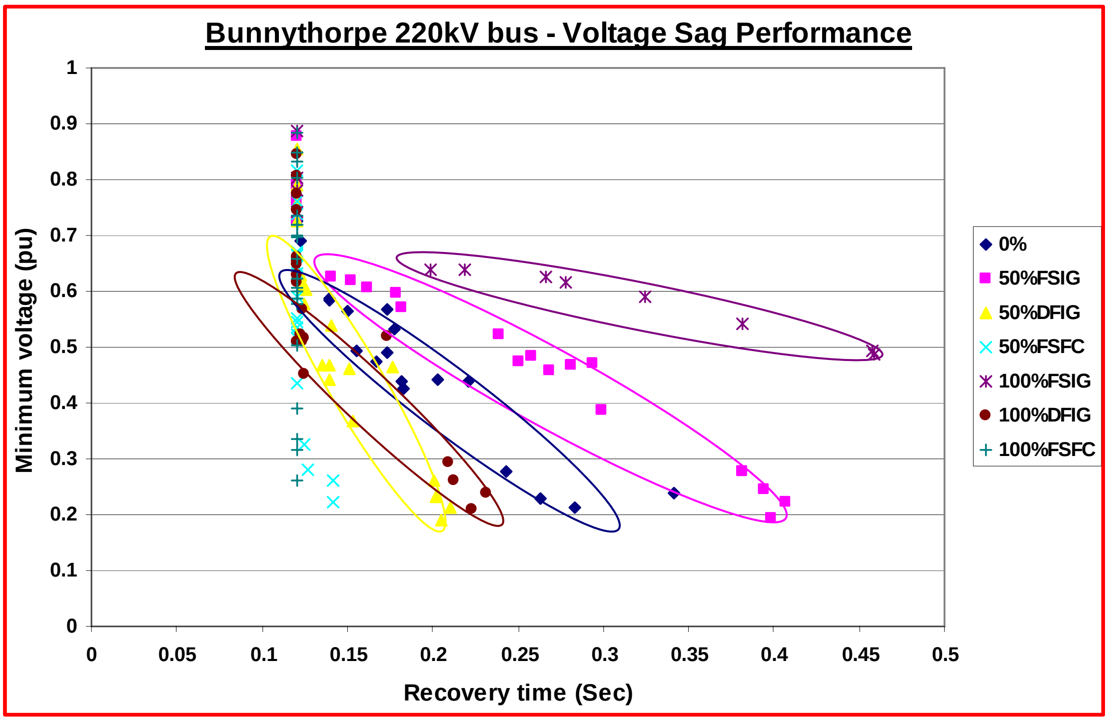


Figure 23:- Voltage sag performance plot for Bunnythorpe 220 kV Bus

The installation of wind generation in regions where there is little other generation can improve voltage sag performance as seen in Figure 23. Analysis shows that dynamic voltage performance at Bunnythorpe 220 kV Bus improves if FSFC and DFIG wind generation technologies are utilised. As before, the use of FSIG technology reduces power system performance and may lead to system collapse.

The lack of fast reactive power regulating capability within the region (giving a reduced ability to restore system voltage post fault) combined with the FSIG technology's absorption of large amounts of reactive power from the power system to facilitate the re-magnetising of FSIG rotor flux field post fault are the two main causes of this failure.

The 0% wind generation output case showed a relatively long fault clearing time. This is a consequence of the technology of the existing regional wind farms at Tararua and Te Apiti, which have a combination of FSIG (with limited rotor circuit control) and DFIG technologies.

Figure 24 shows V (minimum voltage reached) and T (time to recover to 0.9 pu voltage) for voltage sag waveforms calculated for faults located at varying distances from Blenheim 110 kV bus on the 110 kV transmission circuits terminating at Blenheim.

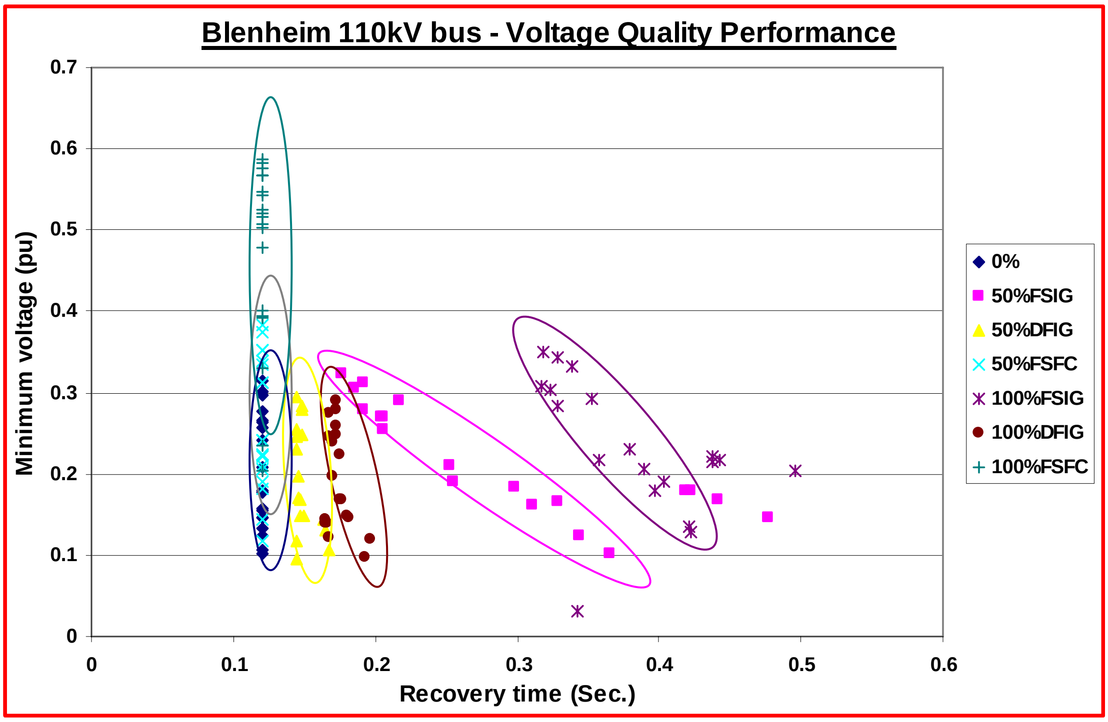


Figure 24:- Voltage sag performance plot for Blenheim 220 kV Bus

The region has little other generation and relies mostly on imported power to meet local load demand. The installation of 50 MW of FSFC wind generation (as per wind generation development scenario C) reduces the voltage sag magnitude. The use of FSIG and DFIG technologies increases the voltage recovery time to, in some cases, about 0.5 second. The use of FSFC technology will improve the dynamic voltage performance at Nelson but the use of FSIG and DFIG technologies will reduce performance.

3.4 Influence of reactive compensation device on the voltage response characteristic of FSIG wind farm

The previous analysis has shown the FSIG technology to reduce voltage sag performance. This arises from the need for the FSIG to draw large amounts of reactive power from the grid post fault to magnetise the rotor circuit and return the generating unit to stable operation. Voltage sag performance can be improved by installing reactive power support devices (such as static compensators (STATCOM) at the wind farm to reduce the amount of reactive power needed to be drawn from the grid post fault. The effects of using a STATCOM on voltage sag performance at the Bunnythorpe 220 kV bus are examined in this section.

Table 3 shows the difference in voltage sag performance at the Bunnythorpe 220 kV bus where the new wind farm (300 MW installed capacity and operating at full capacity) has a STATCOM (35 MVA capacity) and when it does not. The table shows the minimum voltage and the time for the voltage to recover to 0.9 pu.

Fault	**100% FSIG wind generation output**		**100% FSIG with 35MVA STATCOM**	
	Minimum Voltage (pu)	**Time to recover (s)**	**Minimum Voltage (pu)**	**Time to recover (s)**
BPE-TKU				
10%	X	X	0.2851	0.29
30%	0.4937	0.458	0.5487	0.122
50%	0.5915	0.324	0.6578	0.121
70%	0.6262	0.266	0.6972	0.121
BPE-BRK				
40%	X	X	0.2659	0.312
70%	X	X	0.3299	0.274
BRK-SFD				
10%	X	X	0.5591	0.137
40%	0.5414	0.382	0.6097	0.121
70%	0.4856	0.4585	0.5455	0.129
BPE-HAY				
10%	X	X	0.221	0.332
30%	X	X	0.4341	0.19
50%	X	X	0.5138	0.143
70%	X	X	0.5181	0.161

X – Power System collapse.

Table 3: PV Data showing effect of STATCOM

Without the STATCOM, close in faults are likely to result in voltage collapse. The STATCOM significantly reduces both the minimum voltage experienced during the sag and the time for voltage to recover. Figure 25 shows a chart showing the minimum voltage and recovery time for different outputs of wind generation output and the presence of the STATCOM.

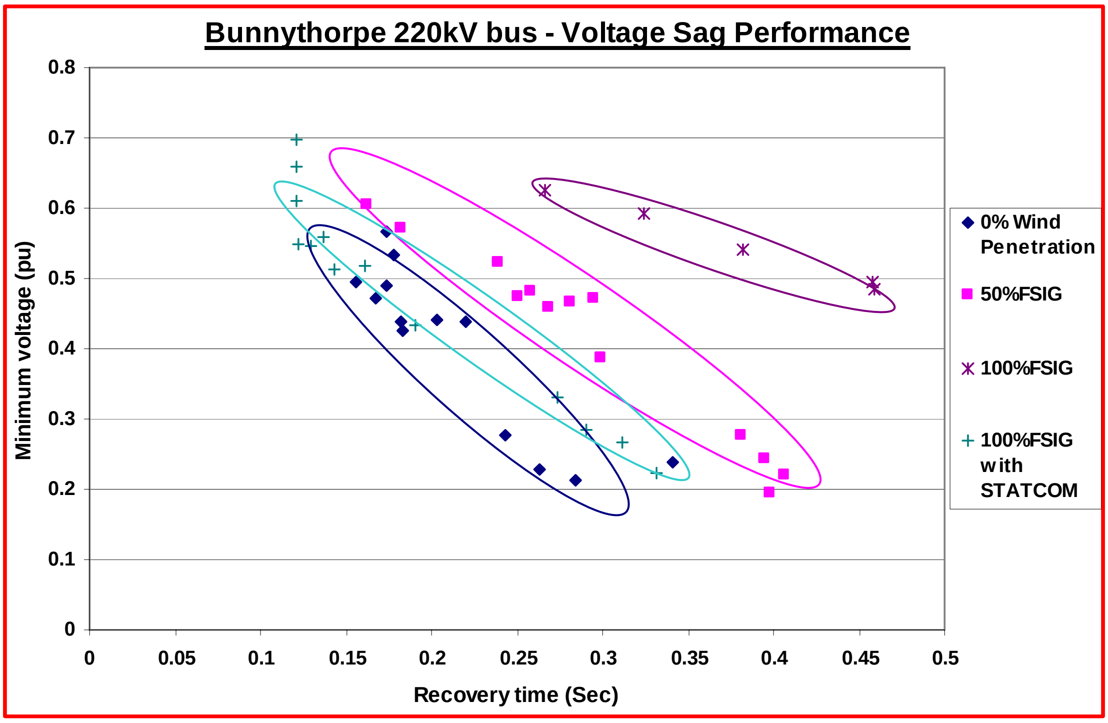


Figure 25:- Voltage sag performance plot for Bunnythorpe 220 kV Bus

4 Discussion

Large scale wind generation will affect power system dynamic voltage support in two ways:

- The displacement of other plant on the power system by wind generation will affect the power system's ability to provide reactive power support during and following faults on the power system. The effects can be positive or negative depending on the location of the displaced generation and the wind generation, and the type of wind generation technology employed.
- The dynamic behaviour of different wind generation technologies during short circuit fault conditions is governed by the intrinsic characteristics of the generators and their control systems.

Wind generation has a more limited capability to provide voltage support during faults than does other generating plant, such as synchronous generating units. The displacement of plant, such as synchronous generating units, by wind generation will lower short circuit levels and lower voltage sag performance. Short circuit levels and voltage sag performance will be most affected in areas where local generation is displaced by remote wind generation. In areas where local generation is displaced by local wind generation the effects on short circuit levels and voltage sag performance are lessened. The installation of wind generation in areas where there is little other generation can improve short circuit levels and voltage sag performance if DFIG or FSFC technology is employed.

The performance of wind generating units during and following faults on the power system depends greatly on the technology involved:

- FSIG units provide mixed benefits. The units will provide considerable short circuit power during the fault (aiding in the correct operation of protection relays to remove the faulted asset) but need to draw large amounts of reactive power from the grid to magnetise their rotor circuits and restore stable operation following a fault. This means that the units are unable to support post fault voltage recovery and may actually cause voltage collapse if the rest of the power system is unable to provide sufficient voltage support to aid recovery.
- DFIG units will perform similarly to FSIG units during fault conditions but can provide improved support to post fault voltage recovery.
- FSFC units effectively decouple the generating unit from the power system. The FSFC unit can provide reactive power up to its full load current rating during the fault. The FSFC can control active and reactive power regardless of system conditions and can provide good support during post fault voltage recovery.

Wind (or any other) generation may lack the capability to remain connected to the power system during and following power system faults. The ability of generation to ride through disturbances on the power system is critical to power system security. The disconnection of large amounts of generation following a fault on the power system could lead to frequency collapse.

Wind or other generation lacking the capability to remain connected during and following power system faults would need to be accounted for in operational practices. The disconnection of generation would be included in instantaneous reserves requirements. A small wind farm lacking the capability to remain connected during faults would not affect the amount of instantaneous reserves required but a large wind farm might end up setting the requirement. A wind farm with installed capacity of greater than around 400 MW in the North Island or 135 MW in the South Island could set the amount of reserves required. Such wind farms would face a share of the costs of instantaneous reserves and face event fees if and when the farms did disconnect during a fault causing the power system frequency to fall below 49.2 Hz. The costs of instantaneous reserves and event fees would provide a large wind generation farm developer with the incentives to ensure that the wind farm had the capability to remain connected during power system faults.

A large wind farm with poor performance (perhaps utilising basic FSIG technology) has the potential to degrade voltage sag performance on the power system to the extent that other nearby generation is unable to remain connected during the post fault voltage recovery period. This issue can be managed by applying constraints to the operation of the wind farm. Such constraints could limit the number of wind turbines that can be connected to the power system under certain conditions. In this case, the wind farm developer can weigh up the costs of constrained operation against using wind turbines with better performance or installing additional reactive support devices at the wind farm.

In practice, issues with lack of low voltage ride through capability or poorly performing plant threatening power system security will be identified at the planning stage of the wind farm development. The developer can then decide whether to proceed taking into account the operational costs (e.g. instantaneous reserves costs and event fees and operational constraints) against the costs of providing mitigating measures (e.g. using different technology or providing additional dynamic reactive support plant).

The EGRs do not set out low voltage ride through capability requirements for wind or other types of generation. There is a requirement that protection systems must operate selectively and disconnect the minimum amount of plant required to remove the fault. Similarly, the EGRs do not set out the dynamic requirements for voltage support during and following faults. There is a requirement to be able to provide a minimum amount of reactive power at full load when the HV grid voltage is within a certain range. There are also requirements that voltage control systems are designed and have settings that support the System Operator in meeting the Principal Performance Obligations (e.g. avoid cascade failure during voltage excursions).

It may be desirable to have the low voltage ride through and dynamic voltage support requirements for all generation incorporated in the EGRs to assist developers in specifying the performance requirements for new generating plant but this is beyond the scope of the WGIP. The development of such requirements depends on other factors including the target performance requirements of protection systems and low voltage ride through capability of connected loads.

5 Conclusions

Wind generation technology has an important influence on voltage sag performance. Certain technologies can enhance performance in regions where there is little other generation and other technologies can significantly degrade performance in regions where synchronous generation is displaced by wind generation.

The analysis indicated that high amounts of wind generation using FSIG technology could cause voltage collapse following severe power system faults at times of light loading. The risk of voltage collapse can be reduced by installing dynamic reactive support devices at the wind farms or by limiting the amount of FSIG wind generation at times of light load.

Issues with new wind farms around lack of low voltage ride capability or poorly performing plant threatening power system security will be identified at the planning stage of the wind farm development. The developer can then decide whether to proceed taking into account the operational costs (e.g. instantaneous reserves costs and event fees and operational constraints) against the costs of providing mitigating measures (e.g. using different technology or providing additional plant).

It is recommended that issues around low voltage ride through capability requirements be given a medium priority for future work and should be combined with any review of dynamic voltage support requirements for all types of generation. It is recommended that any such review of requirements for low voltage ride though and dynamic support capability for all generation considers protection system performance design and the low voltage ride through requirements for load.

6 References

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[4] Markus A. Poller, "Doubly-Fed Induction Machine Models for Stability Assessment of Wind Farms" Proceedings of 2003 IEEE PowerTech Conference, Bologna, 2003.

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Appendix 1 – Standard site abbreviations

Table 4 shows a list of the site abbreviations used in the schematics.

Short Code	Site	Short Code	Site	Short Code	Site	Short Code	Site
ABY	Albury	*HEN*	Henderson	*NMA*	North Makarewa	*TGA*	Tauranga
ADD	Addington	*HEP*	Hepburn Road	*NPK*	National Park	*TIM*	Timaru
ALB	Albany	*HIN*	Hinuera	*NPL*	New Plymouth	*TKA*	Tekapo A
ALD	Arnold	*HKK*	Hokitika	*NSY*	Naseby	*TKB*	Tekapo B
ANC	Anchor Products	*HLY*	Huntly	*OAM*	Oamaru	*TKH*	Te Kaha
ANI	Aniwhenua	*HOR*	Hororata	*OHA*	Ohau A	*TKR*	Takapu Road
APS	Arthur's Pass	*HPI*	Huapai	*OHB*	Ohau B	*TKU*	Tokaanu
ARA	Aratiatia	*HTI*	Hangatiki	*OHC*	Ohau C	*TMH*	Three Mile Hill
ARG	Argyle	*HUI*	Huirangi	*OHK*	Ohakuri	*TMI*	Te Matai
ARI	Arapuni	*HWA*	Hawera	*OKE*	Okere	*TMK*	Temuka
ASB	Ashburton	*HWB*	Halfway Bush	*OKI*	Ohaaki	*TMN*	Taumarunui
ASY	Ashley	*IGH*	Inangahua	*OKN*	Ohakune	*TMU*	Te Awamutu
ATI	Atiamuri	*INV*	Invercargill	*ONG*	Ongarue	*TNG*	Tangiwai
AVI	Aviemore	*ISL*	Islington	*OPI*	Opihi	*TOB*	Tokomaru Bay
BAL	Balclutha	*KAI*	Kaiapoi	*OPK*	Opunake	*TRK*	Tarukenga
BDE	Brydone	*KAW*	Kawerau	*OPU*	Opuha	*TUI*	Tuai
BEN	Benmore	*KEN*	Kensington	*ORO*	Orowaiti Tee	*TVT*	Teviot
BLN	Blenheim	*KIK*	Kikiwa	*OTA*	Otahuhu Substation	*TWH*	Te Kowhai
BOB	Bombay	*KIN*	Kinleith	*OTB*	Oteranga Bay	*TWI*	Tiwai
BPE	Bunnythorpe	*KKA*	Kaikoura	*OTC*	Otahuhu CC	*TWZ*	Twizel
BRB	Bream Bay	*KOE*	Kaikohe	*OTG*	Otahuhu Power Station	*UHT*	Upper Hutt
BRK	Brunswick	*KPI*	Kapuni	*OTI*	Otira	*UTK*	Upper Takaka
BRR	Branch River	*KPO*	Karapiro	*OWH*	Owhata	*WAA*	Whareroa
BRY	Bromley	*KPU*	Kopu	*PAK*	Pakuranga	*WAH*	Wahapo
BWK	Berwick	*KTA*	Kaitaia	*PAL*	Palmerston	*WAI*	Waiotahi
CBG	Cambridge	*KUM*	Kumara	*PAP*	Papanui	*WDV*	Woodville
CLH	Castle Hill	*KWA*	Kaiwharawhara	*PEN*	Penrose	*WEL*	Wellsford
CML	Cromwell	*LFD*	Lichfield	*PKE*	Poike	*WES*	Western Road
COB	Cobb	*LIV*	Livingstone	*PNI*	Pauatahanui	*WGN*	Wanganui
COL	Coleridge	*LTN*	Linton	*PPI*	Poihipi	*WHE*	Wheao
CPK	Central Park	*MAN*	Manapouri	*PRM*	Paraparaumu	*WHI*	Whirinaki
CST	Carrington Street	*MAT*	Matahina	*PTA*	Patea	*WHU*	Waihou
CUL	Culverden	*MCH*	Murchison	*RDF*	Redclyffe	*WIL*	Wilton
CYD	Clyde	*MDN*	Marsden	*ROB*	Robertson Street	*WIR*	Wiri
DAR	Dargaville	*MGM*	Mangamaire	*ROS*	Mount Roskill	*WKM*	Whakamaru
DOB	Dobson	*MHO*	Mangahao	*ROT*	Rotorua	*WKO*	Waikino
DVK	Dannevirke	*MLG*	Melling	*ROX*	Roxburgh	*WMG*	Waimangaroa
EDG	Edgecumbe	*MNG*	Mangere	*RPO*	Rangipo	*WPA*	Waipapa
EDN	Edendale	*MNI*	Motunui	*RTR*	Retaruke	*WPI*	Waipori
FHL	Fernhill	*MOK*	Mokai	*SBK*	Southbrook	*WPR*	Waipara
FKN	Frankton	*MOT*	Motueka	*SDN*	South Dunedin	*WPT*	Westport
GFD	Gracefield	*MPE*	Maungatapere	*SFD*	Stratford	*WPW*	Waipawa
GIS	Gisborne	*MPI*	Motupipi	*SPN*	Springston	*WRA*	Wairoa
GLN	Glenbrook	*MRA*	Moturoa	*STK*	Stoke	*WRK*	Wairakei
GOR	Gore	*MST*	Masterton	*STU*	Studholme	*WTK*	Waitaki
GYM	Greymouth	*MTI*	Maraetai	*SVL*	Silverdale	*WTU*	Whakatu
GYT	Greytown	*MTM*	Mt Maunganui	*SWN*	Southdown	*WVY*	Waverley
HAM	Hamilton	*MTN*	Marton	*TAK*	Takanini		
HAY	Haywards	*MTO*	Maungaturoto	*TAP*	Te Apiti		
HBK	High Bank	*MTR*	Mataroa	*TCC*	Taranaki Combined Cycle		

Table 4: Standard Site Abbreviations