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Nomenclature

Parameters and variables

r_s: Stator winding resistance

L_s: Stator resistance

r_r: Rotor winding resistance

L_r: Rotor resistance

V_s: Supply voltage

V_r: Rotor voltage

S: Rotor slip

I_s: Stator phasor current

I_r: Rotor phasor current

i_s: Stator current

i_r: Rotor current

X_s: Stator winding leakage reactance

X_m or x_m: Magnetizing reactance

U_m or u_m: Air gap voltage

X_r: Rotor leakage reactance

R_c or r_c : Crowbar resistance

X_c or X_c: Crowbar reactance

X' or x': Transient reactance

X'' or x'': Sub-transient reactance

X_o: Initial condition reactance

i_p : Peak short-circuit current

i_b : Base current

i''_k: Sub-transient short-circuit current

i_{th}: Thevenin current

i_{DC}: Direct component of short-circuit current

I_{SC}: Short-circuit current

I_{SS}: Steady state current

R_f: Fault resistance

X_f: Fault reactance

Z_f: Fault impedance

φ_r: Rotor flux

i_d : Direct axis current component

I_q: Quadrature axis current component

$Z_s^{(1)}$: Positive sequence source impedance

$Z_s^{(2)}$: Negative sequence source impedance

$Z_s^{(0)}$: Zero sequence source impedance

$V_f^{(1)}$: Positive sequence fault voltage

$V_f^{(2)}$: Negative sequence fault voltage

$V_f^{(0)}$: Zero sequence fault voltage

$I_f^{(1)}$: Positive sequence fault current

$I_f^{(2)}$: Negative sequence fault current

$I_f^{(0)}$: Zero sequence fault current

P_t: Mechanical power of wind turbine

ρ: Air density

R: Rotor radius

λ: Tip speed ratio

β: Blade pitch angle

C_p: Power coefficient as a function of λ and β

v_w: Wind speed

ω_t: Mechanical frequency of wind turbine

T_m: Mechanical torque applied to wind turbine

T_e: Electrical torque of wind generator

T_{tg}: Internal torque

J_t: Inertia constant of wind turbine

J_g: Inertia constant of wind generator

D_{tg}: Damping coefficient of the flexible coupling (shaft)

K_{tg}: Shaft stiffness

C_{ij}: Frequency index

ε_f: Predefined tolerance of frequency

Acronyms

AC:	Alternating Current
AGO2:	Advanced Grid Options 2
ANSI:	American National Standards Institute
BPE:	Bunnythorpe (Node)
DC:	Direct Current
DFIG:	Doubly-fed Induction Generator
DSM:	Demand Side Management
EA:	Electricity Authority
EGR:	Electricity Governance Rules
EMT:	Electromagnetic Transients
FACTS:	Fast Alternating Current Transmission Systems
FCAS:	Frequency Control Ancillary Services
FCSG:	Full Convertor Synchronous Generator
FCSPS:	Frequency Control System Protection Schemes
FIR:	Fast Instantaneous Reserve
FRT:	Fault Ride-through
FSFC:	Full Scale Frequency Converters

FSIG: Fixed Speed Induction Generator

GSC: Grid-side Converter

GXP: Grid Exit Point

HAY: Haywards

HV: High Voltage

HVDC: High Voltage Direct Current

HVRT: High Voltage Ride-through

IEA: International Energy Agency

IEC: International Electro-technical Commission

IEEE: Institute of Electrical and Electronics Engineers

LV: Low Voltage

LVRT: Low Voltage Ride-through

MPT: Maximum Power Tracking

MV: Medium Voltage

NCSPS: Network Control System Protection Schemes

NI: North Island

NIPS: North Island Power Systems

NZ: New Zealand

NZEM:	New Zealand Electricity Market
PCC:	Point of Common Coupling
PES:	Power & Energy Society
PLL:	Phase Locked Loop
PMSG:	Permanent Magnet Synchronous Generator
PoC:	Point of Connection
RMS:	Root Mean Square
RPC:	Reactive Power Controller
RSC:	Rotor-side Converter
SCADA:	Supervisory Control and Data Acquisition
SCIG:	Squirrel Cage Induction Generator
SI:	South Island
SIR:	Sustained Instantaneous Reserve
SNE:	Sequence Network Equivalents
SO:	System Operator
SPD:	Scheduling, Pricing and Dispatch
SPS:	Special/System Protection Schemes
STATCOM:	Static Synchronous Compensator

SVC: Static Var Compensator

TSO: Transmission System Operator

WDV: Woodville

WGIP: Wind Generation Investigation Project

WRIG: Wound Rotor Induction Generator

WTG: Wind Turbine Generators

Units:

GW: Giga Watt

Hz: Hertz

kW: Kilo Watt

kV: Kilo Volt

m: Meter

MW: Mega Watt

ms: Millisecond

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Chapter 1: Introduction

With increasing focus on renewable energy, wind energy generation is attracting large capital investments and actual deployments worldwide. Most of the mature research outputs established for grid integration of wind energy are primarily for normal system operation. Other specialized analyses such as reliability, power quality, and transient stability impacts following large scale wind integration, are also available. Addressing wind integration issues under abnormal operations such as grid disturbances and faults do exist but will become more important in future with higher penetration and requires better understanding. During abnormal grid situations like faults, the various wind generation technologies exhibit specific dynamic characteristics which is quite unlike conventional synchronous generation units. The introduction of off-shore wind farms and new emerging generation technologies will further require detailed system protection assessment. As the penetration of wind generation changes it will impact the system dynamics and interdependence of systems on collective response will need to be better understood especially during grid fault situation. Stricter grid code requirements including Fault Ride-through (FRT), and other expectations for wind farms such as participation in ancillary services, are expected to further increase the need to understand dynamic responses from wind farms. Large scale wind integration at transmission level voltage levels is likely to reach very larger proportion in future. Such integration is likely to create scenarios where a review of existing transmission protection schemes will need to be carried out. Adaption may be addressed through slight modifications in existing scheme while potential for having new Special Protection Schemes is also expected.

This research is of significant value to comprehensively understand responses from various WTG technologies in terms of voltage and current levels during system faults. Fault ride-through criteria and their interdependence on protection clearance times; fault current behaviour of wind farms and their impacts on protection design, and estimation of positive sequence impedance to calculate fault current contributions are the areas investigated in this thesis.

1.1 Motivation

The main motivation to pursue this research has been the rapid advancements in WTG technology, resulting in the quest for economic ways of generating large amounts of power and its integration into the grid along with existing conventional generation resources. The more wind energy gets integrated into grid, the higher the concerns due to the intermittent nature of its generation and non-uniform behaviour from its generator technology especially during severe grid disturbances. All these impacts raise questions about system protection schemes [1]. Introduction of new smart devices in Power Systems; integration of renewable energy into grid on larger scales; emerging electricity markets and new services; and, depletion of conventional fuel and sources are all driving factors for this research. The final goal is to help contribute towards improvement of reliability of electricity system from wind farms both economically and safely.

Investigation into FRT criteria development provides a pathway for transmission companies to develop their own FRT criteria while taking into account their network and existing generation characteristics. Low Voltage Ride-through (LVRT), one of the grid code requirements that are directly impacted by protection settings of a wind farm, has been investigated as one of the research objectives. The thesis initially carries out a comprehensive review of the existing literature related to large scale wind integration, pertaining to protection of the power system. The treatment in this thesis for case studies revolves around New Zealand Power System and large scale wind integration into its transmission grid.

With higher level of penetration it is possible that WTGs are the dominant generation units providing fault currents, used for sensing by protective relaying scheme, due to faults in specific geographical regions. Unreliable protection performance in such a critical grid situation is highly undesirable from overall power system security viewpoint. Fault current response from WTGs test data in this thesis provides guideline for both relay manufacturing companies and utility companies in dealing with identified protection performance issues.

There are well-established practices to evaluate symmetrical components for fault currents and voltages. Classical methods are valid for conventional generation feeding the faults. Wind generation typically use different technologies but the symmetrical component method has not been yet used as a measure of fault level because of the impact of power electronic control blocks which forms part of the generation unit. Estimation of the symmetrical component-based impedance model for a wind farm, whose control model is not known, will be very useful for transmission utility planning process. These planning processes help finalise significant investments during grid upgrade plans. The outcomes of this research will also lead towards understanding better control and protection strategies for wind turbine-generator manufacturers and transmission grid operators.

1.2 Objectives & Contributions

To avoid disconnection of wind generators from the grid, performance of protection schemes and ability of available generator technologies to stay connected are to be ensured with respect to established fault ride-through (FRT) criteria. This is closely monitored by the grid operators especially under situations when wind generators are disconnected during severe grid faults. In order to investigate the protection performance of wind farms, short-circuit strengths and the ability to ride through the faults will be investigated. Existing literature on FRT criteria is reviewed, particularly from viewpoint of its development in order to form the basis for the first contribution of this thesis i.e. developing a robust methodology for FRT/LVRT criteria which explicitly factors the role of protection and generation technology types.

LVRT criteria, reactive compensation, and wind generation technology are also investigated to understand the interaction between wind farms and transmission system with each other. To carry out these assessments on real systems, New Zealand North Island (NI) and South Island (SI) grids have been used as case studies. The network snapshot used for analysis in this research is shown in Appendix B. Necessary modelling tools were acquired and learnt to carry out the modelling. DIgSILENT® PowerFactory was the one which has been used in this research for large-scale simulation since it is being used by all the major New Zealand power system stakeholders. In order to understand the impact of FRT/

LVRT on protection requirements, development of LVRT criteria for a grid section from the North Island grid has been carried out. Major considerations for the development of LVRT have been included and a general methodology that can be universally applied is proposed. This is followed by scenario based simulations on the North Island network highlighting wind integration impacts. By selecting different wind technologies, transmission voltages and protection philosophies, the case study in chapter 5 reports on aspects of these investigations. Finally, the proposed LVRT criteria for New Zealand NI and SI network are presented which has been achieved through collaborative research with the transmission system operator, Transpower.

Fault current responses are to be examined separately for each WTG type. Fixed Speed Induction Generator (FSIG), Doubly-fed Induction Generator (DFIG), and Full Scale Frequency Convertor (FSFC) types (i.e. Type-1 to Type-4) have been focused on for this thesis. A simplified case study is developed in DIgSILENT® PowerFactory to investigate the fault current response of each type following a severe fault; their responses are then compared. In order to assess protection performance, their responses are generalised in the form of standard transient current curves. Finally, the performance of each major protection scheme i.e. Over-current protection, Distance protection and Differential protection are comprehensively assessed. The objective is to identify possible issues, if any, with these protection schemes.

Acquiring detailed models from the manufacturer of modern WTG unit, has been reported to be always a challenge and this has been faced during the course of this research. Because of the unavailability of the model, one can only estimate WTG impedance towards the fault. These estimations are important for planning studies such as load flow and short-circuit analysis. Positive sequence control units within a WTG model have the ability to change the current response and it becomes difficult to therefore estimate short-circuit strength. An unconventional but simple method has been proposed to estimate the symmetrical or positive and negative sequence impedance values for planning studies. This is achieved through a simplified aggregated DFIG WTG model to be studied under a fault scenario and its voltages and currents recorded to estimate fault impedance values. The importance of additional controls such as crowbar protection and rotor current controllers is also discussed in the context of its impact to the estimation method proposed.

Summarizing, this PhD research targets to:

1. Investigate available WTG technology types for FRT capability and assess their FRT performance through literature survey and case studies.
2. Propose a methodology to develop a test case of FRT criteria; investigate the role of protection clearance time for its development; and assess impacts of FRT criteria on protection schemes and relaying equipment.
3. Investigate existing protection schemes for each WTG type to analyze their performance and identify possible issues for network conditions.
4. Finally, propose a methodology or technique to estimate equivalent short-circuit impedance of DFIG based WTGs based on symmetrical component analysis method.

1.3 Thesis Structure

The scope of the thesis revolves around large scale wind integration and power system protection. The work has been sub-divided into three main objectives of this research i.e. FRT criteria development, fault behaviour of WTG technologies and equivalent short-circuit impedance calculation through modelling and simulation. Firstly, the concept of FRT is discussed and available literature on FRT with respect to wind generator technologies is explored. Contributions by identifying considerations and developing methodology for wind integration into transmission grid in general and in particular New Zealand experiences of FRT criteria development are listed. In the second part the concept of short-circuit strength is discussed and case studies investigating short-circuit currents and voltages for large scale wind farms are analysed from a protection viewpoint. Thirdly, case study equivalent of wind generator models are presented from a symmetrical component perspective to help grid operators to understand response from wind turbines whose equivalent models are not available.

One major motivation was to utilize real test measurements to validate models and consolidate results. However, despite long and consistent effort, no real fault data could be obtained because of commercial sensitivity surrounding the various WTG model used in this thesis. Due to this constraint of getting real wind generator data, Electricity Authority database and Transpower Ltd. support has made analyses described in the thesis possible. This reflects the best estimate of the wind generator characteristics as used by New Zealand Transmission and regulatory agencies.

This thesis has been presented through seven chapters.

Chapter 1 introduces the thesis and describes the nature of the work, its motivation, objective and overall thesis structure.

Chapter 2 reviews the literature around large scale wind integration during normal and abnormal system operations. The expectations from large wind farms are also discussed comprehensively. As New Zealand transmission has been used as case studies for this research, this chapter also reviews the New Zealand Power System and existing wind farms and the experience of various assessment studies for grid integration.

Chapter 3 presents general wind farm modelling aspects for various WTG technology types using various modelling platforms, and discusses modelling considerations in the scope of this thesis using simulation software DIgSILENT® PowerFactory. The methodology has been described clearly to help understand the modelling and analysis steps. This chapter is important for understanding how the modelling has been carried out and what assumptions have been made to carry out the wind modelling case studies of this thesis.

Chapter 4 reviews short-circuit analysis. Multiple short-circuit analysis methods such as ANSI method, IEC 60909/VDE 0102 and the complete method are discussed. The purpose of each method is described briefly. The complete method is discussed at some length as it has been used for short-circuit analysis of case studies presented in the scope of this thesis. Fault types and their network representations are also described.

Chapter 5 discusses the ride-through capability of available WTG technology using available peer-reviewed and commercial literature. This chapter covers prevailing techniques to improve FRT capability of all available WTG technologies. The purpose of this chapter is to propose a standard methodology for the development of FRT criteria for a transmission grid, considering the role of power system characteristics and protection schemes using a specific network section of the New Zealand grid as a realistic example. This chapter also reports a full scale exercise in developing the LVRT criteria for New Zealand and the resulting proposed envelopes for the North and South Islands. The significance of this exercise and compliance tests are also proposed at the end of the chapter.

Chapter 6 investigates the fault current responses, independently for each WTG type. FSIG, DFIG, and FSFC types (i.e. Type-1 to Type-4) have been focused on for this thesis. A simplified case study is developed in DIgSILENT® PowerFactory to investigate the fault current response of each type following a severe fault; their responses are then compared. In order to assess protection performance, their responses are then generalised in the form of standard transient current curves for each type versus time. Finally, the performance of each major protection schemes i.e. over-current, distance and differential are investigated. The objective is to identify possible issues, if any, for these protection schemes.

Chapter 7 proposes a methodology developed in the course of this research to provide some means of comparing DFIG based WTG with other types using equivalent short-circuit impedance technique. Acquiring detailed models from the manufacturer of modern WTG units is always a challenge and has been faced during the course of this research. Unavailability of the model data makes it difficult to estimate WTG impedance experienced towards the fault. Estimations of these fault impedance are important for planning studies such as load flows and short-circuit analysis. Positive sequence control units with in a WTG model can change the current response and it becomes difficult to estimate short-circuit strength. An unconventional but simple method has been proposed to estimate the symmetrical or positive and negative sequence impedance values for planning studies. This is achieved through a simplified aggregated DFIG WTG model to be studied under a fault scenario, and its voltages and currents recorded to estimate fault impedance values. The importance of additional controls such as crowbar protection and rotor current controllers is also discussed.

Chapter 8 is the concluding chapter which summarises the overall thesis and highlights contributions emerging from this research. This chapter presents the challenges encountered during the course of this work and also outlines concrete future directions emerging from this work.

1.4 Publications & Presentations

1.4.1 Peer-Reviewed Publications

1. Qureshi, W. A., N.-K. C. Nair, *Fault Behaviour of Large Wind Farms and their Impacts on Protective Relaying Practices, in Australian Journal of Electrical and Electronic Engineering, 2013*
2. Chakrabarti, B., W. A. Qureshi, N.-K. C. Nair, *Renewable Generation and its Integration in New Zealand Power System,* in IEEE PES General Meeting 2012, July 2012, San Diego, USA
3. Kumar, P. K., W. A. Qureshi, N.-K.C. Nair, *Identification of Coherent Generator Groups in Power System Networks with Wind farms*, in Australasian Universities Power Engineering Conference 2011 (AUPEC 11), 25th-28th September 2011, Brisbane, Australia
4. Qureshi, W. A., N.-K.C. Nair, *Power System Protection and Large Scale Wind Integration*, Electricity Engineers Association Conference 2011, 23-24 June 2011, Auckland, New Zealand, *Available at : http://www.eea.co.nz*
5. Qureshi, W. A. G. Demler, N.K.C. Nair, *Fault Ride Through Criteria for New Zealand Wind Farms Connected to Transmission Grid*, IEEE PES General Meeting, 22-27th July 2011, Michigan, United States
6. Zhao, S. W. A. Qureshi, N.K.C. Nair, *Influence of DFIG Model on Fault Current Calculations and Protection Coordination*, , IEEE PES General Meeting, 22-27th July 2011, Michigan, United States
7. Qureshi, W.A., N.K.C. Nair, *Systematic development of Low Voltage Ride-Through (LVRT) envelope for Grid*, TENCON 2010, 24-26 November 2010, Fukuoka, Japan

1.4.2 Invited Presentations

1. Qureshi, W.A., N.K.C. Nair, Assessment of protection schemes for wind farm grid integration, in Wind Conference and Exhibition 2010, 30th -31st March 2009, Palmerston North, New Zealand
   Available: [http: //www. windenergy.org.nz/documents/conference10/wqureshi.pdf]

2. Qureshi, W. A., N.K.C. Nair, Large Scale Wind Integration and Emerging Protection Requirements, New Zealand Wind Conference and Exhibition 2011, 11-14 April 2011, Wellington New Zealand
   Available: [http: //www. windenergy.org.nz/documents/conf11/wqureshi.pdf]
3. Qureshi, W. A. , New Protection Schemes for Secure Power System Operation in Presence of Large Wind Generation Integration, Research Exhibition Day 2009, ECE Department, University of Auckland, 8th October 2009, Auckland, New Zealand

Chapter 2: Literature Review

2.1 Grid Integration of Wind Power

2.1.1 Wind Turbine Technology Trends

Wind turbines are available having different number, shapes and sizes of blades. A typical wind unit consists of three blades connected to the rotor assembly enclosed by a hub. A shaft connects the rotor hub usually through a gearbox, to rotate the generator as shown in Figure 2.1. The electrical voltage from the generator is then stepped up to be connected to the grid. In some turbine types it is achieved directly, whereas in others it is achieved through frequency convertors using power electronics to synchronise with appropriate grid frequency and voltage.

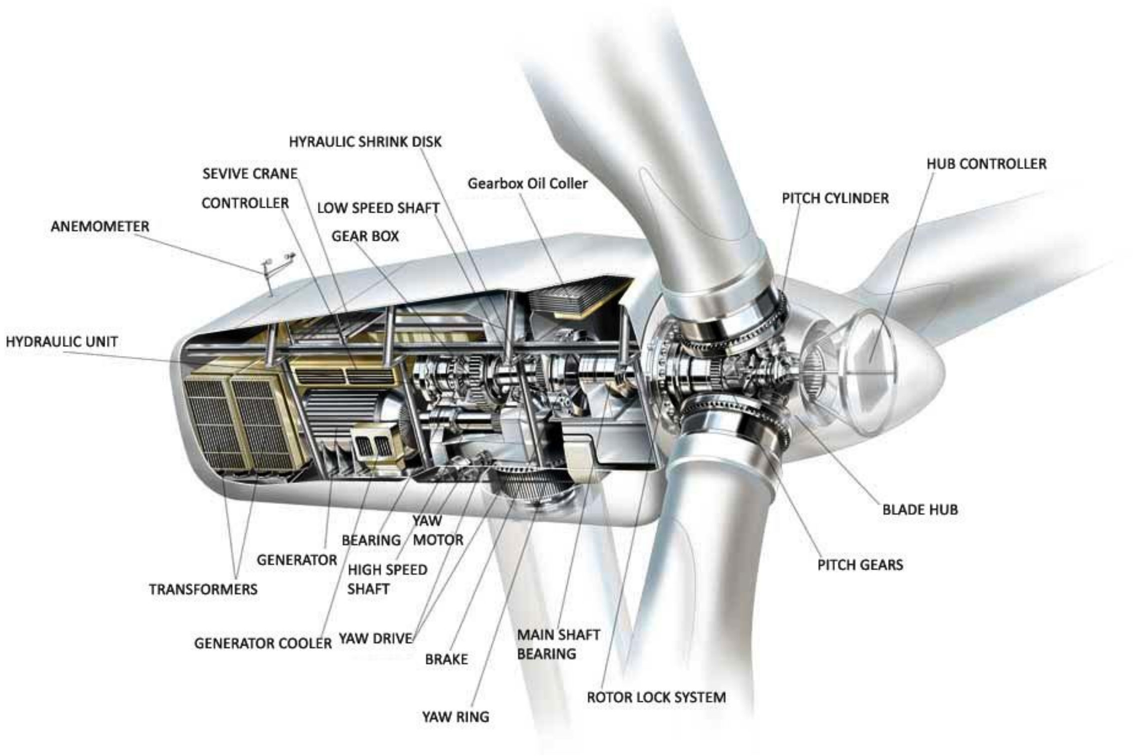


Figure 2.1: Example of modern wind turbine [2]

Wind turbines have, with the passage of time, improved in physical size and generation capacities. In the early 80's, wind turbine generators used to be typically 15-20 m in rotor diameter and produced around 50 KW. Now they can produce over 7MW of electrical power with a rotor diameter of over 100 m. The largest capacity turbines typically around 7-9 MW are being commissioned off-shore [3-5]. A 25 year comparative graphical representation for turbine sizes over time is shown in Figure 2.2. Increases in conventional fuel cost have been driving research and development in renewable technology, especially wind generation. Rapid advances in this domain have enabled manufacturers to develop larger and higher generation capacities leading to lower costs per megawatt; also resulting are improvements in the efficiency of conversion and additional safety and grid provision features, enabling a higher level of integration of wind energy around the globe. Table 2.1 outlines some of the world's major wind turbine manufacturers and the features of their turbines.

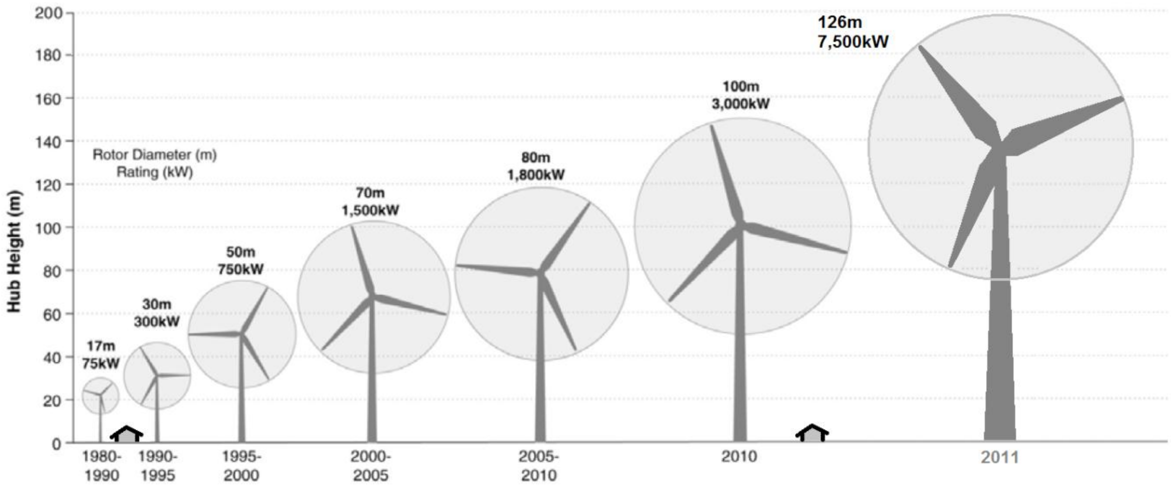


Figure 2.2: Wind Turbine Sizes and Capacities

Large-scale integration for both on-shore and off-shore wind farms raises concerns and challenges for the electricity industry; these include generation, transmission, distribution customers and power retailers. A number of concerns need to be addressed to connect wind power successfully. These include, but are not limited to, grid codes, power quality and power plant capabilities; design and operational aspects such as reserve balance management, short-term forecasting of wind, energy management and storage, and optimisation of flexibility of the system; grid infrastructure issues such as extensions and reinforcements, off-shore grids and their interconnections; and market re-design issues such as market aggregation, adaption of market rules to increase market flexibility particularly for cross-border exchange and operating the system closer to the hour of dispatch [6].

TABLE 2.1: SOME LARGE WIND TURBINE MANUFACTURERS AND THEIR MAIN PRODUCTS [4]

Manufacturers	Wind turbine concepts
Vestas Wind Systems	Fixed-speed with conventional induction generators. OptiSlip with induction generators and adjustable rotor resistance. Variable-speed with doubly-fed induction generators.
GE Wind Energy	Variable-speed with doubly-fed induction generators. Variable-speed with permanent magnet generators and full-rating frequency converters.
Siemens	Fixed-speed with conventional induction generators. Variable-speed with induction generators and full-rating frequency converters. Variable-speed with permanent magnet generators and full-rating frequency converters.
Enercon	Variable-speed with multi-pole synchronous generators and full-rating frequency converters.
Gamesa Eolica	Variable-speed with doubly-fed induction generators.
RePower	Variable-speed with doubly-fed induction generators.
Nordex	Fixed-speed with conventional induction generators. Variable-speed with doubly-fed induction generators.
Others	Fixed-speed with conventional induction generators. Variable-speed with doubly-fed induction generators.

2.1.2 International Experience

China and India have recently progressed well into wind generation. By the end of 2013, China and the US had a share of 27% and 21 % respectively in total global wind generation. Europe has historically been the largest regional market for wind generation in terms of total installed capacity (77GW, or 33% of the world total). Total world wind generation installed capacities are shown in Figure 2.3. [7].

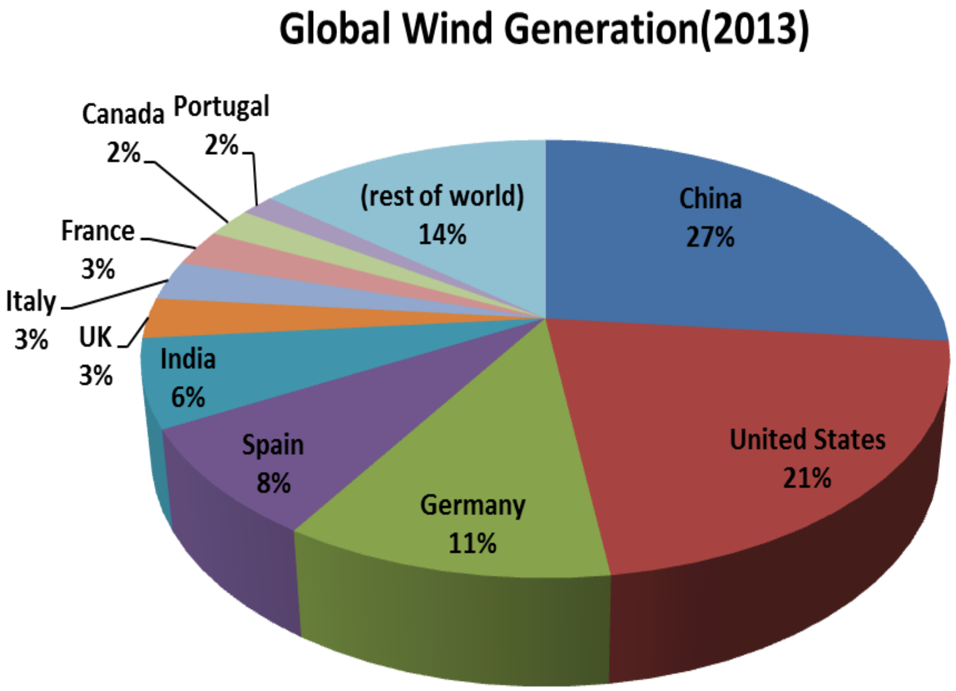


Figure 2.3: Global Wind Power Generating Capacity at the End of 2013

European countries contribute the most to the world's wind generation compared to the rest of the world. Denmark produces 19% of total power generation through wind, while Spain and Germany are at 14% and 8% respectively [7]. The precedence of wind integration at a larger scale in these countries raises questions of standardised methodology for ride-through studies for other countries and also raises the question as to how much wind or renewable integration remains economical while fulfilling other expectations [8].

2.2 Grid Codes and Operational Requirements

Increased penetration of wind power into grid has led to the development of specific technical requirements for the connection of large wind farms in transmission system. As mentioned before, these requirements are referred to as 'Grid Codes', requirements for which have been a major driver in recent development in wind technology.

2.2.1 Fault Ride-through (FRT) Requirements

FRT requirements are one of the essential elements of most of the existing grid codes. Because of the large capacity of wind connected to a transmission system requires wind farms to remain in operation during any network disturbance or fault. FRT means that generator or wind farms should be able to stay connected to the grid during a fault or disturbance across a specified voltage envelope. These requirements are specified in terms of voltage versus time characteristics of the connection point. Different countries have different specified envelopes depending on network voltages or characteristics of the network as shown in Table 2.2 below.

TABLE 2.2: FRT CRITERIA IN PRACTICE [9]

Grid code	Fault duration (ms)	Fault duration (cycles)	Min voltage level (% of Vnom)	Voltage restoratio n (s)
Germany (Eon)	150	7.5	0	1.5
UK	140	7	0	1.2
Ireland	625	31.25	15	3
Nordel	250	12.5	0	0.75
Denmark (<100 kV)	140	7	25	0.75
Denmark (<100 kV)	100	5	0	10
Belgium (large voltage dips)	200	10	0	0.7
Belgium (small voltage dips)	1500	75	70	1.5
Canada (AESO)	625	37.5	15	3
Canada (Hydro-Quebec)	150	9	0	1
USA	625	37.5	15	3
Spain	500	25	20	1
Italy	500	25	20	0.8
Sweden (<100 MW)	250	12.5	25	0.25
Sweden (>100 MW)	250	12.5	0	0.8
New Zealand (HVDC)	200	10	0	1

FRT or Low Voltage Ride-through not only require the wind turbines to remain in operation during a fault or disturbance but also needs swift restoration of active and reactive power after the fault. Certain existing codes, wind farms are required to support the system voltage through reactive power support during the fault.

With several available wind generation technologies, grid inter-connection and having concerns over their capability to support grid as effectively as conventional generation, transmission system dictates the development of stricter grid code requirements. New wind generation technologies claim to support transmission networks but existing large wind generation connected to a transmission system raises many concerns for not being able to fully support the system during system level disturbances. The response of a large wind farm during a voltage disturbance could possibly affect system stability [10-13]. With the increasing capacity of wind farms and the possibility of participation in the electricity market towards real-time frequency keeping and reserve management, wind farms cannot afford to go off-grid.

To ensure security of supply, increased penetration and emerging requirements in the form of grid codes different parts of the world including, USA, UK, Germany, Denmark, France, Netherland, etc., oblige wind farms to ensure certain specified capabilities and frequency response [9]. These codes also demand existing and newly installed wind farms to stay connected during various voltage and frequency events.

To avoid disconnection of wind generators from the grid, the performance of protection schemes and the ability of available generator technologies are to be tested for compliance with the internationally available fault ride-through criteria. This is strictly monitored for adherence by the grid operators under situations where generators are disconnected during grid faults. The protection performance of wind farms, short-circuit strengths, fault responses and ability to ride through the faults, needs to be well understood as part of this research. Literature on FRT criteria is available but does not cover their development of criteria detailing the role of protection and wind technology types.

Some grid operators require participation towards voltage stabilization and system recovery during both a fault and the post fault period [14]. FRT not only requires the wind turbines to remain in operation during a fault or disturbance but also needs fast restoration of active and reactive power after the fault. In certain codes, it is required to support the system voltage through positive reactive power during the fault. FRT is subdivided into Low Voltage Ride-through (LVRT) and High Voltage Ride-through (HVRT). FRT capability implies that generators must be able to remain connected during any fault event for defined voltage profile. In some countries, grid codes require all newly installed wind turbines to have FRT or LVRT capability [15-17], enough to satisfy voltage duration curves. These curves require wind farms to achieve certain voltage support, protection co-ordination and considerations with the system to ensure that they could ride through any fault event [18] [8, 19].

2.2.2 Active Power and Frequency Control

Wind farms could possibly take part in control and operation of the grid through regulation of output power. Almost all codes oblige wind farms to achieve certain power regulation capabilities which can be realized through different operating modes. These modes of control bear a fixed relationship with active power as shown in Fig 2.4-2.6 [9]. These power regulation modes are as follows:

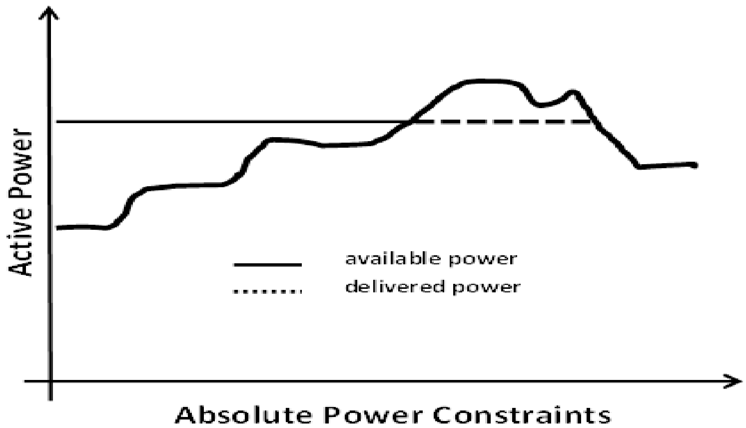


Figure 2.4: Absolute Power Constraint

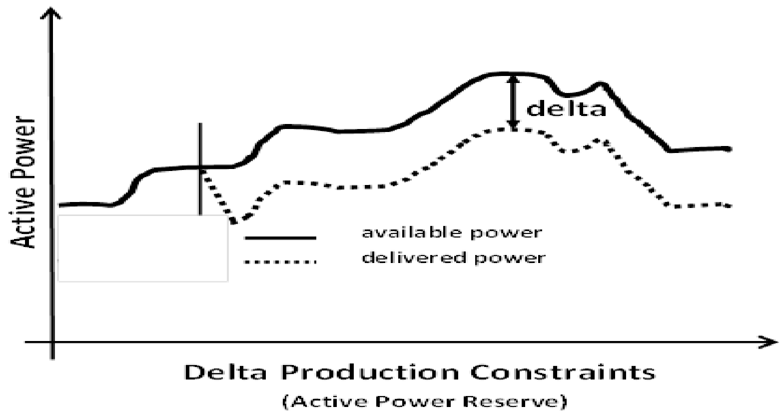


Figure 2.5: Delta Production Constraint

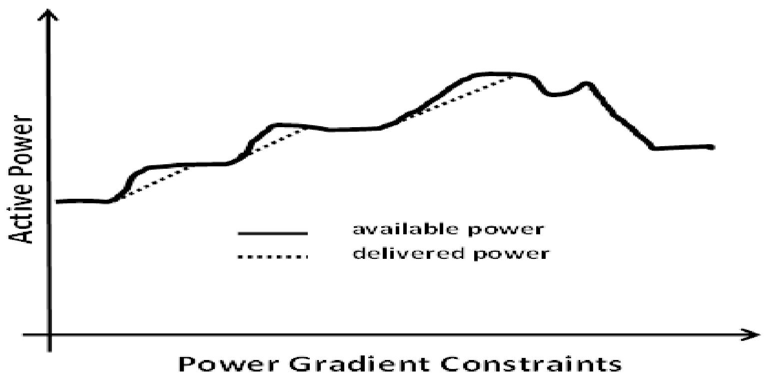


Figure 2.6: Power Gradient Constraint

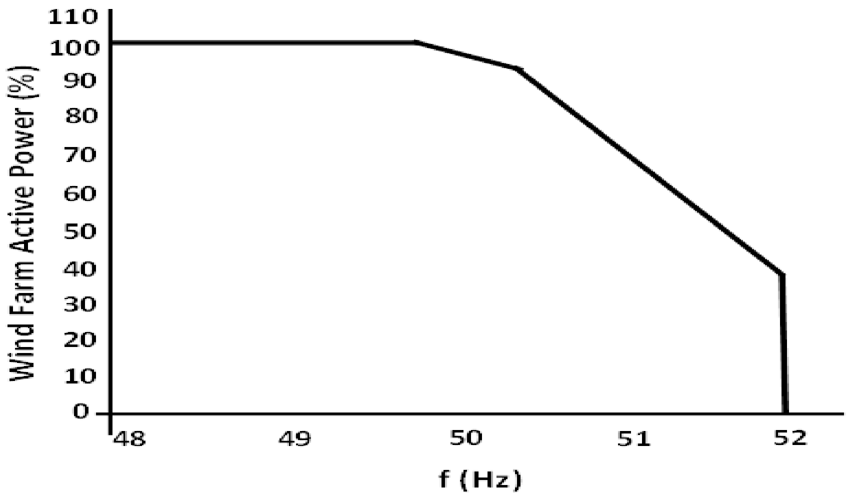


Figure 2.7: Typical power-frequency response curve

With the provision of active power control, a wind farm may participate in ancillary services such as frequency control. The System Operator may request a frequency response from the wind farm through dictating the amount of active power being fed to the system. A typical power-frequency response curve is shown in Figure 2.7.Grid Codes of Germany, Ireland, the Nordic grid and Denmark demand that wind farms have the ability of active power curtailment.

2.2.3 Extended Voltage and Frequency Limits

In addition to the voltage envelope requirement during abnormal operation, grid codes also demand that wind farms operate on extended voltage and frequency limits during normal operation. Very well defined in some of the grid codes this requirement is sometimes to be satisfied even at the expense of active power. .

2.2.4 Reactive Power Control and Voltage Regulation

Voltage regulation is directly dependent on reactive power control the requirements of which are linked with the characteristics of each network, such as short-circuit capacity and impedance [20]. Since reactive power control is an important issue for wind farms, some grid codes demand as much response from wind farms as from conventional generators. The facts that wind farms are installed at remote locations, and not all the technologies have the same reactive support capabilities, is worth considering.

2.2.5 Other Requirements

There are several other requirements from grid codes for wind farms or generators in general that are not included in this literature review. Requirements such as FRT, active power and frequency control, and reactive power control and voltage regulation may sometimes relate to protection and coordination issues of large wind farms, some of them have been investigated in the scope of this research.

2.3 Special Protection Schemes & Wind Integration

Electrical Power systems initially started as self-sufficient and independent units with an exact match between generation and demand. In any case of system failure or severe collapse, the system state could easily be restored because of its small size.

With increasing industrialisation and domestic needs, the power system infrastructure has grown in size and complexity to meet the phenomenal growth in demand. Events which could cause a system level disturbance, and endanger normal operation of electrical power networks are:

- Frequency Instability – Steady Frequency of the power system cannot be maintained by the power system within the operating limits.
- Voltage Instability – Steady acceptable voltages at all buses of the power system cannot be maintained by power system within the operating limits post disturbance.

"*A system enters a state of voltage instability when a disturbance, increase in load demand, or change in system conditions causes a progressive and uncontrollable drop in voltage. A system is voltage unstable if, for at least one bus in the system, the bus voltage magnitude decreases as the reactive power injection in the same bus is increased*" [21, 22].

"*Transient Angular Instability (also called Generator's Out-of-step) – It is the inability of the power system to maintain synchronism when subjected to a severe transient disturbance. The resulting system response involves large excursions of generator angles and is influenced by the nonlinear power-angle relationship" [21, 22].*

“Local mode of Small-signal Angular Instability (also mentioned as Generator’s Swinging or Power Oscillations) – is the inability of the power system to maintain synchronism under small disturbances. Such disturbances occur continually on the system because of small variations in loads and generation. The disturbances are considered sufficiently small for linearization of system equations to be permissible for purposes of analysis. Local modes or machine-system modes are associated with the swinging of units at a generating station with respect to the rest of the power system. The term local is used because the oscillations are localized at one station or small part of the power system” [21, 22].

With the rising dependence and importance of electricity for industrial and domestic consumers and as well as for the economy, the reliability of supply is seen as a serious concern. Interconnection of the independent network or power systems has offered a number of advantages and benefits including reserve sharing for normal and emergency situations, additional frequency regulation support, economical generation and transportation of electrical power to enhance trade and economy [23].

These above mentioned advantages of interconnected networks, have also resulted in a new problem of small-signal angular instability.

“*Inter-area mode of Small-signal Angular Instability – inter-area modes are associated with the swinging of many machines in one part of the system against machines in other parts. They are caused by two or more groups of closely coupled machines being interconnected by weak ties”* [21, 22].

Nowadays, with market deregulation, new regulations to operate power systems, strict grid codes and other environmental and economic challenges, building power plants have become even more difficult. Thus, power systems are now being operated closer to their stability limits. Integration of renewable generation from environmental and economic perspective also can potentially endanger the reliability of the system for operation of the power system with very narrow stability limits. An abnormal state or event not eliminated in time, it could lead to catastrophic failures [24-27]. If this happens, an extremely quick and complicated restoration procedure must subsequently take place [28].

Initially, local protection devices and schemes such as under frequency and under voltage relays were attempted to avoid such scenarios. It was then observed that these disturbances are not local that can be contained, but global in nature thus requiring system level data and wide area orientation. Protection schemes designed to handle such situation are mostly referred to ‘Special Protection Schemes’ (SPS).

Special Protection Schemes are also termed as ‘System Protection Schemes’. Satisfactory operation of a power system requires tools additional to conventional control and protection schemes. SPS are tools to ensure satisfactory operation following an involved contingency. Satisfactory operation refers to the system state where all system elements remain in operation, equipment ratings are not exhausted, system voltages are within tolerance limits of operation, power flows are stable and frequencies are within defined limits.
SPS’s can be of the following two types;

1. Frequency Control SPS (FCSPS)
2. Network Control SPS (NCSPS)

Loss of load or loss of generation may force system frequencies to deviate from acceptable limits. FCSPS are required in such cases where tripping of generation following or load loss or interrupting load following a loss of generation is required to keep system frequencies in specified limits. Since, this scheme needs to act immediately within a few hundred milliseconds, following any of above events, high speed protection signalling is required to securely issue trip signals to generating units or load sections.

Other than loss of generation or load network, elements may experience thermal overloading issues following a contingency. An NCSPS is implemented to prevent such scenarios in a transmission network. The selection of generation unit or load section to be tripped is dependent on the location to be protected. If a generating unit is tripped during an NCSPS operation, other generation needs to increase the output, or new generation needs to be added to the system, to keep frequencies within limits. The same purpose can also be fulfilled by Frequency Control Ancillary Services (FCAS).

2.4 Wind Generator Technologies and Grid Operation

A number of wind generator types are available and installed currently. These may be identified as four different generator types [29]. To make things simpler they have been named Type1 to Type-4 WTGs.

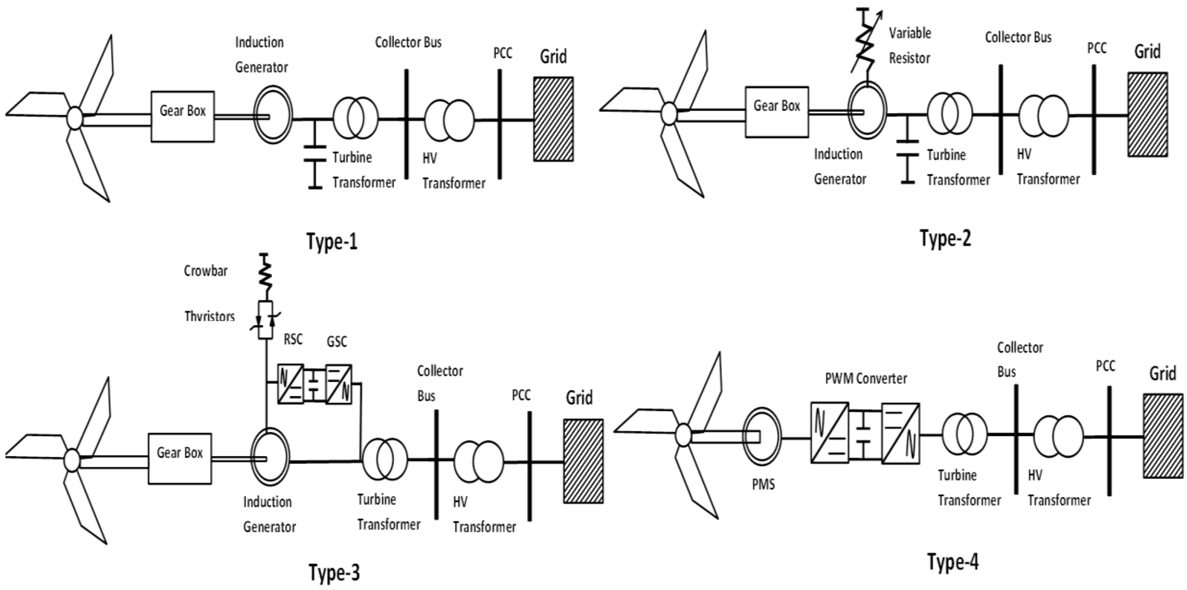


Figure 2.8: Wind Turbine Generator (WTG) Types

Type-1 WTG is a squirrel cage induction generator with fixed rotor resistance, while the Type-2 WTG is a wound rotor induction generator with variable resistance with a high-frequency switch control. Type-3 WTG is configured by a DFIG. It is also a variable speed induction generator capable of speed control with +/- 30% of slip range. Additional feature is the voltage produced by the power converter between rotor and grid. Type-4 WTG is configured using a permanent magnet synchronous generator (PMSG) with full power conversion through frequency converters. All four types of WTG arrangements are shown in Figure 2.8.

Short-circuit currents for different WTG types and their maximum values have been discussed in References [30-32]. Single phase equivalent models of all four types of WTGs could be represented as shown in Figure 2.9. The Types 3 & 4 WTG short-circuit model may not be generalised since power converter transfer functions may control or change the response of the WTG altogether. In Type-4 WTG, the design of converter and its control is more important than the type of the generator used.

Figure 2.9 presents equivalent models for commonly agreed four WTG types is to give a comparative sense of the fault behaviour of each WTG type.

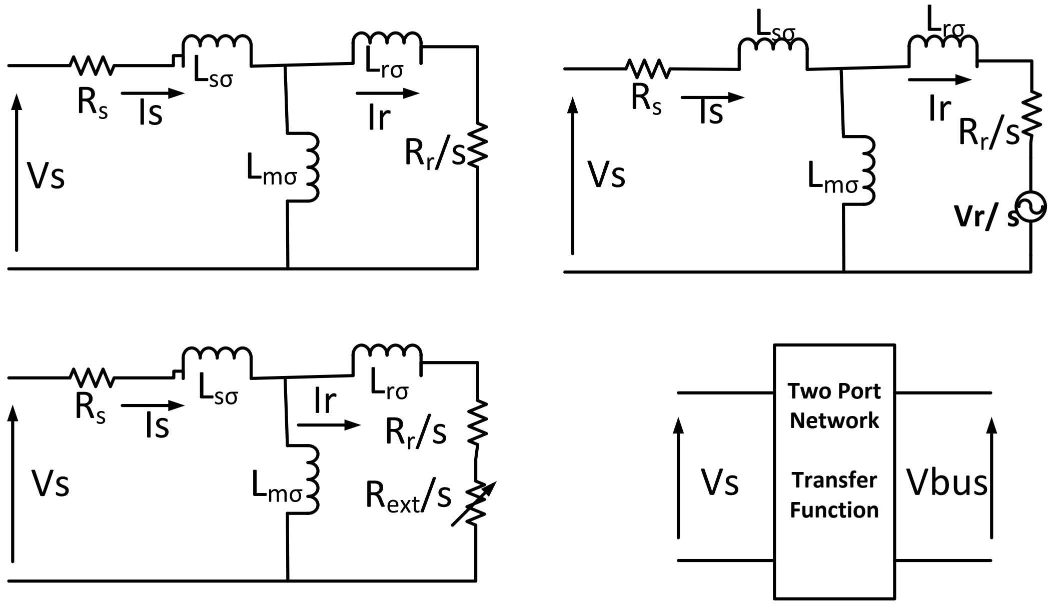


Figure 2.9: Wind Turbine Generator (WTG) Equivalent Models

In the presence of grid code, all WTGs are required to stay connected to ensure system security and stability. They may disconnect if the system voltage moves beyond allowed voltage-time profile envelopes. Based on the grid code requirements, manufacturers have come up with various solutions for all types of WTGS.

It is well known that reactive power injection can improve ride-through capability [33-35]. Similarly ,Types 1 & 2 units, with and without Static VAR compensation and Type-3 have also been compared in reference [34]. Types 1 & 2 could ride through faults at the Point of Common Coupling (PCC) with effective reactive power support and this is apparently the only technique for these types. However, various techniques using convertors and controllers are available for Type-3.

Type-3 generators can ride through a system fault using the controller technique applied to the grid-side converter presented in reference [36]. To enhance the FRT capability, a series-connected voltage-sources converter has been proposed in reference [37]. A commonly used and proposed technique is a bypass resistor known as crowbar resistor which is connected to rotor terminal to improve FRT capability for Type-3 which is discussed in several references [38-42]. Bypass technique not only improves the FRT capability but also protects the rotor from being damaged. However, when the crowbar is connected, a Type-3 behaves more like a conventional induction generator thus compromising the control performance [43, 44]. The choice of an appropriate value of crowbar resistor could further improve performance of DFIGs as suggested in reference [42]. Another technique proposed suggests that both grid-side and rotor-side converters inject reactive power to the grid during the fault along with improved timing algorithms for the crowbar resistor, which thus improves the FRT capability even better [45]. The choice of crowbar resistance and bypass time has direct impacts on the fault response of the wind farm [46]. Because the crowbar technique is not acceptable anymore in some countries e.g. Germany, therefore, some manufacturers offer advanced controls such as the AGO2 provided by Vestas [47]. During normal system operation, P and Q references are sent directly to PQ controller. However, in the case of LVRT/FRT the P and Q references are adjusted by AGO2 with predefined settings. In one configuration AGO2 control adjusts the references to provide maximum active power and minimum reactive power. In a second configuration, both references are adjusted equally to provide balanced active and reactive power i.e. 50/50 %. In the third of severely low voltages, more voltage support may be required from the WTGs, thus the AGO2 adjusts the P and Q references to provide zero active power and maximum reactive power.

Type-4 has an arrangement different from the above technologies. This technology isolates the induction generator or synchronous generator from the grid through a back-to-back frequency converter. The control and protection of the converter is quite important and challenging for this configuration. The research in this particular technology is limited because of the unavailability of standardised converter models for dynamic fault studies of power systems.

2.5 The New Zealand Electricity Industry

The electricity industry consists of transmission providers, the System Operator (SO), generation companies, retailers, distribution line companies and regulatory bodies, i.e. the Electricity Authority (EA) and Commerce Commission.

EA looks after compliance issues related to electricity production, transmission, distribution and operations. It is responsible for efficient, optimal and reliable delivery. EA administers The Electricity Industry Participation Code 2010 (The

Code), which defines the obligations of the system operator and other market participants [48]. The Commerce Commission looks after competition and transmission grid enhancement approval issues.

Transpower has been appointed by EA as the System Operator for the electricity industry. The responsibilities of SO involve the real-time co-ordination of electricity generation, transmission and demand, and the management of the electricity market in New Zealand. Thus, Transpower is both transmission provider as well as System Operator.

The market participants are generators, transmission providers, retailers and the distribution network companies. The large generation companies, in order of percentage of energy share they contribute, are Meridian Energy (32%), Contact Energy (24%), Genesis Power (18%), Mighty River Power (13%) and Trust Power (5%) the rest generating 9%. Thus the above five generators provide 91% of New Zealand's electricity generation [49].

Infrastructure between Grid Exit Point (GXP) and Point of Connection (PoC) with the consumer is owned and maintained by distribution line companies of which there are 28 distribution companies in New Zealand, ranging in size from around 4,000 to 620,000 connections. Most of the distribution companies do not have a direct contractual relationship with consumers but they work closely with retailers since the code does not allow retailers to deliver electricity. Normally, distribution line companies are only allowed a limited generation of up to 25 MW, or 10% of peak loads. The distribution line companies charge consumers on the basis of fixed lines charges plus variable demand charges for smaller and larger consumers, or a combination of these.

Some of the retailers also possess a generation business and maintain a net generation level due to the integration of retail and generation business in New Zealand Electricity Market (NZEM). Retailers buy electricity from the wholesale market and sell it to different customer types such as domestic, commercial or small scale industry users through various tariff arrangements.

2.5.1 New Zealand Power System and Generation Mix

The New Zealand power system has a peak demand of 3500 MW in the South Island and 4500 MW in the North Island, a total of 8000MW. These two islands are connected through a 1200 MW HVDC link. The energy produced to cater the energy need by different kinds of generations from 1990 to 2010 is shown in Table 2.3 [49].

TABLE 2.3: ANNUAL ELECTRICITY GENERATION, GWH

Year	Hydro	Thermal	Geothermal	Wind	Total
1990	22953	5956	2049	0	31467
1995	27259	5426	2049	1	35244
2000	24387	10474	2756	119	38285
2005	23094	14286	2981	608	41514
2010	24470	11140	5551	1618	43401

The New Zealand electricity market currently consists of a mix of thermal, geothermal, hydro and wind generation. Figure 2.10 shows the mix of installed MW generation in 2010. In 2010, the mix was hydro 62%, thermal 20% ,geothermal 12%, co-generation 2%, and wind 4% in the installed capacity of 8700 MW [50]. This mix shows that about 78% are renewable generation. The NZ Government has announced that the renewable target of 90% needs to be fulfilled by 2025. It seems this target is easily achievable because there are significant additional wind plants and geo-thermal plants under construction or planned for the near future. Large load reduction, like the closure of aluminium smelter (which consumes about 15% of annual energy consumption) can also play a significant part in this context.

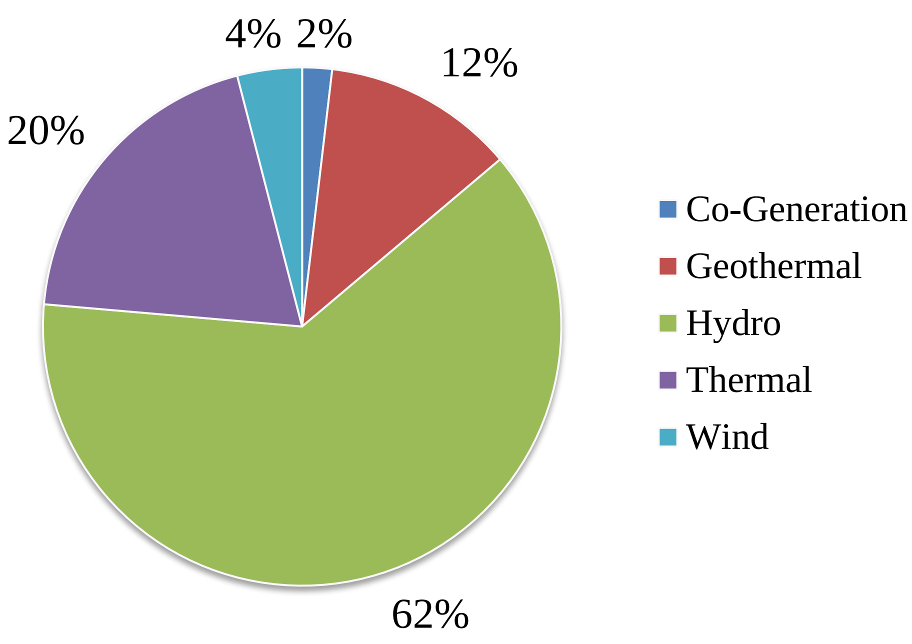


Figure 2.10: Typical New Zealand Generation Mix

2.5.2 Renewable Energy Target by 2025

Currently, the existing share of renewable energy in electricity generation, in terms of installed MW is 78%. There is 540 MW installed capacity of wind power in NZ at present [51]. According to New Zealand Energy Strategy report, by 2025, 90 % of electricity will be generated from renewable sources, provided supply security is maintained [42]. This percentage has increased from 68% to 74% in the last three years. According to data, the total renewable generation was about 68% by end of 2007. With the existing pace and commitment the New Zealand Government reaffirmed the 90% renewable energy target in August 2011 [52].

We understand that some generators seek to operate a wind plant optimized with its own hydro generation portfolio, primarily to maximize their profits in the electricity market. There are applications for installing wind power for approval for over 2800 MW. Some already are the approved and some are still awaiting for approval [51].

Geothermal plant installed capacity is 720 MW, of which 108 MW and 163 MW were commissioned in 2008 and 2010 respectively [49, 51].

Hydro plant current installed capacity is about 5000 MW and there are a number of hydro projects which have either been granted resource consent or are waiting. At least two projects of total 87 MW are likely to be commissioned in 2012-2013 in South Island. A few others are expected to be commissioned in 2015 or later [49, 51].

2.5.3 The Transmission System

Transpower grid consists of 220kV, 110Kv, 66 kV HVAC networks and the inter-island 1200 MW HVDC links. Figure 2.12 shows the core grid and generation and load centres. HVDC link helps to bring cheap hydro generation from the South Island to the North Island. Transpower has a vital role, being the planner of New Zealand transmission system [53]. It is to ensure the sustainable supply of energy for existing demand and consider of future growth aspects as well. A major 400 kV AC corridor is under construction which will ease power transfer from the generation centre at the south of North Island to the load centre at the north. The grid is equipped with static and dynamic reactive power sources to counter the low voltage and voltage instability problems. There are a number of Phasor Measurement Units (PMUs) installed at different sub-stations which adds enhanced value to the monitoring, calibrating and controlling of the power system elements.

The transmission owner allows open access to the market players in their transmission assets. A number of technical studies are conducted by the transmission provider and the system operator to assess the feasibility and grid performance of generation connection into the grid. The objective of these studies is to ensure that the static and dynamic performances of the grid are not be compromised by the added generation. If there are any problems in terms of grid performance, the associated entity like the generator is asked to address them.

2.5.4 The New Zealand Electricity Market

In the New Zealand Electricity Market (NZEM), the generators are self-committed through their offers and must submit their generation-price schedules before the gate closure of two hours before real time operation. The forecasted demands (and demand bids used only in pre-dispatch schedule) are used in the market optimisations before real time operation. This is a ½ hourly nodal spot price market, but it also has five minutes dispatch and pricing schedules. Final prices are settled after collection of meter data, next day.

In the NZEM, sufficient contingency reserve generation in the system is maintained so that these reserves can be called on and used to cover the outage of the 'risk generators'. Risk contingencies are well defined, and the amount of reserve needed to cover such contingencies is determined dynamically using energy and reserve co-optimisation. The generators can offer same generation capacity from a unit into both energy as well as reserve markets at the same time interval. In addition, frequency regulating reserves and black start capabilities are procured separately through a tendering process, outside optimisation.

At the centre of the dispatch procedure is the 'Scheduling, Pricing and Dispatch (SPD)' tool. Market is cleared using the SPD. The functional diagram of SPD is shown in Figure 2.11. After the solution, SPD gives the optimal and secure dispatch of energy and reserves, the bus energy prices and the island reserve prices [54].

The characteristics of the New Zealand Electricity Market reveal that it is an 'Energy Only' market, which means that generators do not get any incentive to maintain system capacity besides energy charges. They receive payments based on the amount of energy delivered, so they try to maximise the energy charges. Participating in Fast Instantaneous Reserve (FIR) and Sustained Instantaneous Reserve (SIR) are other significant incentives which a supplier could receive in the form of payment to maintain the reserves.

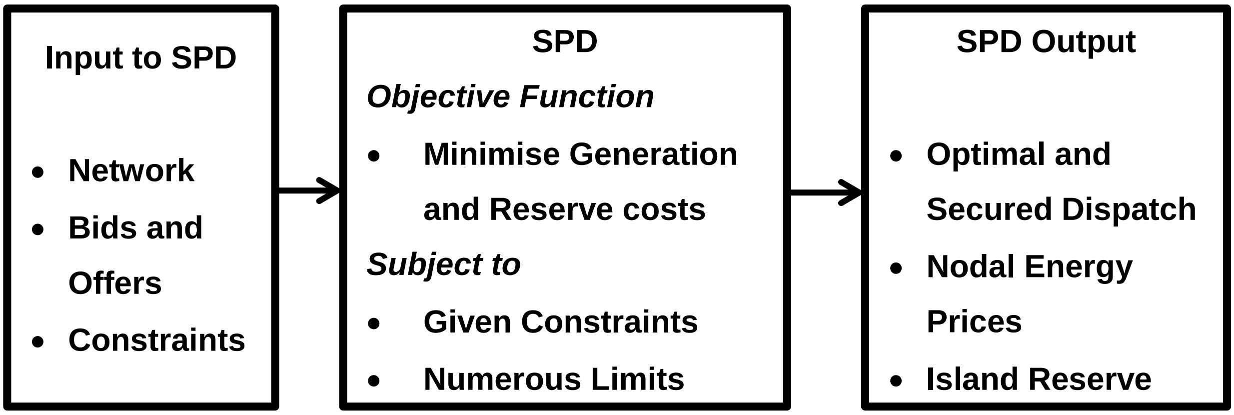


Figure 2.11: Functional Diagram of SPD

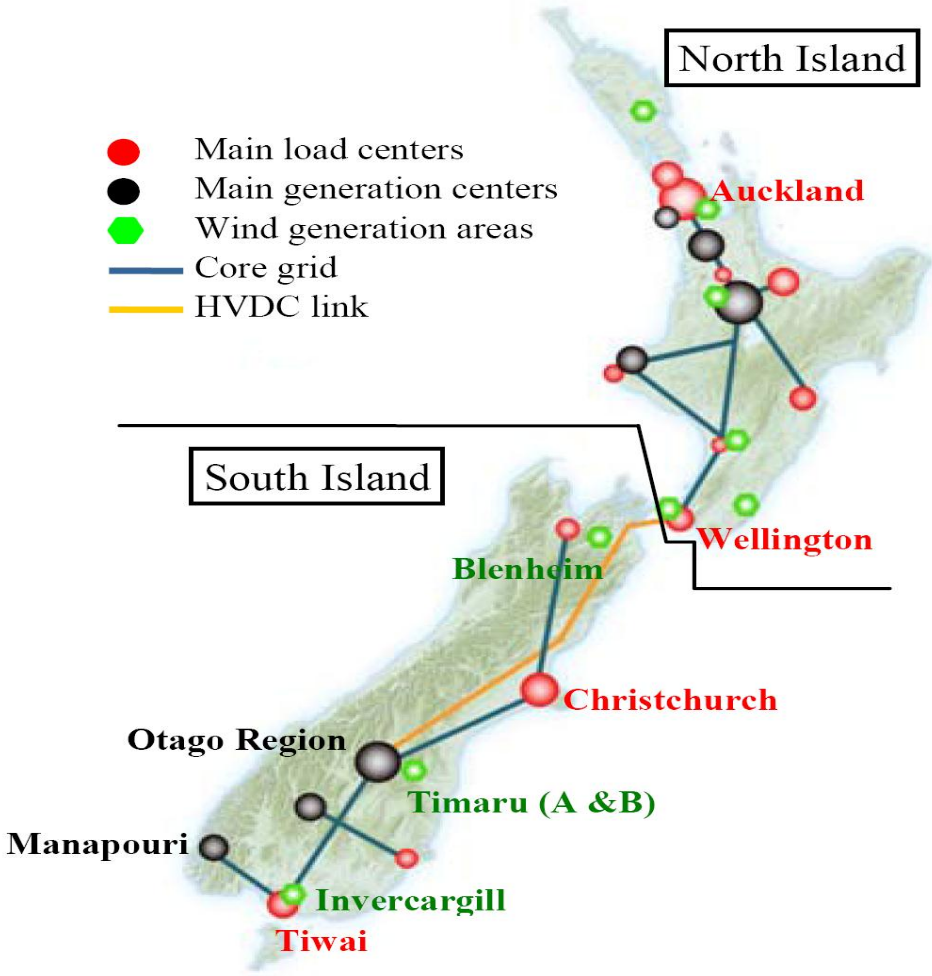


Figure 2.12: Transmission System in New Zealand [55]

The New Zealand Electricity Market has a key challenge of capacity. New Zealand electricity generation is mostly hydro dominated, with high initial cost and low operating cost throughout the year. These sources have one disadvantage of having low storage capacity. In times of dry season or peak demands, generation from other sources such as thermal and especially fuel plants is required, in order to meet the demand. Since the electricity cost from fuel plants is high, it increases the spot prices in market. Due to high operating costs of fuel plants and non-utilisation of these plants under presence of cheap electricity from hydro plants, investors become discouraged. To cater for the capacity issues, there are three options: additional generation sources demand side option, and energy storage option. Due to such a situation energy storage may become very attractive for the future needs of the New Zealand electricity industry.

Reliability of electricity supply is also a growing challenge for New Zealand. It is equally important for citizens and policy makers especially in this digital world where power outages are rarely unacceptable. Power generation in New Zealand being dominated by hydro-electricity, and its limited capacity to store water, puts the electricity industry at risk of supply shortages in dry years [56] [57]. Other renewable energy options such as wind, geothermal, solar and energy storage plants could possibly contribute towards reliability but the extent of this contribution still needs to be better understood.

As discussed above, NZEM is 'Energy Only Price Signal'; there exist price volatility from the annual spot price series. This volatility can be attributed to the wide range of marginal cost generation offered into the wholesale electricity market; substantial variation of demands within minutes; and commitment and capacity issues. One option to dampen the volatility is DSM [57]. The next possible option could be increasing the penetration level of wind and other renewable sources in the grid. The next section will discuss wind generation in New Zealand and its integration into the NZ power system.

2.6 NZ Experience of Large Scale Wind Generation

Wind Generation and its integration in the New Zealand grid are not as old as compared to some other countries. Successful overseas experiences of large scale wind generation have provided much support for New Zealand wind farms. Some countries in Europe are already at a very high penetration level of wind into their power systems. They also have interconnected grids with other neighbouring countries, while the New Zealand power system is very different.

These transmission ties, common in Europe could be beneficial, as they help to cope with the short-term power variability inherent in renewable, especially wind-generated, electricity. In contrast, the New Zealand grid is small and has only two islanded networks interconnected through HVDC links as shown in Figure 2.11. However, New Zealand is regarded as having one of the best wind resources in the world [58]. The significant amount of existing hydro-based generation (around 60%) could also play an important role in offsetting the variable nature of wind-based generation [59].

Currently, approximately 5% of the installed capacity of the total generation is contributed by wind farms in New Zealand. This percentage is expected to increase as some of the larger wind farms are still under the commissioning process [60]**.** There are more than 15 small or large wind farms operating in New Zealand. These include over 415 turbines of various manufacturers and sizes, with a total operating capacity of 622 MW. Of these, 6 are large scale wind farms connected at transmission and sub-transmission level. Table 2.4 lists the existing wind farms in New Zealand. Figure 2.13 shows the location of some of the largest wind farms of the lower North Island as mentioned in Table 2.4.

TABLE 2.4: WIND FARMS OPERATING AND UNDER CONSTRUCTION IN NEW ZEALAND [60]

Wind farm	Region	Wind farm capacity (MW)	Turbines
Brooklyn	Wellington	0.225	1
Gebbies Pass	Canterbury	0.5	1
Hau Nui	Wairarapa	8.7	15
Southbridge	Canterbury	0.1	1
Tararua	Manawatu	161	134
Te Apiti	Manawatu	90.8	55
Te Rere Hau	Manawatu	Operating: 32.5 Under construction: 16	32
White Hill	Southland	58	29
West Wind	Wellington	142.6	62
Horseshoe Bend	Central Otago	2.25	3
Weld Cone	Marlboroug h	0.75	3
Te Uku	Waikato	64.4	28
Mahinerangi	Clutha	36	12
Mt Stuart	Clutha	7.65	09
Mill Creek	Wellington	under construction:59.8	26

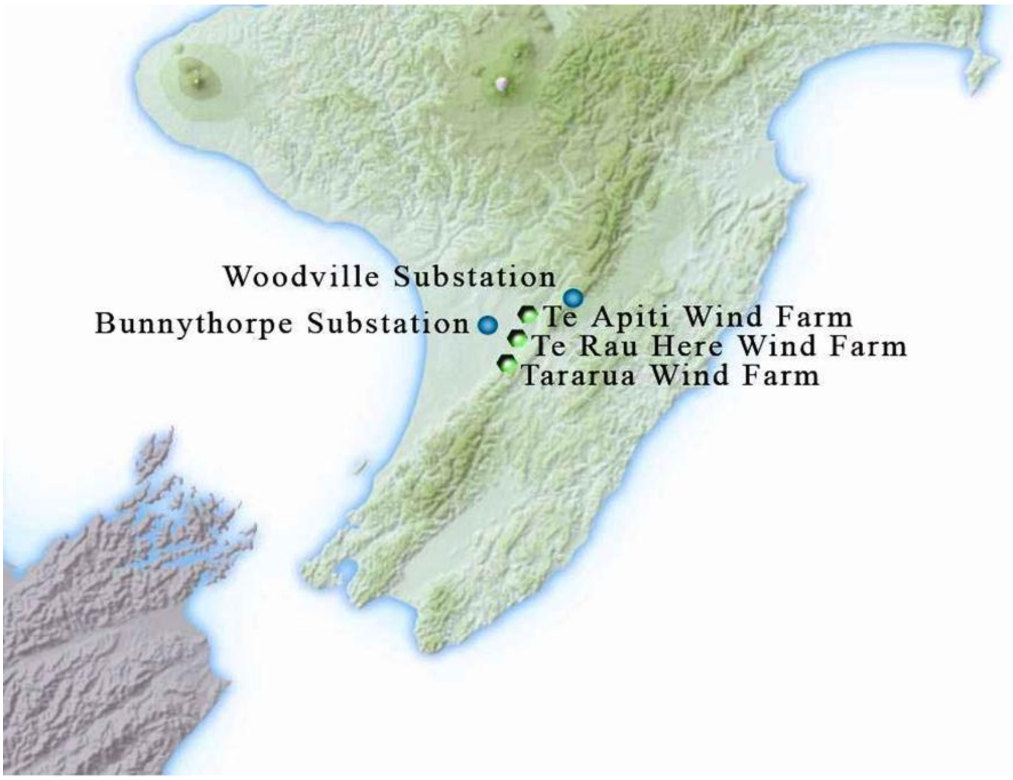


Figure 2.13: Existing Wind Farms in the Lower North Island [55]

Increased wind penetration and the integration of large wind farms in high voltage transmission systems require the development of tighter grid code requirements in New Zealand to maintain security of supply. The response of wind generation during system disturbances differs from that of conventional generation which may affect the System Operator in operating the grid in a secure manner.

The response of a large wind farm during a voltage disturbance can possibly affect system stability as discussed in [10-13]. The New Zealand Electricity Authority has carried out a variety of investigations into large wind integration scenarios including impacts on generation, transient stability, small signal stability, power quality, and dynamic response of wind farms during disturbances [48]. One of the major concerns is the Fault Ride-through (FRT) capability of all types of generation, specifically large wind farms, in order to ensure security of supply. In some countries, grid codes require all newly installed wind turbines to have FRT or LVRT capability [15-17]. Conventional generators are normally capable enough of meeting these requirements, while wind generators vary in capability depending on the technology used.

All generators are to remain connected to the grid under certain operating conditions to maintain system security. They may disconnect if the voltage enters into the region below or above allowable limits. This voltage profile or FRT requirement can be part of grid code or grid connection guidelines established by the Transmission System Operator (TSO).

To avoid situations where generators are disconnected during grid faults, grid operators define a ride-through profile. Some grid operators require participation to voltage stabilisation and system recovery during both the fault and post fault period [14].

There are no criteria or grid code requirements specific to Wind Farms presently, in New Zealand to address these technical issues. The System Operator has proposed voltage envelopes for the North Island and South Islands. The document is in consultation phase at the moment [61, 62]. All generators connected to the grid must comply with part C of the Electricity Governance Rule (EGR). As the penetration level of wind energy may increase, the system operator may expect wind farms to deliver the following services to the grid:

- Fault Ride -through Capability
- Extended System Voltage and Frequency Variation Limits
- Active Power Regulation / Frequency Control
- Reactive Power / Power Factor
- Voltage Regulation Capabilities

Not all wind generator technologies have the same capability to address the above services. They differ in capability and responses to system events. The responses can be improved through control modification or with application of SVC or STATCOM. Capabilities for FRT for various technologies are discussed in Chapter 4 “Fault Ride-through Criteria”, discussing a contribution from this work into New Zealand power systems for devising methodology and procedure for ride-through criteria development.

2.7 NZ Wind Farm Operational Experience

In early 2005 a study was carried out to identify the effects of large wind farms on NZ power system operation. As per an available technical report, wind generation in the Manawatu region in 1999 comprised the Tararua wind farm, expanded to 68MW in 2004, However, the Te Apiti Wind Farm connected to the same region was commissioned in late 2004, having capacity of 91 MW at that time [63]. This study also included a correlation between outputs of the two mentioned large wind farms and accuracy of wind generation forecast.

A number of large megawatt changes have been observed over short time duration. Coping with these changes is a big challenge and could pose operational difficulties in real time. Two types of apparent and sudden changes were identified in the generation megawatt [63]. The first type was observed to happen under certain weather conditions of an average size of 100MW over five minutes. This is approximately equivalent to 35% of the current operation wind generation capacity in the Manawatu region. It is quite possible that this change is specific to this location’s specific weather conditions. The second type of sudden change seems to be the result of natural wind variability, which is smaller in size (around 50MW in five minutes).

There are two possible reasons to identify and examine such events given below;

- A 50MW change in five minutes equates to the minimum required frequency keeper response rate of 10MW per minute (the frequency keeping station or the 'frequency keeper' is responsible for maintaining each Island frequency. changes output to match changes in generation and load in order to maintain power system frequency between 49.8Hz and 50.2Hz), and

- The dispatched frequency keeping band size is ±50MW.

A large event occurred on 15th November 2004 at about 01:00 am in the North Island. Figure 2.14 shows the impact of this change of NI frequency keeper and NI frequency; the response and efforts of frequency keeper are illustrated as per the given frequency keeping band of 50 MW in figure below.

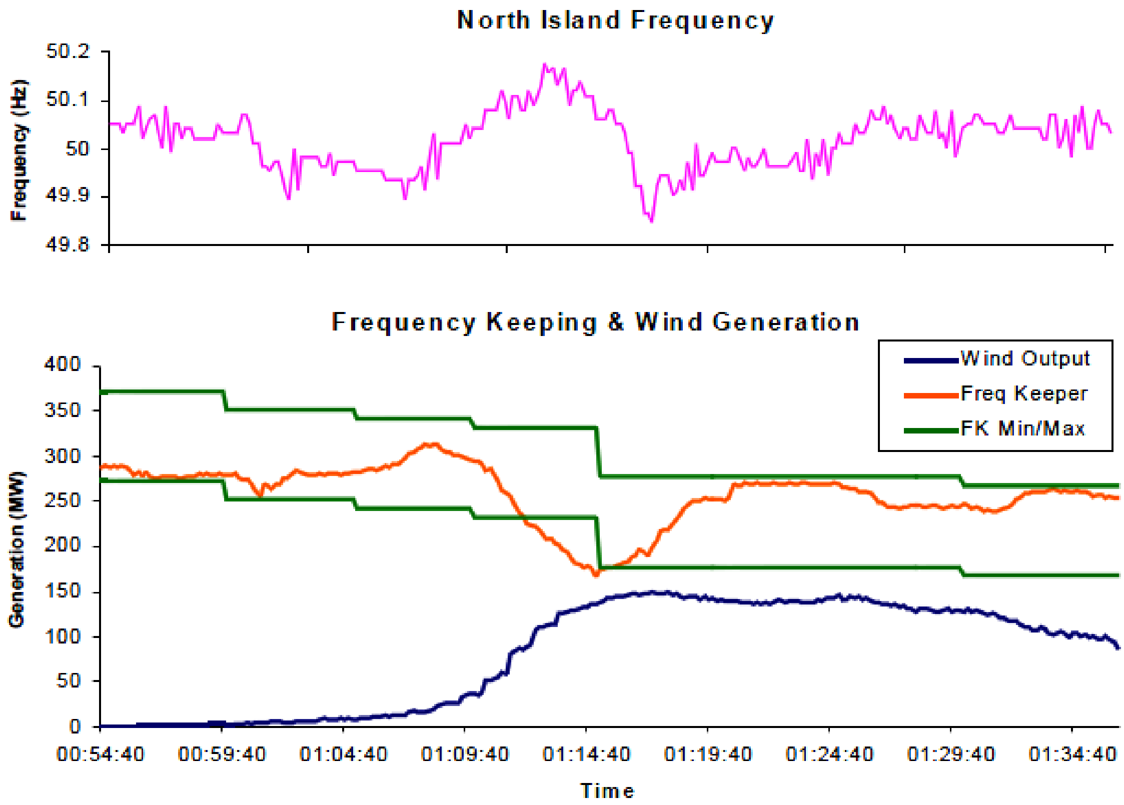


Figure 2.14: North Island frequency, frequency keeping generation (and frequency bands) in response to the events of 15 November 2004 [63]

In this particular event, wind generation output stepped up gradually to a value of 105 MW in 15 minutes and about 150 MW in nearly 20 minutes. Frequency keeper immediately kicked in to offset this big change in generation by reducing the output of their plant in response to the increase in NI frequency, as clearly visible in Figure 2.14. During this event the frequency keeper had to move below the dispatched frequency band of 50 MW, while the NI frequency moved to 50.2 Hz with the 0.3 Hz increment. It is interesting to report that 50.2 Hz is the upper limit for the normal frequency band for NI.

It is worth mentioning that this frequency keeping service was provided by a hydro station. These plants have a normally high response rate with regard to frequency keeping. The impact of wind variability was managed well because of the combined response of other generation plants and the availability of high response frequency-keeping station. Thermal generation plants may also be used for this purpose but their response is slightly slower than hydro plants; however, they can be equally effective for longer duration frequency keeping. Higher penetration of wind in NZ power system may pose some threats to the system frequency-keeping response due to increased variability, a result of more wind generation units and decreasing dependence on conventional plants (hydro & thermal) for frequency-keeping purposes.

There are no certain grid code requirements designed specially, for wind farms but under the New Zealand technical performance standards for generation plant. The Generating units connecting to the grid, these units are required to meet similar performance standards as other plants. Following the commissioning of first fixed speed induction generator-based plant, (i.e. Te Apiti), Transpower, the Transmission System Operator (TSO) carried out studies to identify interim changes to technical standards in advance of further studies to determine the necessary long term changes to the standard. These concerns and issues were addressed in the Wind Generation Investigation Project (WGIP) [64], briefly reviewed in the next section.

2.7.1 Summary of Investigations

The Wind Generation Investigation Project (WGIP) was initiated in late 2005 [64, 65]. A total of nine studies/ investigations were carried out by the System Operator (Transpower) for the Electricity Commission, now known as Electricity Authority [48]. These studies on the impacts of large scale wind integration on NZ Power System and NZEM are summarized in Table 2.5 below. Findings from these investigations helped in identifying the areas of immediate and future concerns for the NZ grid with an increasing level of penetration of wind generation. This also helped in the prioritising of the future work directions. Figure 2.15 presents a comprehensive and well-illustrated summary of the estimated implication level based on magnitude and timing.

In Figure 2.15, five years equates to an additional 1,000 MW of installed wind generation capacity. In this diagram X-Axis represents the timeline in terms of years, Y-Axis represents time scale in terms of years required to address those particular issues. The intensity of the issues is determined by the diameter size of the corresponding issues. These two timelines, and the intensity of the issues, helped to prioritise each issue.

All the issues have been prioritised in the given table. The most immediate issue has been found to be the effect of unpredictability of wind generation output on pre-dispatch processes.

TABLE 2.5 : IMPLICATIONS INVESTIGATION IN WGIP [65]

Category	No.	Description
Variability and unpredictability of wind generation output	1	Effect of unpredictability of wind generation output on pre-dispatch processes
	2	Effect of wind generation variability on dispatch
	3	Effect of wind generation variability on transmission asset loadings
Wind generation technical capability - voltage and frequency management	4	Effect of wind generation on ability to manage system voltages within voltage quality targets
	5	Effect of wind generation on management of frequency excursions
	6	Effect of wind generation on small disturbance voltage stability
Wind generation technical capability - power system stability	7	Effect of wind generation on transient stability
	8	Effect of wind generation on oscillatory stability
	9	Effect of wind generation on dynamic voltage stability

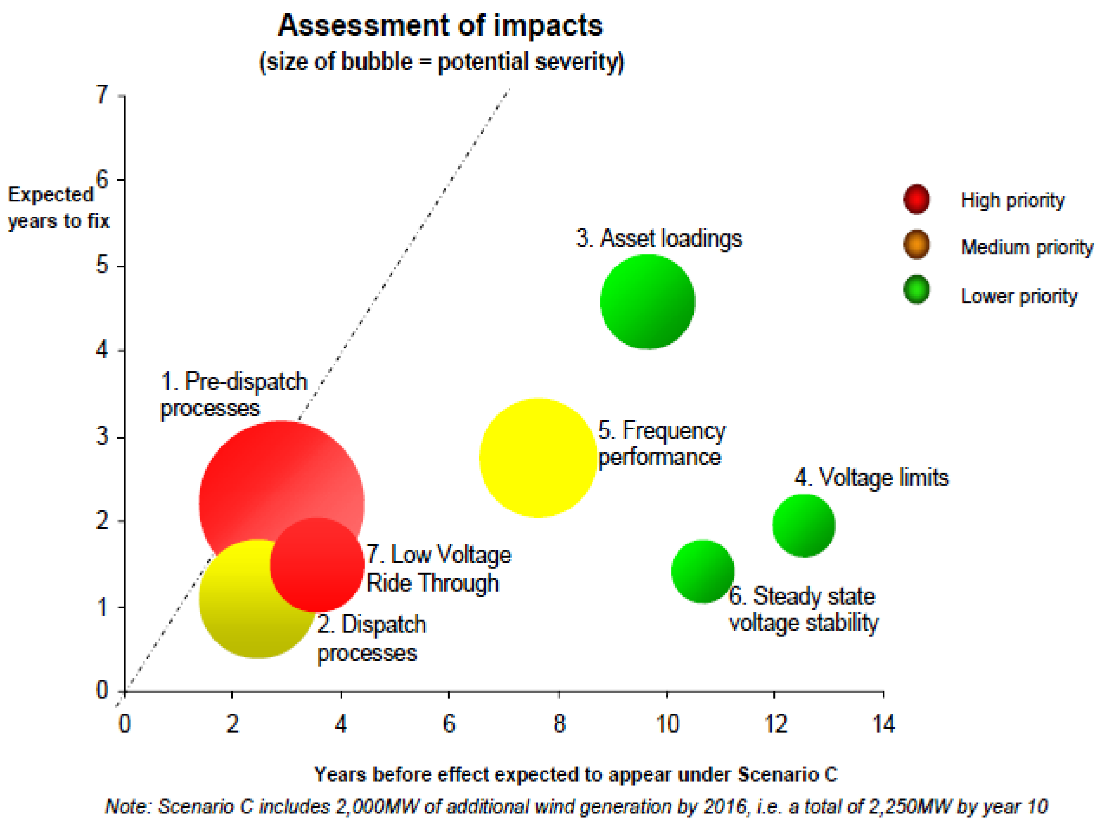


Figure 2.15: Assessment of impacts of wind generation under Scenario C [64]

From the investigations and limited operational experience of wind integration in New Zealand, it has been concluded that sudden large wind generation output variability has been observed. These changes would directly assert pressure on ancillary services in terms of frequency keeping and dispatch band. With the increasing penetration of wind into grid, the expectation of ancillary services from future wind farms opens more challenges for the System Operator and market system. Additional reserve plants and other generating plants would be required to provide frequency support to maintain system security. It was also recommended that geographic dispersion is an important aspect as opposed to clustering wind units, for integrating high levels of wind power into grid.

2.8 Summary

These investigations and analyses also identified Fault Ride-through (FRT) capability of wind units as an area requiring immediate attention. As discussed earlier, disconnection of a large wind farm or group of wind farms in the same geographical region of the electric grid following a disturbance or fault on the grid may cause a considerable frequency event. Such situations may require additional reserves to balance the loss of large wind generation plants not being able to ride through the fault.

Such disconnections of wind plants from the grid may cause widespread tripping of wind units in the absence of FRT capability. This may also cause issues like frequency stability, transient stability or even dynamic voltage stability problems resulting in loss of power to customers, in the form of load shedding. Identification of transient stability has also been briefly explored [66].

Consequently, it was determined that the most practical solution for avoiding considerably reduced reliability of supply in the New Zealand power system is to allow only new wind farms with FRT capability as per the EGR [55]. With wind farms being able to ride through the faults, additional reserve is required only for minor wind fluctuation but not for tripping of wind units.

The main concern was the unavailability of ride through criteria for New Zealand Inter-Island connected power system. The candidate has worked along with Transpower to develop the ride-through criteria for the NZ grid and methodology. Considerations and proposed criteria have also been published in multiple IEEE and PES conferences [8, 62]. Discussed in detail in Chapter 5, this study has been carried out in context of fault ride-through criteria development and major considerations involving protection clearance times and settings.

It can be seen in Figure 2.15, that accurate models of wind generation are important for any impact analysis. From the viewpoint of Low Voltage Ride-through (LVRT)/ FRT, wind farm protection or fault response of wind units for effective operation of relays has also become significant. The author has therefore investigated responses from various wind technology types and compared their protection performances to support implementation of FRT criteria into grid. The same study also includes the impacts of modelling and control aspects on fault studies. These investigations are discussed in chapter 6. The availability of fault models or short-circuit model for new wind farms is a major challenge. The author in collaboration with another researcher investigated the impacts and importance of correct model type for fault response studies [67]. To address this challenge for transmission System Operators and other investigation experts, the author has proposed a technique to discover the symmetrical components of wind farms for which manufacturer model is encrypted or not known. The technique proposed is to provide an estimation of dynamic fault impedance from wind farms during cases of fault, which is presented in chapter 7. All of the mentioned studies are contribution from the author towards the research of 'Performance Assessment and Management of Large Wind Farms under Abnormal Grid Operating Conditions'.

Chapter 3: Wind Generator Modelling

This chapter covers the modelling aspects of various wind generator types. Although generator types have briefly been mentioned in the previous chapter, this chapter gives a slightly detailed perspective regarding their background and inter-connection. Besides static, dynamic performance knowledge is essential for wind generators because of the non-uniformity in performance expectations from the transmission grid owner. There are several modelling and simulation platforms for static and dynamic analysis for these wind farms as mentioned in the previous chapter. DIgSILENT® PowerFactory is one of the available tools used for similar studies worldwide. DIgSILENT® PowerFactory has multiple advantages over other software because of its simplicity and reliability of the analysis evident from being used by transmission system operators in several countries with large-scale wind integration. DIgSILENT® PowerFactory is available at Power System Lab of the University of Auckland with professional license for research purpose. DIgSILENT® PowerFactory has many integrated wind generator models available for dynamic/transient studies, which could be modified for specific purpose of assessment. Wind generator types and their modelling aspects have been discussed in this chapter in similar context.

3.1 Wind Generator Technologies

3.1.1 Fixed & Variable-Speed Wind Turbines

Generally, wind generators are classified on the basis of speed. They can operate on fixed speed operation or variable speed operation based on the generator technology used. They have further classifications based on power generation phenomena. Fixed speed and variable speed wind machines are briefly described in subsequent sub-sections.

3.1.1.1 Fixed-speed Wind Generators

Fixed speed generators were common type of generators used with wind turbines installed in the early 1990s [68]. Fixed or variable speeds are associated with rotor speed of generators. A fixed speed wind generator or turbine has fixed rotor speed in contrast to wind speed which is variable in nature. These machines are designed to achieve optimum efficiency at certain speed. Because of its fixed speed power generation mechanism, speed variations may lead towards power or voltage fluctuations towards grid in case of weak grid situation.

Fixed speed machines with wind turbines are generally equipped with Induction generator (Squirrel Cage Rotor i.e. Type-1 or Wound Rotor i.e. Type-2). These generators have a direct connection with the grid through simple soft starter and reactive compensation units. The disadvantages of these machines include uncontrollable reactive power flow, mechanical fatigue and power quality issues. Despite disadvantages, these machines are simple, low cost and robust.

3.1.1.2 Variable-speed Wind Turbines

Because of the variable nature of wind, variable-speed machines are designed to achieve maximum efficiency by absorbing wind fluctuations and keeping the machine torque fairly constant. These machines have dominated the wind energy industry for the past several years. They achieve maximum aerodynamic efficiency through adapting the constantly changing wind speed by accelerating or decelerating the wind turbine.

Variable-speed generators may utilize conventional induction generator, doubly fed induction generator, or even synchronous generator along with power convertors for grid connection. The power/frequency convertor has the capability to control wind turbine for variable speed, reduce mechanical fatigue on turbine or even improve power quality through wind generator. These convertors also provide other advantages such as fault ride-through capability and reactive compensation to certain level. These additional components/convertors increase the losses in wind unit and the overall cost of wind unit as well. Variable-speed wind turbines are typically equipped with an induction or synchronous generator, and are connected to the grid through a power converter. The introduction of variable-speed wind turbine types increases the number of applicable generator types and also introduces several degrees of possibilities for the combinations of generator type and power converter type.

3.1.2 Four Types of Wind Turbine Configurations

There may be several types of wind turbine configurations or topologies, but the four prominent types of are illustrated in Figure 3.1a-3.1d. A detailed evaluation of these configurations has been discussed in Chapter 6, particularly from ride-through perspective.

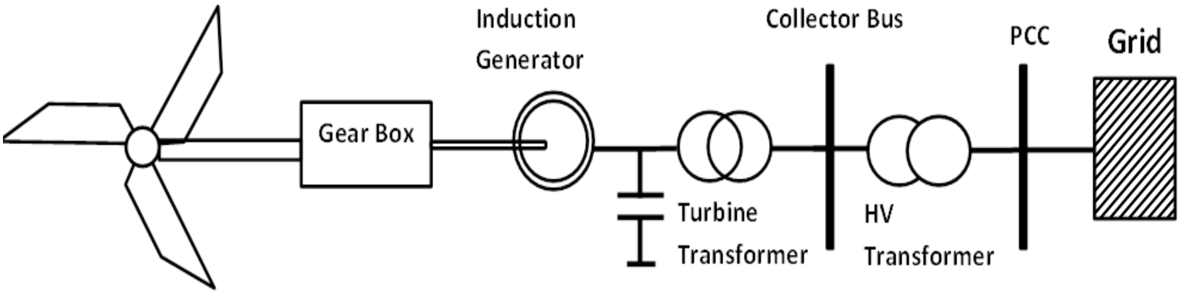


Figure 3.1a: Squirrel Cage Induction Generator (SCIG) Wind Turbine (Type-1)

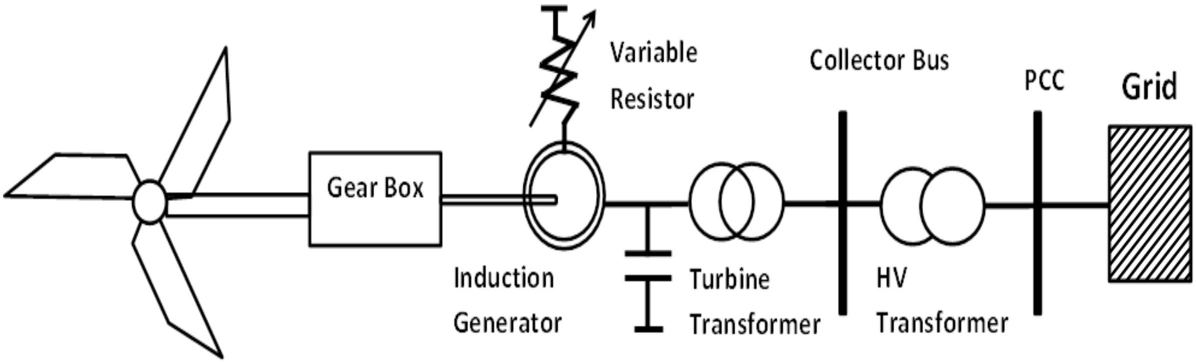


Figure 3.1b: Wound Rotor Induction Generator (WRIG) Wind Turbine (Type-2)

As discussed earlier, the first configuration (Type 1) is a fixed speed wind turbine along with a SCIG. The direct grid connection is smoothly achieved via a soft-starter. To limit torque of the turbine, passive and active stall mechanisms are utilized.

The second configuration is a slight variation of the first type. This configuration utilizes Wound Rotor Induction Generator (WRIG). The rotor winding is accessible and the rotor resistance could be altered to achieve limited speed variations, such as OPTISlip for Vestas manufactured turbines [69]. The rotor resistance variation is achieved through power electronics components such as IGBTs or Thyristers. The speed variation could typically be around 0-10% of the synchronous speed; however, it actually depends on the magnitude of the resistance used [10].

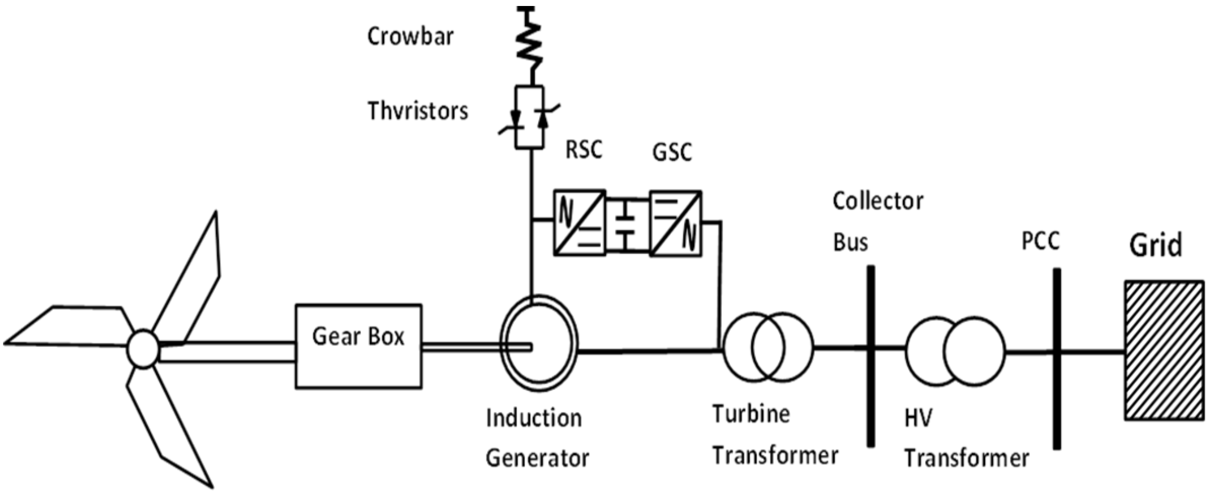


Figure 3.1c: Doubly Fed Induction Generator (DFIG) Wind Turbine (Type-3)

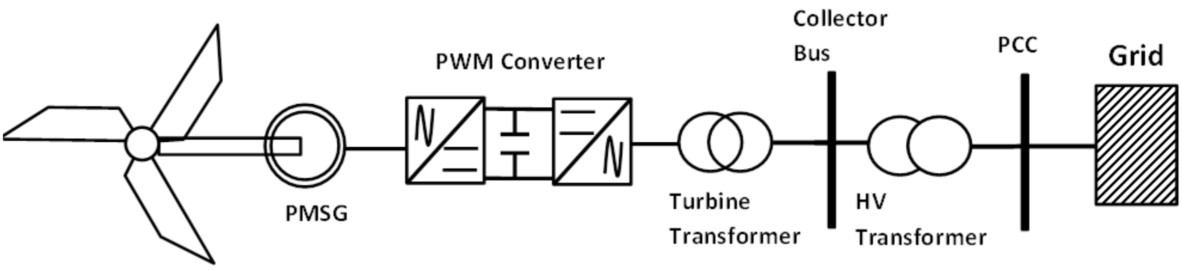


Figure 3.1d: Full Scale Frequency Convertor (FSFC) Permanent Magnet Synchronous Generator (PMSG) Wind Turbine (Type-4)

The third configuration i.e. Type-3 utilizes a Doubly-fed Induction Generator (DFIG) and is a variable speed wind turbine unit. Power from generator is extracted not only from stator but also from rotor. A partial frequency convertor having capacity of almost 30% of the generator capacity connects rotor to the grid. A wider range of speed control is possible through this configuration, which could typically reach -40% to +30%, depending on the size of frequency convertor. This configuration is more efficient and has better control over generator but convertor protection is another challenge of this configuration.

The fourth configuration i.e. Type-4 utilizes the Full Scale Frequency Convertor (FSFC) along with different generator types such as PMSG or synchronous generator or even induction generator. Most of the FSFC type wind units have gearboxes but in some cases wind units may not have gearbox, utilizing a directly driven multi-pole generator.

3.2 Power System Modelling

Previous section discussed various types of Wind Turbine Generators (WTGs). To assess response from each WTG it is essential to understand the dynamic performance of each configuration. Assessment of the response is only possible through dynamic modelling of these types in robust simulation platform. There are two types of analyses generally, static and dynamic analysis, as discussed in detail below.

Static simulations are used to determine power flow and short-circuit power contributions under certain contingencies to ascertain steady state security. They are also useful for assessing the impacts of different network conditions and generation/ load scenarios. Through static analysis, short-circuit level at a number of buses and the power system is calculated for different system conditions and generation dispatch scenarios. Static analysis is not included as part of the scope of this thesis.

Dynamic studies are carried out for analysing the response and voltage/current/frequency/power profile during or following any power system event such as disturbance, fault etc. The list of contingencies is applied on the network models and dynamic responses are measured and recorded. These studies determine system response during/post fault, voltage and power recovery characteristics of the system. For LVRT studies all busbars are considered and analysed for all possible case studies identified for this process as mentioned earlier. This section will briefly review WTG modelling for dynamic analysis.

3.2.1 WTG Dynamic Models

To accurately model the dynamic behaviour of a WTG, following listed components are needed to be modelled precisely. They are also shown in Figure 3.2 below.

- Aerodynamics of wind turbine
- Mechanical controls of wind turbine
- Connecting shaft dynamics
- Electrical generator characteristics

- Electrical/ Electronic controls
- Protection settings
- Measurements

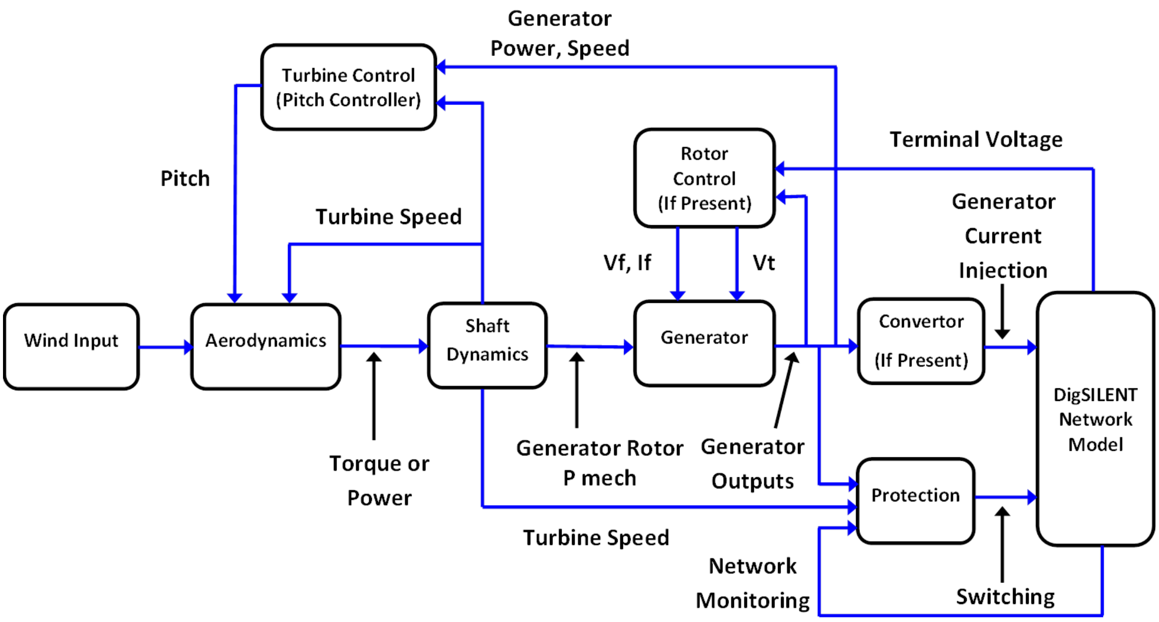


Figure 3.2: General structure of a wind generator model

The model arrangement and components such as aerodynamics, various control systems and protection devices for various WTGs shown in Figure 3.2 would fundamentally be comparable. However, the parameters may vary from one manufacturer to the other. For the transient simulations such as, stability, ride-through and fault related dynamic studies; the wind variations are not related, thus, for such simulations wind speed is assumed constant and most of the complexities related to aerodynamics could easily be ignored. Normally, during wind variations the wind blade impact span has the duration of minutes or hours, while these simulations are only carried out for 10-15 seconds maximum, making this assumption fairly reasonable. Some studies like forecasting and output studies or estimations one requires accurate wind models, making mechanical and electrical models of secondary importance.

For some of the older turbine generator technologies, to carry out system level studies, the shaft dynamics are usually modelled as a two-mass system. Generator fluctuations due to wind disturbance or fluctuations are directly translated into voltage or frequency fluctuations towards grid. These variations are of critical importance in case of weak grid situation near wind turbine and their dynamic studies. These variations are of least importance in case of a Type-4 WTG technology due to back-to-back frequency convertor de-coupling. Thus, these disturbances in the WTG speed may not be ideally seen on the system, as the grid-side converter could appropriately control and manage the grid side voltage and frequency deviations.

However, the protection devices and their controls are specific to WTG technology and manufacturer; for instance crowbar protection of Type-3 (DFIG) WTG and AGO (Advanced Grid Operation) control for Vestas manufactured Type-3 WTG.

3.2.2 Simulations in DIgSILENT® Power Factory

With the increased level of penetration of renewables and specifically wind energy into grid, simulation platforms provide some of the essential types of WTG models built in the examples and standard library types. Similarly, the DIgSILENT® PowerFactory also has similar integrated transient and dynamic models [70]. It is of extreme importance to classify model types based on study. All the discussed aspects hold valid for other power system component such as generators, FACTs devices, lines and etc.

Generally, two types of network models are used for power system simulations as given below;

1. Steady-state network model: Such models utilize complex algebraic equations for modelling network inductances and capacitances. This is referred as RMS Simulations in DIgSILENT® PowerFactory.

2. Transient network model: Such models utilize differential equations for network inductances and capacitances and/or utilize travelling wave equations for transmission lines. This is referred as EMT Simulations in DIgSILENT® PowerFactory.

Steady state models are used for planning and upgrade purpose to determine simple load flows, short-circuit levels and also utilized for simulating stability phenomena in power systems [71]. They may also be used for simple security and forecasting studies for WTG integration.

However, for cases like fault dynamics and voltage profile studies a detailed and precise approach is needed, where each component characteristics and dynamics are important for system level impacts; transient network models must be used. DIgSILENT® PowerFactory has the capability to carry out both type of studies on a single platform and is well suited for this research.

3.3 Technical Challenges in Model Development

3.3.1 Unavailability of Standardised Literature

Rapid advancements in wind technology in recent years, pose added challenges to conduct research on large scale wind integration issues. Being a new area of research, sufficient public literature is not available for some of the modern wind turbines and generators. One of the main reasons for unavailability of literature is the commercial sensitivity of the information.

3.3.2 Unavailability of Standardised Model

Apart from literature, standardization of mechanical model type of the wind farm is also a challenge. Most WTG manufacturers are reluctant to reveal the full details of their wind technology due to commercial aspects. For the fact, WTG models are not standardized amongst manufacturers for various platforms of simulations. Different simulation packages use different model types and it is a challenge to compare results from different packages. This brings more confusions and uncertainties in dealing with simulation and validation results. Apart from mechanical model type, unsymmetrical fault model are also unavailable for most of the WTG types. Most of the system faults are unbalanced in nature but some of the newer wind technologies have not been modelled for unbalanced dynamic studies. It is still awaited to get unbalanced models from turbine manufacturers to validate generator models using real fault data of system which is normally unbalanced in nature. The models can be validated and tested against various dynamic studies if recorded data can be made available from wind generators. It is a challenging task to get data from all major wind generator manufacturers to carry out such system level studies. Usually, the model provided by the manufacturer to the System or Grid Operator is in form of a "black-box". The transmission system operator normally does not know the details of the model and remains unsure about the performance of the model for various types of studies. Multiple simulation tools provide generic models for older wind generators; however, the newer WTG models are still awaited. To have full confidence on the accuracy of the studies model standardization is extremely important. In current scenario, identification of "black-box" fault response to develop an unsymmetrical fault model has been included as scope of this thesis.

3.3.3 Model Implementation Challenges

3.3.3.1 Numerical Integration Time-step

The uniformity of the integration time-step of newly integrated wind model with existing power system model is also a bigger challenge. There has to be a very fine balance between compatibility of the integration time step with existing model and degradation of the performance of the same model for various studies. To avoid such situations, in many countries' Grid Codes require specific numerical integration time-step for WTG models [72, 73]. In reality, various simulation platforms do not offer much higher time-step as expected or specified in Grid Codes [73]. Such situations may result in numerical or simulation errors particularly when WTG models require very small time-step for integration into large power system network models. The time-step size is generally, estimated based on the complexity of the network/section being investigated in order to reduce simulation times. This brings out a new challenge of reducing the complexity of the wind turbine without compromising on the performance of the model for particular study type. This has to be taken into account from utility perspective for simulating a smaller portion of the network involving WTG integration.

3.3.3.2 Initialization

Initializing wind turbine models is a critical stage. Models must be properly initialized to perform correctly for specified assessment or investigation type. It has been observed that in many dynamic models inappropriate responses are the result of incorrect initialization [73]. These inappropriate responses may include unexpected simulation behaviours and outcomes at the beginning of the simulation. It has also been observed that some of the models do not converge if not initialized for more than 50% of their rated capacities due to lack of considerations at model development stage.

Now, it is very clear that initialization is an important stage in transient simulations. A commonly followed power system dynamic simulation procedure is illustrated in Figure 3.3. From illustration, it can be seen that initialization is achieved at the start of a transient simulation in order to ensure that the dynamic system is at a particular steady-state operating point [74]. Thus, in order to avoid convergence issue and achieve correct dynamic responses, initialization must be well taken care of.

3.3.3.3 Validation

Validation of dynamic models is another very important phase. To be confident about dynamic responses, model validation is crucial. Although manufacturers validate their models before supplying to Wind Farm Owners, consultants or even System Operator, but authenticity of those validation studies are still doubted due to unavailability of the model details. System Operators may have lesser confidence around model validation during integration studies over unexpected responses. Further work is required on various simulation platforms to provide validated generic models for specified study types such as protection and fault response studies.

Wind turbine electrical and mechanical measurements are required for validation process. These measurements may be collected in a number of ways and at various resolutions. Studies like protection performance and fault response may require high resolution measurements, which make this validation process even more difficult. There are three approaches (Staged generator testing, staged full-scale turbine testing, opportunistic wind farm testing) briefly discussed in references [73, 75].

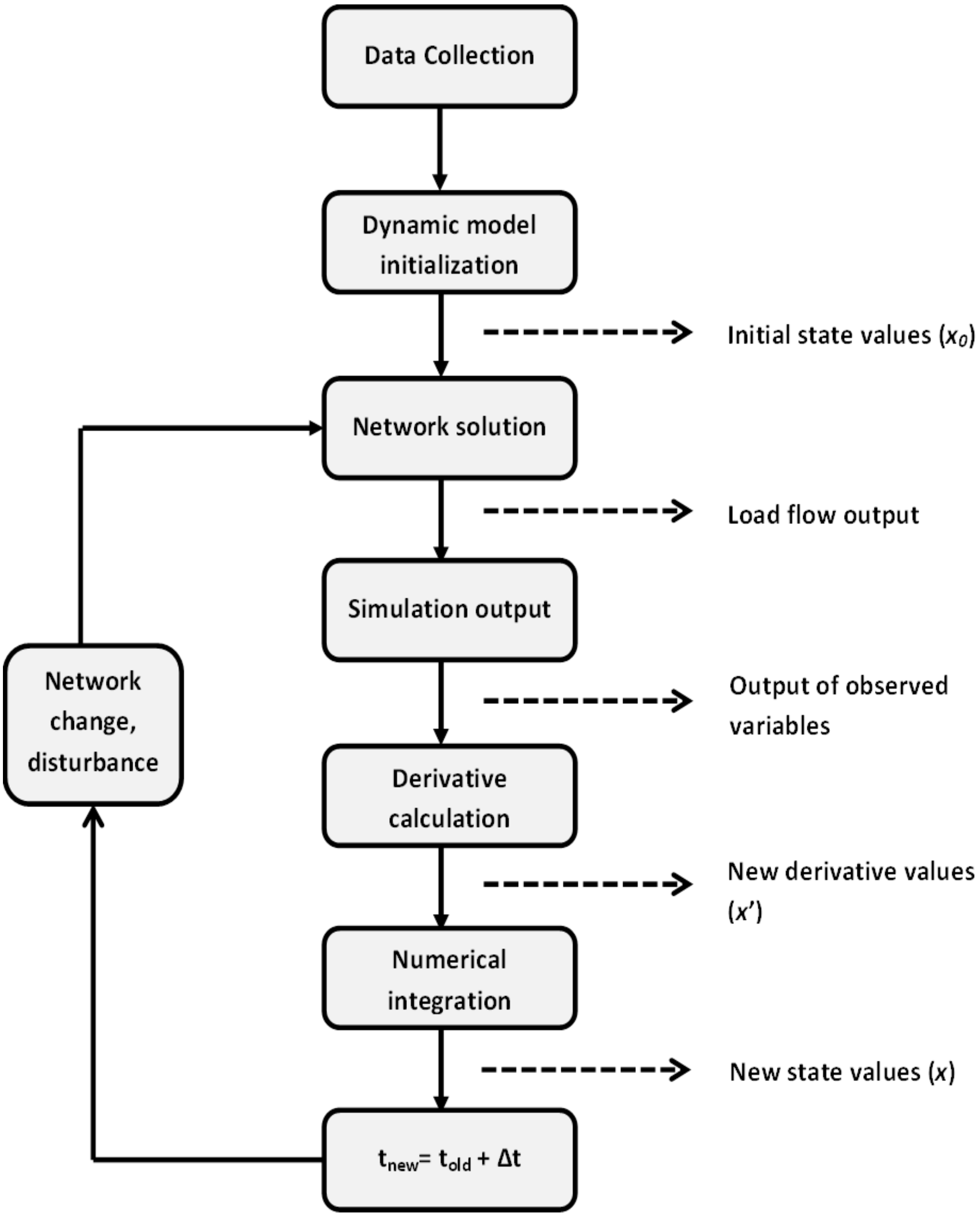


Figure 3.3: Dynamic simulation flow

The first type of testing i.e. staged generator testing is only for generator, power converter and controls. The turbine blade structure and characteristics are not required at the test facility, making this testing feasible. During severe transient events, the response of the power/frequency converters and their controllers could be sufficiently demonstrated. However, unavailability of the full representation of drive-train and turbine blade components does not allow the model to capture the dynamic behaviour of these components for a stability study.

Staged full-scale turbine testing requires a full-scale turbine installed at the facility. These turbines are exposed to electrical disturbances for model validation purposes.

Factors such as full scale wind turbine installation and the size of the facility, it make this type of validation study very expensive. However, such studies are mostly carried out to seek compliance with multiple Grid Codes for modern wind turbines.

The opportunistic testing is relatively economic but difficult to achieve as it is carried out by commissioning measurement units on an existing wind farm site to record naturally occurring power system events. Those measurements are then used for model validation for specified wind turbine type.

3.4 Detailed Model VS Aggregated Models

Electricity generation through wind is increasing as the wind generation technology is advancing. This number has even reached to 20% of the total generation levels in some countries. Large wind farms are connected at transmission or sub-transmission levels or high voltage levels. In context of large wind farms, low level details or each unit mostly become insignificant due to least impact on system. Thus, to make modelling and analysis task easier, aggregated models play an important role. It has also been found that modelling does not need to be very well detailed for certain assessment [76]. For the Transmission System Operator aggregated models are equally effective as detailed models due to type of studies and analysis they perform through these models. Much research is required in area of detailed modelling or even aggregated models to represent wind farms accurately, for studies such as ride-through or fault analysis aggregated models may be used with a higher confidence level. However, unbalanced or unsymmetrical models needed to be developed by manufacturers for utility companies to address the fact that most of the system level fault or events are unbalanced in nature.

For this research, aggregated models have been utilized to perform all analysis presented here. All the relevant modelling aspects have been briefly discussed in this chapter.

3.5 Wind Generators Modelling Experience

Dynamic models are needed to carry out dynamic system studies; new advanced models are available to model the effect of various types of electrical systems used in wind turbines. For this purpose wind turbine models have been developed for most of the available wind turbine types i.e. fixed speed and variable speed [77-91]. International Energy Agency (IEA) has also carried out research on dynamic modelling of wind turbines [92]. Various platforms are available to carry out analysis for developed wind turbines and models using different mathematical approach [93-96]. For each specific wind technology and analysis requirements correct models representing true controls need to be used for analysis. For instance, synchronous generator models are discussed in [83, 90], and doubly-fed induction generator (DFIG) models are presented in [80, 81, 85, 87, 88, 97].

3.6 Summary

This chapter summarizes the modelling aspects of wind generators. The generic models for various wind generation technologies have been discussed. Power system modelling is discussed using DIgSILENT® PowerFactory practices. The simulation methodology of this specialized simulation tool is also detailed with clear diagrams and steps. Important aspects and challenges of simulation are highlighted such as choice of time-step, initialization and validation steps. A brief comparison of detailed and aggregated model is also provided. Towards the end, some of the wind generation modelling experiences are briefly analysed.

Chapter 4: Fault Analysis

Following robust modelling of WTG, robust short-circuit (fault) calculations are very important. For this research work, the simulation software 'DIgSILENT® PowerFactory' has been utilized for all the modelling and analysis purposes. Power Factory is able to simulate individual faults or a number of faults of most complexities. Short-circuit (fault) calculations are used for various objectives and DIgSILENT® PowerFactory supports most of those methods for evaluation of short-circuit currents.

During planning stage, the planner is interested in identifying the ratings of network equipment though knowing expected maximum currents, for designing the ratings, and minimum currents to design the protection schemes. These calculations performed at planning stage do not require detailed network modelling (i.e. load information is not required) and applied to extreme case situational analysis. These methods include the ANSI method and IEC 60909/VDE 0102 method. Another purpose is to identify precise estimation of fault current. This is needed to investigate malfunctioning caused by relay or improper configuration. Such methods are called exact methods or 'complete' methods and they estimate based on specific operating point (Operation Stage).

This chapter gives an overview of the short-circuit calculation methods as implemented in DIgSILENT® PowerFactory and its 'Complete Method' is covered in detail as it has been utilized for simulations carried out in this work. Further technical background is presented in Section 4.1.

4.1 Technical Background

Short-circuit analyses are most commonly used calculation functions besides load-flow analyses when analysing power system networks. They are effective for both planning and operation stages. They are used in system planning and system operations. All the methods and their derived quantities are illustrated in Figure 4.1. Method 2.1 and 2.2 included in operational stages are also used for network planning in special cases. Calculations quantities used in DIgSILENT® PowerFactory are presented in Figure 4.1, while a graphical representation of the short-circuit current time function is illustrated in Figure 4.2.

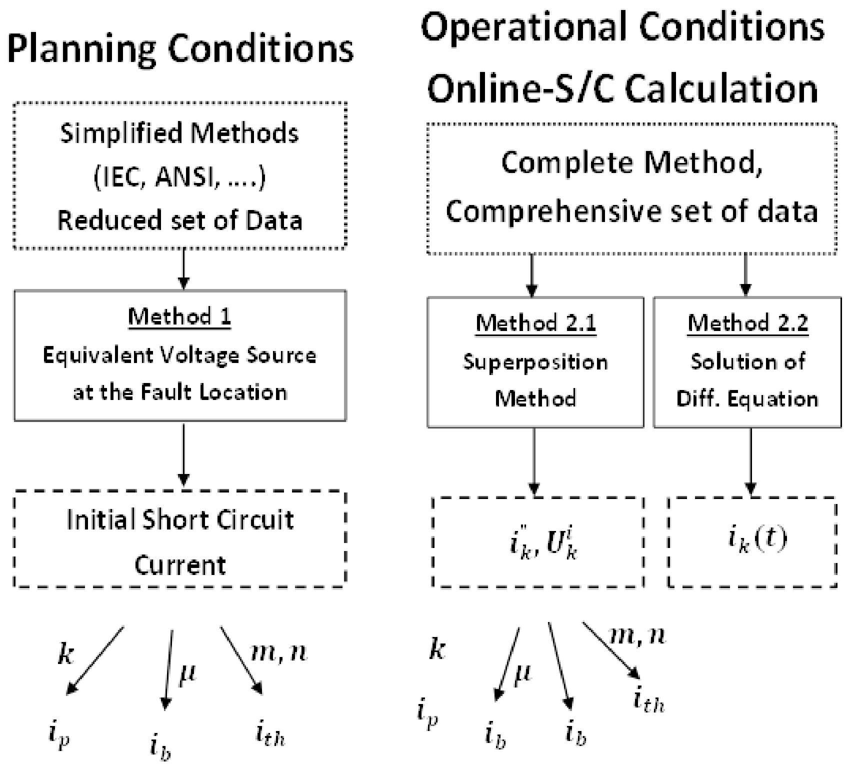


Figure 4.1: Areas of Application of Short-Circuit Calculations

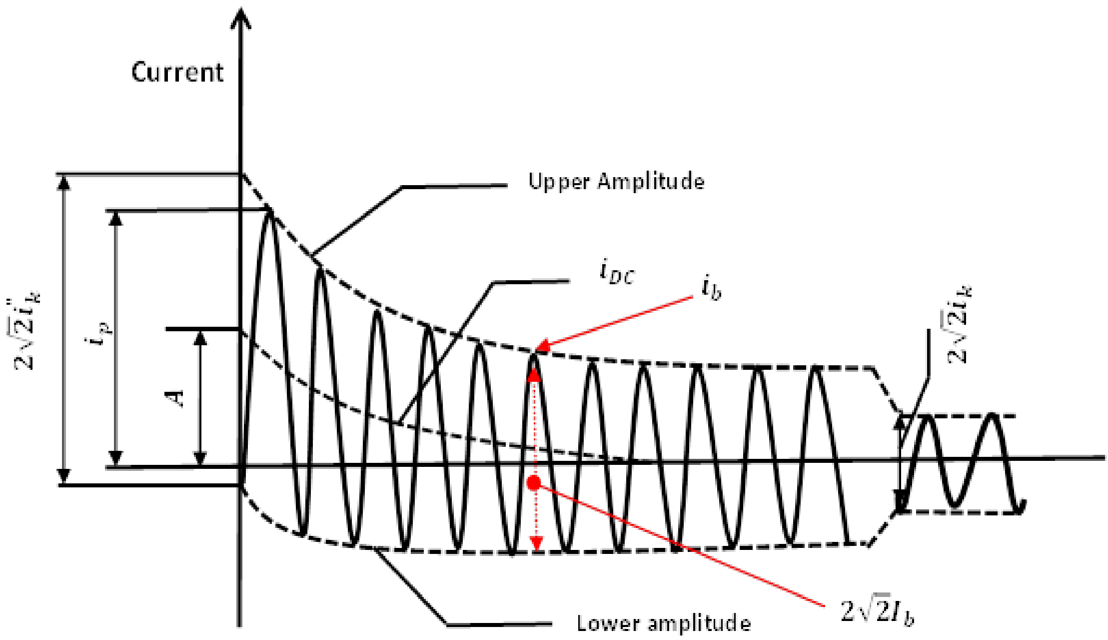


Figure 4.2: Short-Circuit Current Time Function

System planning short-circuits examples include:

- System strengthening or expansion impacts on equipment defined short-circuit capacity.
- Protection co-ordination i.e. multiple relays, fuses etc.
- Designing grounding system
- Load point fault level capacities verifications.
- Cables and transmission lines admissible thermal limits verification.

System operations short-circuit examples include:

- System reconfiguration impacts on short-circuit limits of equipment.
- Fuse sizing and relay setting determination.
- Fault location calculation for relays storing fault disturbance recorded data.
- System faults analysis, e.g. malfunctions of protection devices.
- Mutual interference analysis of parallel lines in case of system faults.

The basic difference between calculation assumptions amongst methods is that for system planning studies the system operating conditions are not yet available, thus, requiring estimations. Therefore, the method using equivalent voltage source at the fault location has become commonly accepted in Western Europe according to IEC 909 (VDE 0102). In July 2001, a revised version was published as IEC 60909.

Once the system operation conditions are known then for short-circuit calculations the superposition method can be used for the sake of accuracy. This method is also known as complete method as mentioned earlier. This method calculates short-circuit currents based on the existing network operating condition in the network. In certain cases, this method could become more extensive and time intensive.

4.1.1 The Complete Method

The superposition method, also known as the complete method, is particularly preferred for accuracy of the short-circuit estimations. For this method, the load flow conditions are predetermined for overlaying before short-circuit introduction with a situation where all voltage sources are connected to ground and the negative operating voltage is connected at the fault location. The procedure is illustrated in Figure 4.3.

Figure 4.3a represents the system at the operating condition of the system before short-circuit initiation. This state of the system represents generators' excitation conditions; regulated transformers' tap positions and the breaker status imitating the operational changes during a fault.

Using these pre-fault conditions the pre-fault voltage of the faulted busbar is estimated. For the pure fault condition the system state is calculated for the situation where all voltage sources are connected to ground and the negative operating voltage is connected at the fault location as shown in Figure 4.3b.

Assuming linear network impedances, the system condition after fault introduction is determined by complex addition of both the pre-fault and pure fault conditions as shown in Figure 4.3c.

All the quantities described below are already shown in Figure 4.4:

- In this method, a more accurate Peak Short-Circuit Current i.e. i_p is calculated based on the accurate sub-transient short-circuit current estimation (calculated using the superposition or complete method) and the R/X ratio (based on the IEC 60909 standard);

- The Short-Circuit Breaking Current I_b (RMS value) is estimated/calculated based on the sub-transient short-circuit current and the transient short-circuit current (both are calculated by the superposition or complete method);

- The Peak Short-Circuit Breaking Current i_b is calculated from the RMS short-circuit breaking current Ib and the decaying DC component;

- The Thermal Equivalent Short-Circuit Current I_{th} is calculated based on the IEC standard, using the **m** and **n** factors (Figure 4.1). The n-factor calculation uses the transient current instead of the steady-state current;

- Further, the loads may have a contribution to the short-circuit current, which are defined in the load element.

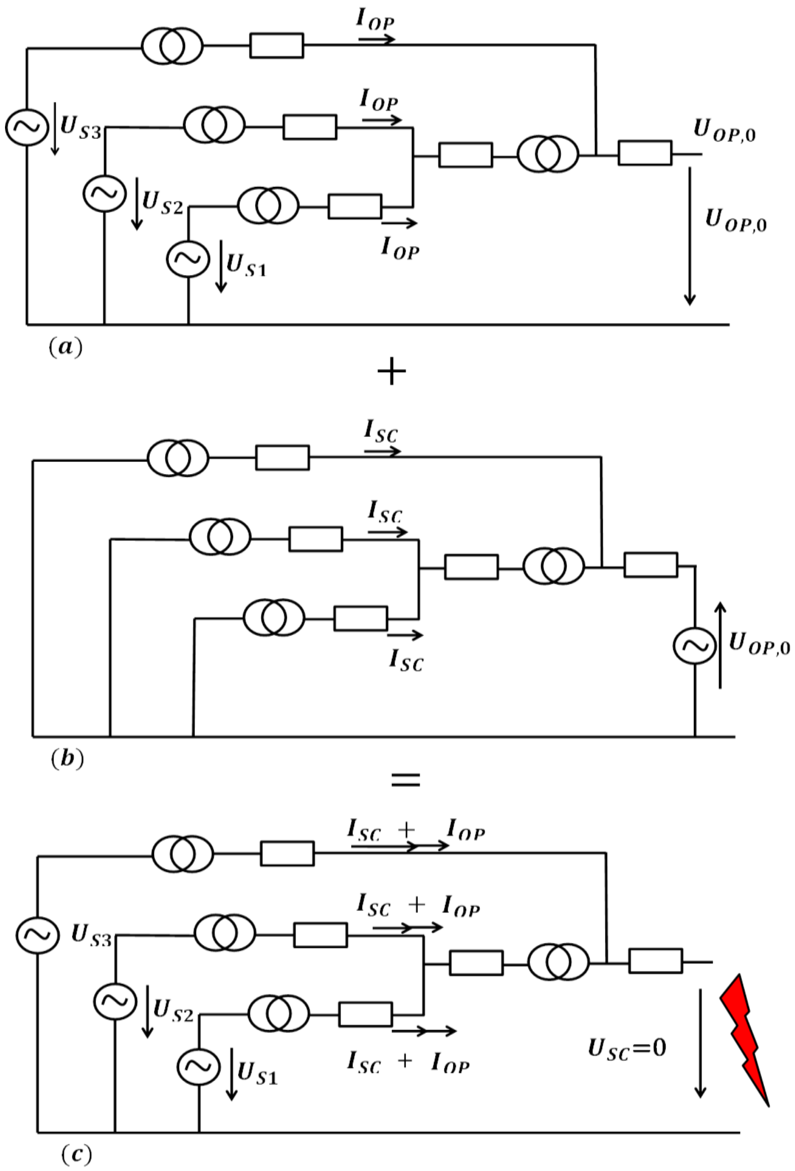


Figure 4.3: Illustration of the Complete Method

4.2 Fault Type

The following fault types are available:

- 3-Phase Short-Circuit
- 3-Phase to Neutral
- 3-Phase Neutral to Ground
- 3-Phase Short-Circuit (unbalanced)
- 2-Phase Short-Circuit
- 2-Phase to Neutral
- 2-Phase Neutral to Ground
- 2-Phase to Ground
- 1- Phase to Ground
- 1-Phase to Neutral
- 1-Phase Neutral to Ground

The above fault types are all potential faults in category of symmetrical and unsymmetrical fault categories. Not all faults have been considered during the course of this research. For the case studies utilized in Chapter 5, and Chapter 6 symmetrical faults or three phase fault have been focused for worst possible scenarios. However, for Chapter 7, Three-Phase Short-Circuit, Two-Phase short-circuits and Single Phase to Ground faults have been considered.

4.3 Fault Impedance

The sum of fault resistance and reactance is called fault impedance i.e. impedance of short-circuit path or even impedance of the arc. They can be defined in detail using the enhanced models where R_f and X_f represent the resistance and reactance of the fault respectively, and L-L and L-E represents the line to line or line to earth state of the resistance or reactance. If the Enhanced Fault Impedance option is not enabled, fault impedances are defined by their equivalent values, R_f and X_f.

Figures 4.5 to 4.7 illustrate the dissimilarities between the enhanced and the simplified forms of fault impedances for the 3-phase short-circuits; 2-phase faults to ground; and 2-phase faults.

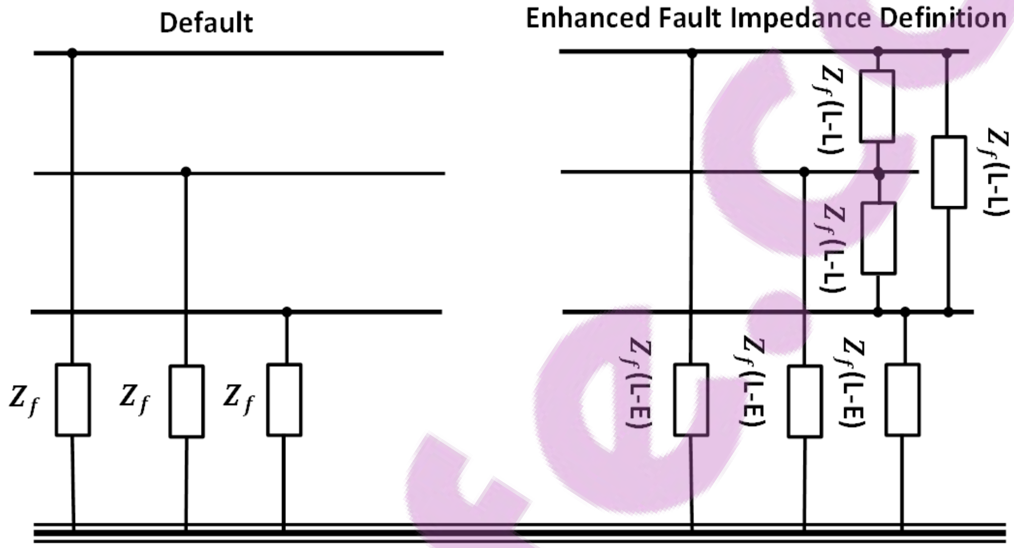


Figure 4.4: Fault Impedance Definition: 3-Phase Short-Circuit

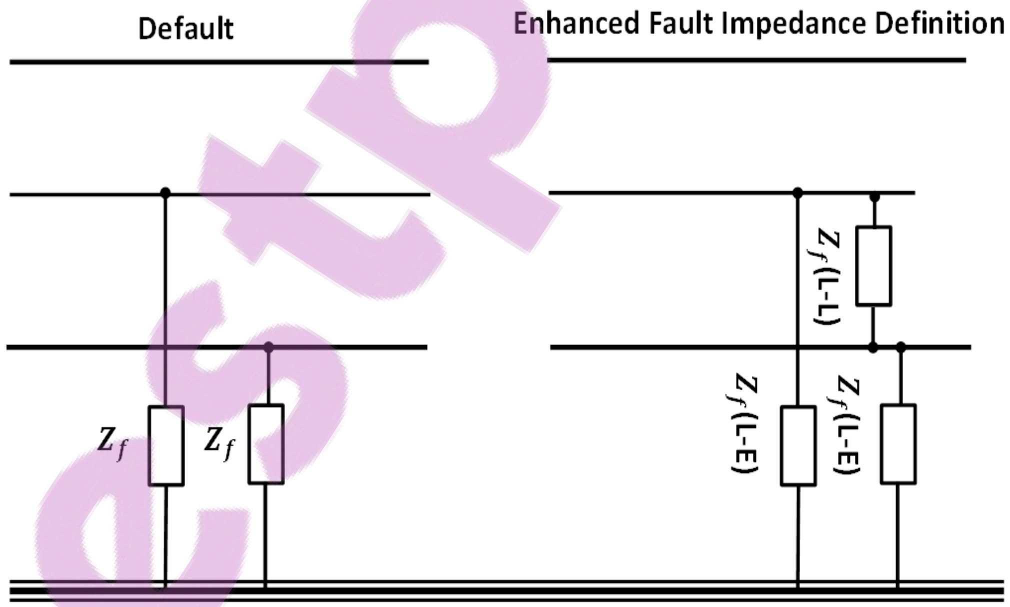


Figure 4.5: Fault Impedance Definition: 2-Phase to Ground Fault

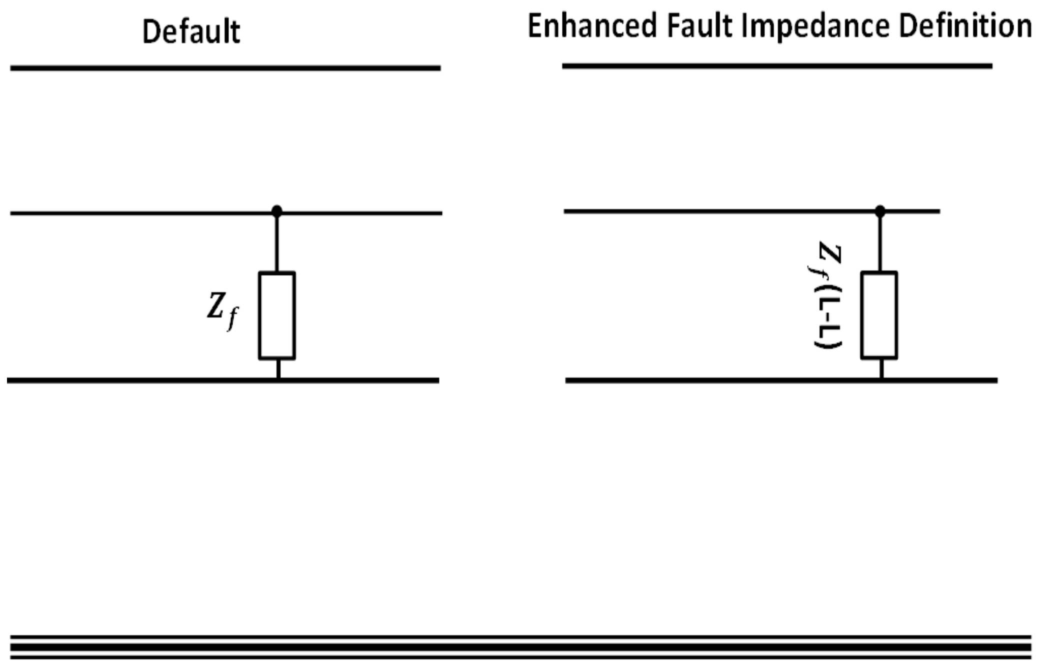


Figure 4.6: Fault Impedance Definition: 2-Phase Fault

4.4 Summary

This chapter provides background about short-circuit analyses and methods commonly used in practice. The types of faults are identified which are common in power system networks. Fault impedance types and their definitions are also explained. The main purpose of this short chapter is to provide a quick revision for the short-circuit analysis and explain the method adopted for simulations and scenarios developed for this research.

Chapter 5: Fault Ride-through Assessment

Increased wind generation and its integration on transmission system dictate the development of stricter grid code requirements to maintain the security of supply. Large wind generation connected to transmission system raises many concerns for not being able to support the system during disturbances. The response of a large wind farm during a voltage disturbance can possibly affect system stability as discussed in [10-13]. One of the major requirements is Fault Ride-Through (FRT) requirement. FRT is subdivided into Low Voltage Ride-Through (LVRT) or High Voltage Ride-Through (HVRT). LVRT capability means that generators should be able to remain connected during any fault event. In some countries, grid codes require all new installed wind turbines to have FRT or LVRT capability [15-17]. Most Conventional generators are normally capable enough to meet these requirements while wind generators vary in capability depending on the technology used. Wind generator capabilities and different techniques used to satisfy LVRT criteria are also discussed in next few paragraphs. A typical LVRT criteria or voltage duration profile is shown as in Figure 5.1.

All generators are required to stay connected to satisfy the system security. They may disconnect if the voltage enters into the region below the line. These voltage profile or LVRT requirements are part of grid code or grid connection guidelines established by transmission system operator. Based on the grid code requirements manufacturers have designed various solutions for different wind generator such as Fixed Speed Induction Generator (FSIG), Doubly Fed Induction Generator (DFIG) and Full Convertor Synchronous Generator (FCSG) in order to meet ride through requirements.

In [33-35] reactive power injection during the fault to support and improve voltage ride through capability has been discussed. A comparison of performance of uncompensated large scale wind farm having FSIG units have been provided with wind farm having similar units with Static VAR Compensation (SVC) and wind farm having DFIGs in [34]. Reactive power support is apparently the only technique for FSIG to ride through the fault at the Point of Common Coupling (PCC). However, various techniques using convertors and controllers are available for DFIGs.

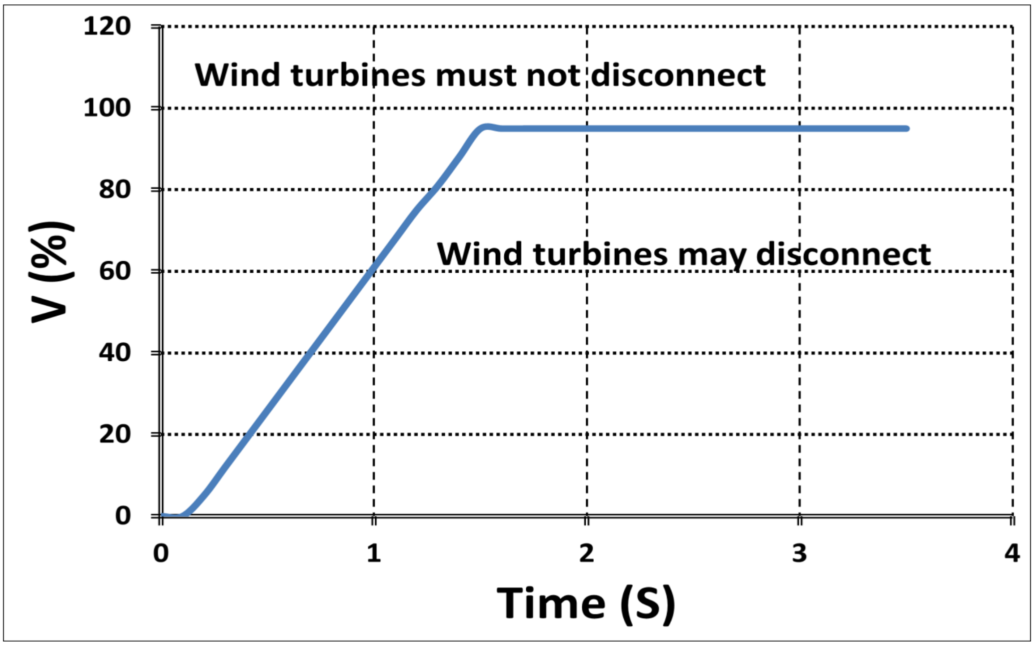


Figure 5.1: Typical limit curve for LVRT requirements

A controller technique applied to grid-side converter to keep DFIG connected to the system during the fault is presented in [36]. Series-connected voltage sources converter has been proposed for enhancing the FRT capability in [37].Crowbar resistor which is a bypass resistor-set connected to rotor terminal is also proposed as technique to improve FRT capability for DFIG in publications [38-42]. Crowbar improves the FRT capability along with protecting the rotor from damage but it converts a DFIG into a conventional induction generator thus degrading the DFIG performance [43, 44]. However, in [42] it is suggested that DFIG performance can be improved if appropriate value of crowbar resistor is selected. [45] proposes that both grid-side and rotor-side converter inject reactive power to the grid during the fault along with improved timing algorithms for crowbar resistor, thus improving the FRT capability even more.

FCSG has a totally different arrangement than above two technologies. FCSG is a relatively new practice for large wind farms connecting into transmission system. It has been found to have better FRT capability and grid support during the fault.

Sufficient documents and grid codes have been found stating LVRT criteria for various countries [9]. However, no significant literature could be found discussing FRT development from a transmission network's perspective.

5.1 FRT Criteria Development for New Zealand

The increasing amount of wind generation that is proposed for connection to the New Zealand transmission system has prompted the need for tougher grid code requirements for generators to maintain the security of supply. The technological variations in wind generator technology available for large scale wind farms raise concerns around their ability to support the grid during system events. Most conventional synchronous generators in New Zealand have the capability to meet these requirements while wind generators vary in capability depending on the Wind Turbine Generator (WTG) technology employed. Section 5.2.2 discusses WTGs types and their capabilities and different techniques used to satisfy FRT criteria. A typical FRT (LVRT + HVRT) criterion or voltage duration profile is shown in Figure 5.2.

Sufficient documentation and grid codes has been researched which cites FRT criteria for various countries [9]. However, no significant publication has been found discussing FRT criteria development in detail from a network's perspective.

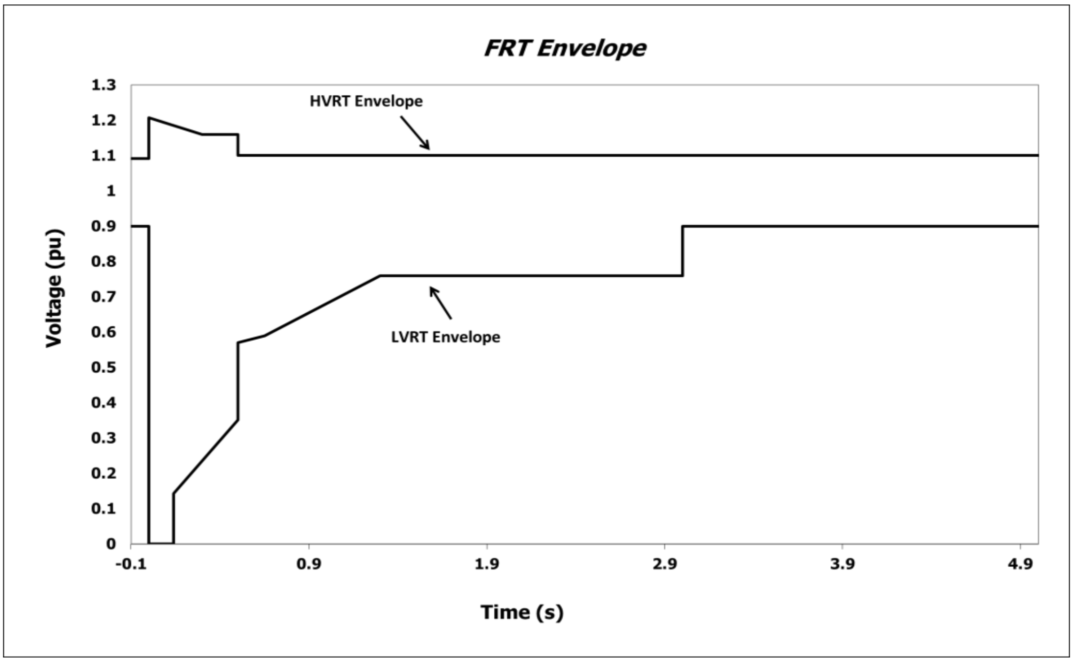


Figure 5.2: FRT requirements (LVRT + HVRT)

At present wind farms have a total installed capacity of 5% in New Zealand. An increase in this percentage is expected as there are on-going projects yet to be commissioned [60]. There are about fifteen small and large wind farms operating in New Zealand. These include turbines of various manufacturers and sizes with a total operating capacity of over 600 MW. Five of these are connected at high voltage or medium voltage levels. Security of supply is a concern when large wind farms are connected at the high voltage transmission level with little or no demographic separation, thus requiring stricter grid code requirements. The response of conventional generators or plants are well known but wind farms having different technologies may differ in responses and may affect the Transmission System Operator’s ability to manage and operate the grid in a secure manner.

A variety of investigations have been carried out by the New Zealand Electricity Authority (EA) for large wind integration scenarios. These include the impacts on the market, transient stability, small signal stability, power quality, and dynamic response of wind farms during disturbances [48]. These studies have also been briefly discussed previously in Chapter 2. FRT capability is one of the major concerns of all types of generation, specifically large wind farms, in order to ensure security of supply in New Zealand. Wind generator technologies in New Zealand and their FRT capabilities are discussed in Section 5.2.2.

By definition, FRT requirements bind generators to operate between allowable voltage limits and stay connected to the grid within the same voltage envelope to maintain the security of supply. Normally, these FRT requirements become the part of grid code requirements established by the Transmission System Operator (TSO).

Grid operators define a ‘ride-through’ profile in order to avoid situations where generators are disconnected during grid faults. Some grid operators not only require participation from generators during the fault but also post-fault period towards voltage stabilization and system recovery [14].

In this chapter, the process for designing a FRT criterion is outlined from a TSO perspective. Next section discusses fundamental considerations followed by the methodology used for development of FRT criteria. It is followed by a section discussing assumptions for the FRT studies which have been taken into account for analysis and a New Zealand grid case study detailed in Section 5.4. This section also briefly discusses some of the large wind farms integrated in the New Zealand transmission system categorized by Wind Turbine Generator (WTG) Type. Following that, the processes of developing voltage envelopes for FRT criteria are given, and this proposed criterion is then compared with existing Transpower and international criteria. Finally, recommendations for future development and conclusions are presented.

It should be noted that the HVRT curve originally proposed is currently under review by the regulator and therefore the analysis for LVRT development only is given in the scope of the thesis.

5.2 Fundamental Considerations

5.2.1 System Characteristics

The first and foremost consideration towards developing a FRT criterion is to understand the characteristics of the transmission network. For instance if we consider the New Zealand Network then we have a two island network i.e. the North Island (NI) and South Island (SI) networks interconnected through a 2 pole HVDC link currently. The total network is comprised of 173 substations and over 1200 power transformers. The transfer capacity of the HVDC link is 1040 MW with two cables on pole-1. Another pole is under commission process to increase the transfer capacity between two islands. The transmission voltages in both networks are 220 and 110 kV, with some 66 kV transmissions in the SI. The generation sources are scattered through the NI that include hydro, thermal, combined cycle gas, co-generation, geothermal and wind. However, the SI is mostly hydro generation which serves as the base load and under normal system conditions energy is typically transferred from SI to NI via the HVDC link to meet the demand of major load centres in NI such as Auckland City.

Due to the isolated nature of the New Zealand power system it means that it prone to experiencing frequent voltage and frequency disturbances. To avoid cascade failure, it is critical that generation remains connected and the system may require a specific fault ride through criteria that differ from those specified in large well-interconnected continental power grids [61, 98]. There are few obligations towards generators side as per existing requirements in New Zealand. The requirements are as follows:

- Maintain a certain level of reactive power output under steady state conditions
- Plant must continuously operate in a manner to support voltage and frequency stability

FRT is part of the latter requirement to a generators capability for voltage and is a key factor in assisting the System Operator to manage the system to avoid black outs.

5.2.1.1 Fault Types

In order to make the criteria more robust, a history of network faults which may have direct impact on system stability is considered. Fault types vary from network to network but their classifications are universally accepted. Grid planning guidelines in New Zealand state that power system should remain stable for fault types such as loss of generation, three phase, single and double phase faults transmission faults [98].

The most common faults in power system are short-circuits. Three phase balanced short-circuit or a balanced three-phase to ground short-circuit are referred to as symmetrical faults. They cause highest fault currents but are less frequent power systems. Machine short-circuit ratings are designed based on balanced or symmetrical fault current calculations. The most common short-circuits in any system are unbalanced or unsymmetrical in nature. These can be single line to ground, double line to ground, or line to line faults. Unbalanced faults to ground are affected by fault resistance, soil resistivity, fault position, and grounding technique used: thus related issues also need to be considered while addressing unbalanced or unsymmetrical faults. Other types of faults may include the sudden loss of any generating unit or plant which causes severe voltage drops thus requiring other generation to support the system through frequency and power control. Apart from short-circuits such outages are also included in the possible list of contingencies.

5.2.1.2 Protection and Fault Clearance Times

Voltage envelopes are influenced by fault clearance times for any network or part of the network. Standard distance or differential protection schemes protect transmission lines. The transmission protection coordination with neighbouring sub-transmission circuits, bus bars and other DC/AC links plays a significant role. High voltage transmission line protection normally has very short clearance time in order to maintain system security and avoid catastrophic failure of the system. In New Zealand transmission level protection schemes target 120ms clearance times for critical parts of the grid to avoid blackouts. Without aided signal schemes some parts of the 110 kV transmission network are subject to prolonged clearance times. Protection philosophies and clearance times in practice have direct part in development of FRT criteria for any network. Protection performance assumed in the FRT studies is discussed in Section 5.3.5. Typically, In NZ power system 110 kV voltage, sub-transmission is aimed to achieve 10-12 cycles, while transmission protection scheme is targeted to achieve 5-7 clearance cycles.

Along with standard protection schemes some special protection schemes designed for specific contingencies may also be considered for FRT studies. These are generally either runbacks or overload schemes, and operate within the period of voltage recovery following a fault removal. These schemes only be active during specific grid conditions. In case of New Zealand FRT studies, there are a few special protection schemes but they have not been considered for this analysis.

5.2.1.3 Protection Issues

Longer clearance times may also be expected due to other protection issues within the system and need to be considered during FRT analysis. These issues are specific to networks and could be identified from history of fault events from available data. Some of these issues might be high resistance faults, weak in-feeds, weak back-feeds, system configuration changes, grounding issues, circuit breaker failure, loss of signalling for transmission protection, loss of reactive compensation etc. Not many of these issues have been identified for New Zealand; thus any additional issues have not been included in the analysis.

5.2.2 Technology

Modern wind farms employ different types of wind generators and these can be categorized into five main types. These types vary in inherent FRT capabilities. In the context of the case study for this work; New Zealand has five different wind generator technology based farms [60].

5.2.2.1 Type-1 and Type-2 (Fixed and Variable Speed Induction Generators)

Type-1 and Type-2 utilize conventional induction generators as shown in Figure 3.1a and 3.1b in Chapter 3. They are basically constant speed machines with the minor fluctuation of speed during change of load. Type-1 has a squirrel cage induction generator. However, wound rotor induction generators for Type-2 have some speed control through rotor winding access. In order to avoid an adverse impact on system performance and voltage, these generators use soft starters for grid connection. They absorb reactive power from the system to maintaining the rotating field in the air gap between rotor and stator winding. Naturally they do not have much ride-through capability for not supplying reactive power in case of a voltage event. Earlier designs of these types were connected to distribution scale without any binding to stay connected to the grid. Thus, the probability of disconnection for any fault in the vicinity was always high. In order to improve FRT capability turbine manufacturers offer FRT packages to comply with grid codes requirements. SVC or STATCOM support is used to improve FRT capability of these types. One of the very first grid connected wind farms in New Zealand was the Te Apiti (TAP) Wind Farm. The capacity of this wind farm is around 90 MW and all 55 turbines are Fixed Speed Induction Generators (FSIG) i.e. Type-1. Type-2 Wind technology is also available in New Zealand but not on significant scale.

5.2.2.2 Type-3 (Doubly-fed Induction Generator (DFIG))

One of the most widely used variable speed WTG is the Type-3. This WTG arrangement is shown in Figure 3.1c of Chapter 3. This is wound rotor machine, fed through a series back to back frequency converter at rotor side, having a rating of 30% of the maximum stator power rating. The total power is the arithmetic summation of powers from stator and rotor. The DFIG operates either in super-synchronous, synchronous or sub-synchronous modes. Power is injected from the rotor, through the converter, into the system when the DFIG operates at super-synchronous speed. The real power is absorbed through the converter from the system by the rotor when the DFIG operates at sub-synchronous speeds. There is no power exchange through rotor at synchronous speed as voltage at the rotor is essentially dc.

Reactive power is supplied to the system through d-axis excitation control on rotor in most cases. The convertor could also be used as STATCOM for dynamic reactive compensation even when the turbine generator is not operational. In earlier designs the Type-3 has been more sensitive to disturbances and would disconnect from the network in a much shorter duration than conventional generators. The safety of DC convertors was the main cause. Now DFIG machines employ more controls than FSIG.

The first proposed solution for the above mentioned issue is known as crowbar protection. This technique short-circuit's the rotor side converter with or without additional resistance and leaves the DFIG as standard induction generator during the disturbance or fault and brings the convertor back after pre-defined time period. This technique is not acceptable anymore in some countries like Germany. Thus turbine manufacturers are coming up with more advanced controls to protect the rotor and provide P and Q control at the same time. One of the techniques is called advanced grid option (AGO) by the Vestas Ltd. This is an additional control which is only activated in case of a ride-through requirement. The details about crowbar and AGO2 are discussed further in Chapter 2.

Most of the wind farms commissioned in New Zealand after 2004 employ Doubly Fed Technology. The Tararua-3 was commissioned in 2005 has the capacity of 93 MW. This is wound rotor machine which is fed through a series voltage-source converter.

5.2.2.3 Type-4 (Full Scale Frequency Converters (FSFC))

In Type-4 the wind generator is decoupled through full back-to-back convertor. These could be conventional generators, dc field or permanent magnet generators. The generator spins at any available rotational speed through direct coupling to the turbine. The frequency may not be 50 Hz at the generator end but electrical power is converted through a back-to-back converter to the required grid frequency, thus giving generator a wide range of speeds because of full frequency convertors. The arrangements of Type-4 are shown in Figure 3.1d of Chapter 3. The grid side convertor has the ability to independently control real and reactive power to improve FRT capability, voltage regulation, and reactive power control of the electrical generator.

In New Zealand, the West-Wind farm was first connected in 2009 and employs the Type-4 WTG arrangement. This wind farm has a total capacity of around 140 MW. Another large wind farm, the Te Uku wind farm employs the same technology but this wind farm is connected at a sub-transmission level of 33 kV.

5.2.2.4 Type-5 (Synchronous Generator Technology)

The Te Rere Hau Wind Farm employs Type-5 WTG arrangement in New Zealand. Type-5 WTGs have locally been developed and commissioned by a local New Zealand company [99]. It is based on a gear box technology, converting the variable wind speed to a fixed shaft speed for synchronous generator as shown in Figure 5.3. The synchronous generator then generates the electricity at grid frequency. Currently, these turbines are smaller and are not widely used but give much better advantages during integration. FRT capability of this type is as good as conventional generators.

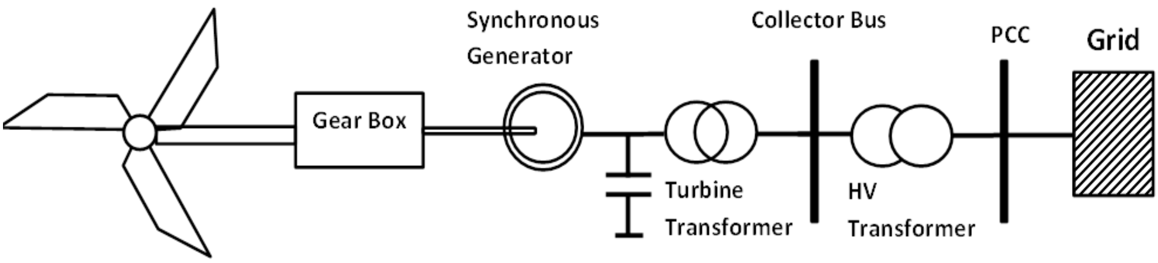


Figure 5.3: Type-5 Wind Turbine Generator

5.2.4 Frequency Ride-Through

Apart from voltage ride-through requirements, smaller grids like New Zealand and Ireland are also concerned about frequency ride-through of the modern wind farms. In New Zealand the North Island (NI) the lower frequency limit is 47 Hz and upper frequency limit is 52 Hz. However, In South Island (SI) Frequency limits are slightly extended due to presence of most of hydro plants in South Island and a positive flow of real power from SI to NI. The SI lower frequency is 45 Hz and upper limit is 55 Hz.

Normally, the modern wind farms have arbitrary frequency settings and design capability of 47 to 52 Hz. This configuration may suit the under frequency protection operation of wind farms in NI but their suitability in SI can be an issue[100].

5.2.5 International Practices

The consideration of existing criteria gives a better understanding towards development of new criteria. FRT criterion has already been established and is mandatory in many countries. International experiences have also been considered while developing criteria for the New Zealand system and have been used as a comparison in Section 5.4 as shown in Figure 5.4 [9].

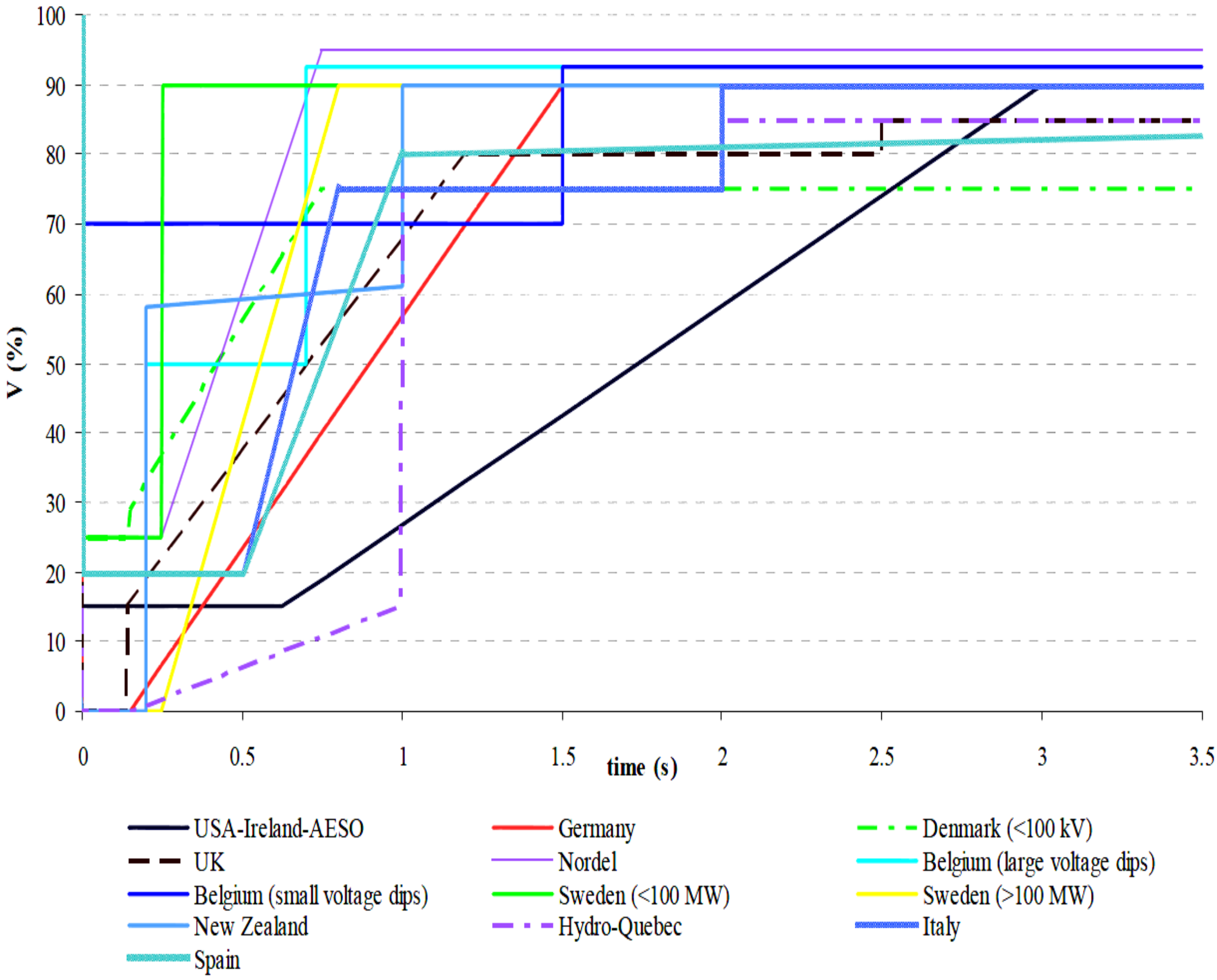


Figure 5.4: International FRT Criteria in Practice

5.3 Methodology & Assumptions

The proposed methodology towards development of ride-through envelope could be summarized as shown in the Figure 5.5.

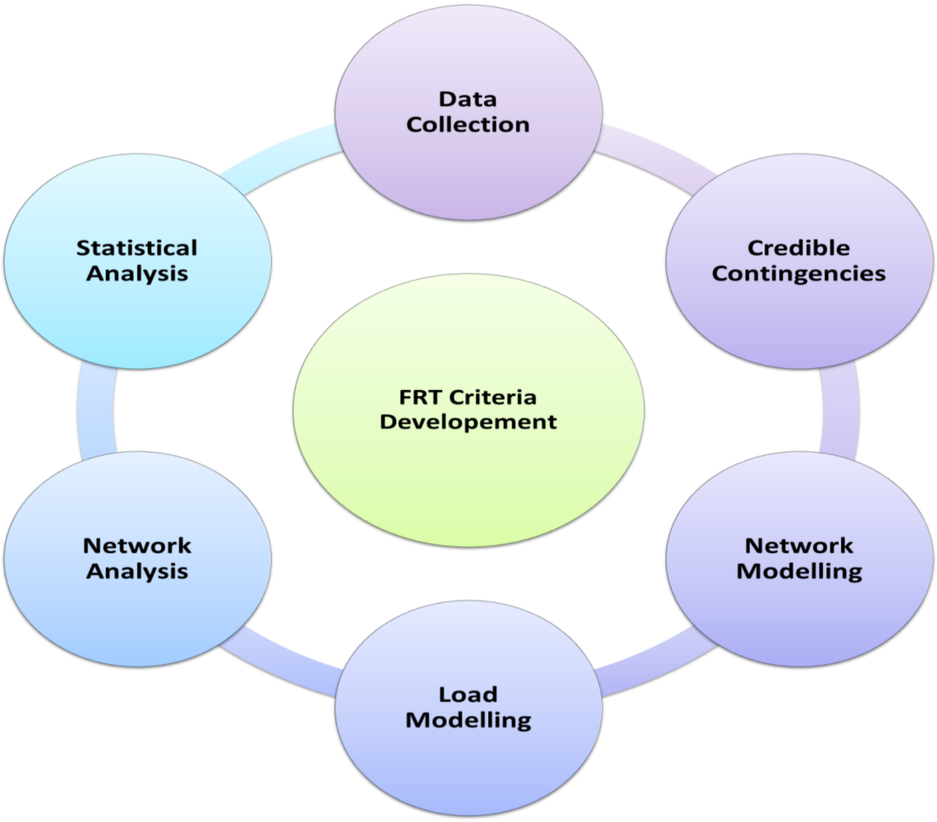


Figure 5.5: Proposed Methodology for FRT Criteria Development

The above illustration shows the six steps towards developing a FRT criterion. Data collection about the network, faults, protection schemes and other network related information is the first step towards the criteria. Based on the data available a full list of credible contingencies is formed. Normally, the network models are available with Transmission System Operator (TSO), if not then required validated models need to be developed. Electrical load could be static or dynamic in nature, thus basic load modelling assumptions are to be made as well. Static and Dynamic network analysis are carried out to determine, short-circuit strengths at different buses and also obtaining voltage profiles at various buses. Through statistical analysis of the weakest nodes the final voltage profile is achieved for most affected bus bars.

The purpose of this study is to formulate FRT requirements for all generation, wishing to connect to the New Zealand power system through dynamic studies. The outcome of this study is determination of FRT criteria for the New Zealand power system. This criterion is under process of approval and planned to be implemented into the transmission code to assist the SO in managing system security; it will provide a benchmark for manufacturer type testing and commissioning testing [61, 101].

Transpower has existing FRT requirements for the HVDC upgrade project and these and other international criteria are also considered and compared as part of this study as shown in Table 2.2 [61, 98, 101]. The existing HVDC design requirements of System Operator have been used as inputs into the development of a FRT standard for the transmission system.

The New Zealand transmission system is dispersed into its respective electrical regions. The assumptions discussed below from Section 5.3.1 to 5.3.5 are applied and bus voltages recorded to determine the worst case system response or performance to an N-1 scenario. Performance and existing criteria are then analysed towards development of suitable criteria.

5.3.1 Load Modelling Assumptions

For the New Zealand case study a composite load model has been assumed based on similar studies to determine reactive reserve requirements for the grid. For the dynamic studies aggregated load model at Grid Exist Point (GXP) has been assumed. [61, 101].

The aggregated load model includes dynamic load such as motor load, static load, and a distribution system model. The motor load model has three different protection groups (Group I, II and III). These groups are determined based on protection type and motor control each group has further subdivisions into groups based on motor sizes i.e. large and small [102]. A middle ground approach has been adopted for this study, where it is assumed that 25% of motor loads may trip under low voltage conditions and up to 50% for high voltage conditions. The distribution system is modelled as an 8 to 10% impedance transformer based on the forecasted summer or winter MW load respectively [61, 101].

The proportion of each load type at each GXP is derived through survey data for different regions in the system [102-104]. These load surveys were conducted for a peak winter and the extreme summer period.

5.3.2Additional Controllers

The study assumes that the transient period is well within the operating times for shunt connected reactive equipment and tap changer controllers This equipment is therefore assumed to be fixed at the pre-contingent state for the duration of the dynamic study. An exception to this are the HVDC filters that are controlled by the fast acting Reactive Power Controller (RPC) [61, 105].

5.3.3Load and Generation Scenarios

A basic assumption was made that all existing wind farms are unavailable. This assumption is based on the fact that existing wind farms may not remain connected for close in faults, with the exception of Type-4 wind farm in the North Island, where their unavailability is the worst case condition for the scenarios considered. The load and generation scenarios are based on historical data collected through SCADA. High seasonal loads are assumed for LVRT that corresponded with high HVDC north transfer with respect to the North Island studies, and low north or south transfer for the South Island and lower North Island regions. The lowest short-circuit capability is assumed through minimum number of machines available, due to the level of HVDC transfer offsetting the dispatch of synchronous generators. In order to reduce the amount of studies required, the seasonal peak loads are tested for worst case response for various system faults, i.e. high summer load with more motor load or higher overall winter load but with a higher static load percentage. The summer load condition was also a limiting factor. [61].

5.3.4 Credible Contingencies

Considering N-1(loss of a single power system element) contingency level, all the contingencies are chosen based on their impacts they have on a regional and sub-regional transmission level. Faults at the Low Voltage (LV) level are not modelled as these are considered an issue local to a single generating station only. The following credible contingencies have been considered [61]:

- Loss of single transmission circuit
- Loss of single generating unit
- Loss of a single dynamic reactive plant (SVC)
- Loss of an HVDC pole

The complete list of credible contingencies in North and South Islands are given in Appendix Table A-6 and Table A-7, respectively.

5.3.5 Protection Performance

Three-phases, zero impedance faults resulting in the loss of a single element are assumed for all studies. Clearance times assumed are actual operating times; if this information is unavailable then standard operating times are used. With protection signalling, the fault is cleared almost simultaneously at both ends of the circuit. Where signalling is unavailable, zone based protection timings are assumed for Zone-1 and Zone-2. For some of the HVRT contingencies, it is assumed that the equipment is disconnected from the system without any fault at the transmission level. The targeted protection clearance times of various level of protection in New Zealand transmission system as follows:

- Main protection for 220kV (Transmission) circuits : 120 ms (6 cycles)
- Main protection for 110kV (Transmission) circuits : 200 ms (10 cycles)
- Main protection for 66kV (Sub-Transmission) circuits : 200 ms (10 cycles)
- Circuit Breaker Failure Time : 350 ms (17.5 cycles)
- Auto-reclosing Time : 1.5 S (75 cycles)

5.3.5.1 Significance of Clearance time on Voltage-time Profile

In a voltage-time profile (LVRT), the magnitude of the voltage is determined by the system characteristic and network configuration. However, targeted protection clearance times are a simple guideline for achieving duration in voltage-time profile, and actual protection clearance times dictate the performance of those criteria during the fault. This ride-through study is a simple extension of investigation of protection performance of WTG system in large scale wind integration context. In order to achieve results closer to realistic network conditions; approximately similar protection clearance times have been used for the network under study as shown in Table 5.1.

5.4 Analyses & Results

5.4.1 Test Case Study

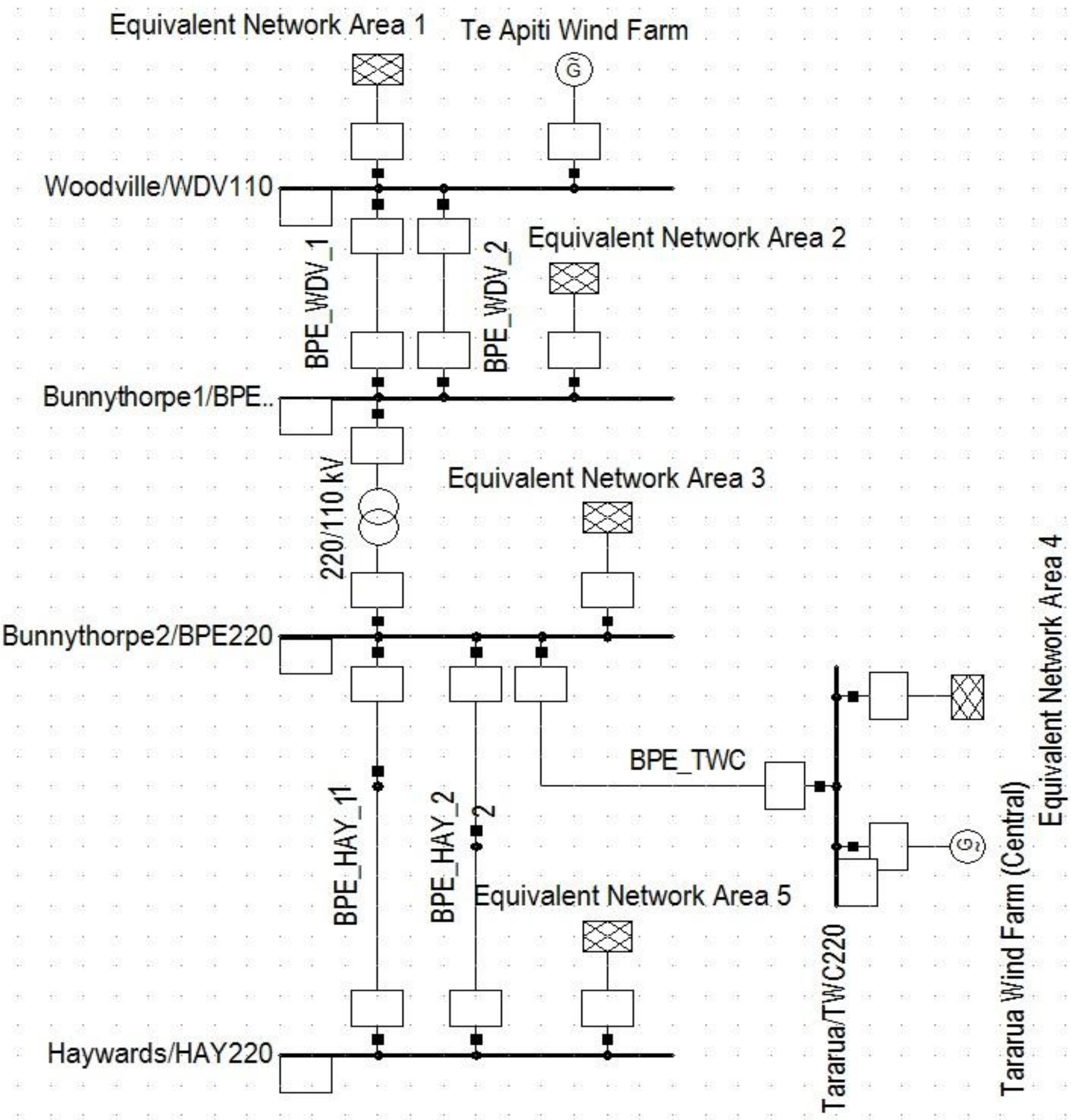


Figure 5.6: New Zealand Test Case Study

Based on the discussed methodology a brief laboratory based contingency analysis was carried out with the help of New Zealand North Island Power Systems (NIPS) as presented in Appendix B. The system diagrams of North Island and South Island Power System Networks are also presented in Appendix B.

In this section some contingencies are analysed on two different voltage levels i.e. 110kV and 220kV. Woodville (WDV110), Bunnythorpe (BPE110, BPE220), and Haywards (HAY220) are the bus bars under the scope of this test case study. WDV110, BPE110, BPE220 are busbars very close to the region where most of the wind generation of New Zealand is currently installed, including Te Apiti Wind Farm, Tararua Wind Farm etc as shown in Figure 1.13. The network under consideration is as shown in Figures 5.6 & 5.7. The study includes three different contingencies each for scenarios as shown in Table 5.1. Table 5.1 also illustrates the targeted protection clearance times of each bus bar. These protection clearance times are realistically close to actual targets by Transpower.

TABLE 5.1 : STUDY SCENARIOS

	Contingency Type	**Protection Type**
1	3-phase local fault on BPE_WDV_2 line near Woodville 110 bus bar	Zone based protection (Zone 1:200 ms, Zone 2:600 ms)
2	3-phase local fault on BPE_WDV_1 near Bunnythorpe110 bus bar	Zone based protection (Zone 1:200 ms, Zone 2:600 ms)
3	3-phase local fault on BPE_HAY_1 near Bunnythorpe220 bus bar	Main Protection with Signalling (Main : 120 ms, Back up : 350 ms)

In order to assess the ride-through capability of each of the wind farm we need to collect the voltage profiles of neighbouring buses under worst fault conditions. The voltage profiles for these busbars i.e. Woodville110, Bunnythorpe110, Bunnythorpe220, and Haywards220 are presented for all three scenarios.

Figure 5.7: Grid section under study

5.4.1.1 Scenario 1

A 3-phase fault was created on BPE_WDV_2 (110kV) transmission line at a 10% distance from Woodville Substation. This line is protected using zone based protection scheme and clearance times are mentioned in Table 5.1. The voltage response of bus bars under study is shown in Figure 5.8.

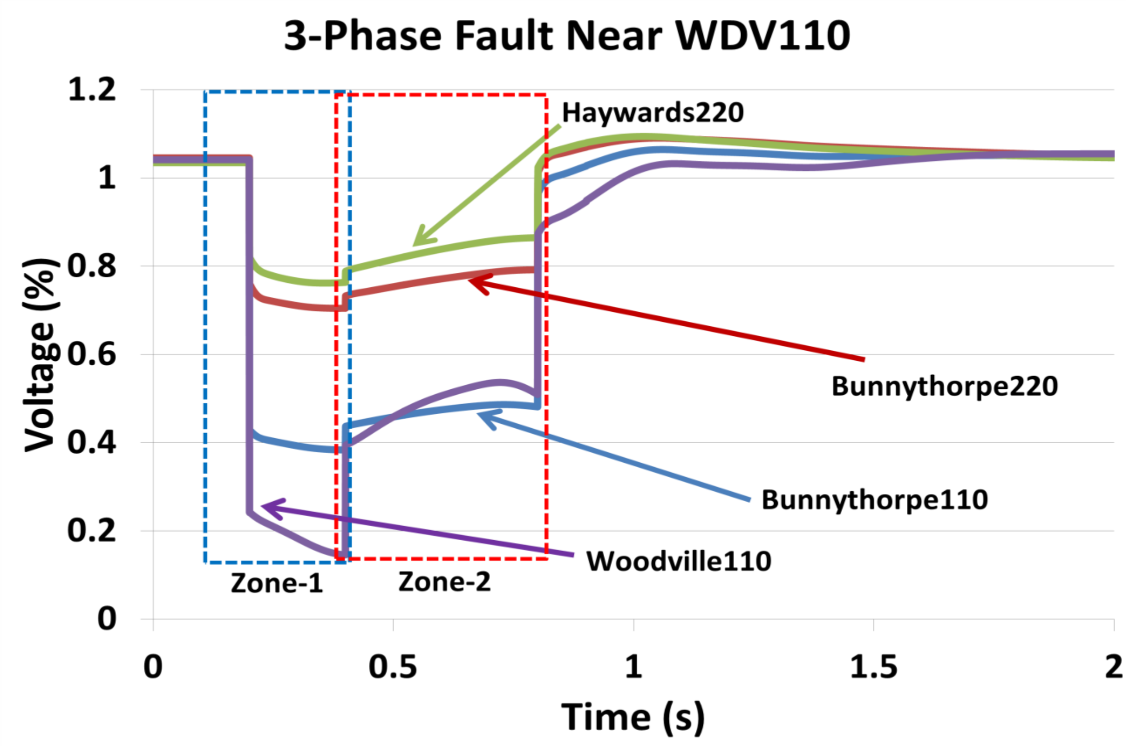


Figure 5.8: A 3-phase symmetrical fault near WDV110

The worst voltage is observed on WDV110 before operation of Zone1 protection after 200 ms. The voltage drops down to a value of 15% of the nominal voltage. The second bus affected is certainly the other end of the line i.e. BPE110 which has a droped volatge of 40% of the nominal value. After Zone1 protection operates the voltage at WDV110 and BPE110 returns back to 45-47% of the nominal value. After Zone 2 protection operates and fault is completely cleared, the voltage quickly recovers and settles back to the nominal value within 1.6 s.

5.4.1.2 Scenario 2

A 3-phase fault was created on BPE_WDV_1 (110kV) transmission line at a 10% distance from Bunnythorpe substation. This line is protected using zone based protection scheme and clearance times are mentioned in Table 2.3. The voltage response of bus bars under study is shown in Figure 5.9.

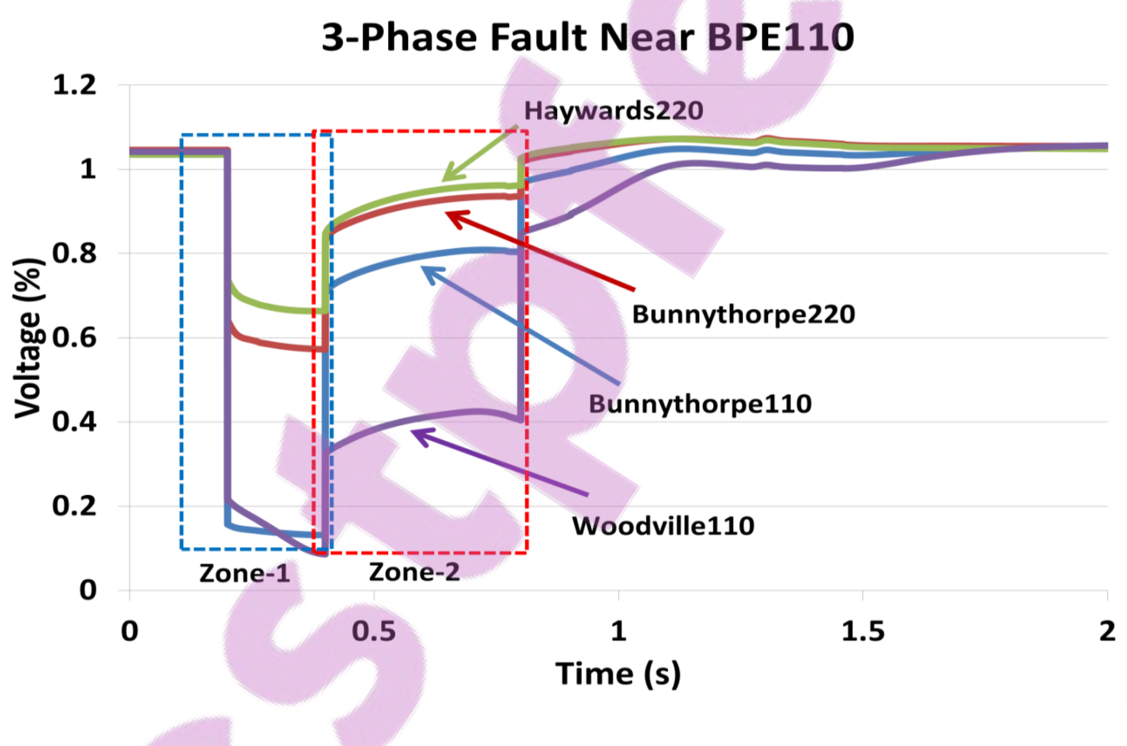


Figure 5.9: A 3-phase symmetrical fault near BPE110

The worst voltage in scenario 2 is also observed on WDV110 before operation of Zone1 protection. It shows that this part of the network is very weak and there is not much voltage support at this busbar from any adjucent generation. There is a Wind Farm connected to this busbar which is FSIG wind farm and cannot contribute much towards voltage support at this busbar. The voltage drops down to a value of 10% of the nominal voltage. The second bus affected is certainly BPE110 as fault was closest to this busbar, which has a droped voltage of 15% of the nominal value. After Zone1 protection operates the volateg at BPE110 recovers back to 75% of the nominal value while the voltage at WDV110 could still return to 40% of the nominal value. After Zone 2 protection operates and fault is completely cleared the voltage quickly recovers and settles back to the nominal value within 1.75 s.

5.4.1.3 Scenario 3

A 3-phase fault was created on BPE_HAY_1 (220kV) transmission line at a 10% distance from Bunnythorpe substation. This line is protected using main and back up protection scheme and clearance times are mentioned in Table 5.1. The voltage response of bus bars under study is shown in Figure 5.10.

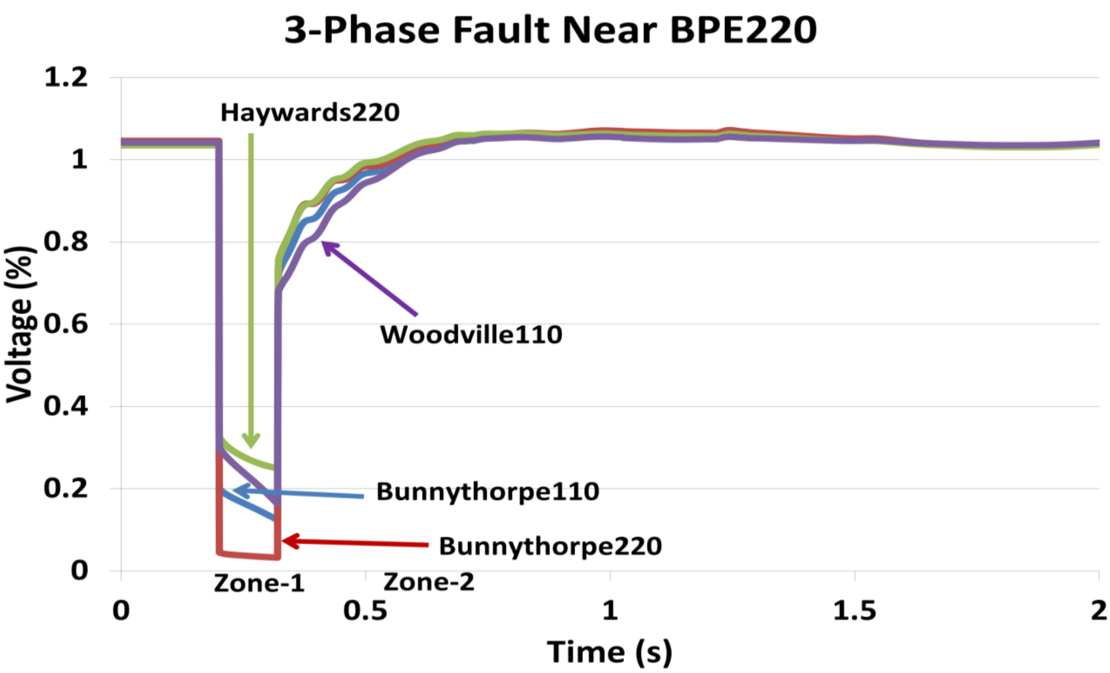


Figure 5.10: A 3-phase symmetrical fault near BPE220

The worst voltage in scenario 3 is also observed on BPE220 during the fault. The voltage drops down to 5% of the nominal value. After Main protection operates the voltage at all buses recovers back to 70% of the nominal value and gradually in duration of 500ms it reaches the nominal value of 1 pu.

Three scenarios have been presented here and four different bus bars of two different levels of transmission voltages and protection philosophies were selected.

Figure 5.8 to Figure 5.10 presents different voltage envelopes which could be combined together to achieve one single voltage duration profile for the network under study. The accumulative LVRT voltage-time profile is presented in Figure 5.11.

A detailed contingency analysis was carried out at Transpower to suggest voltage profiles for New Zealand Power System. The author spent a few months at Transpower to observe and be part of this process

Section 5.4.2 describes the analysis and final results of that collaborative study with Transpower. These envelopes and ride-through criteria have been developed under similar methodology; considerations and assumptions as discussed above.

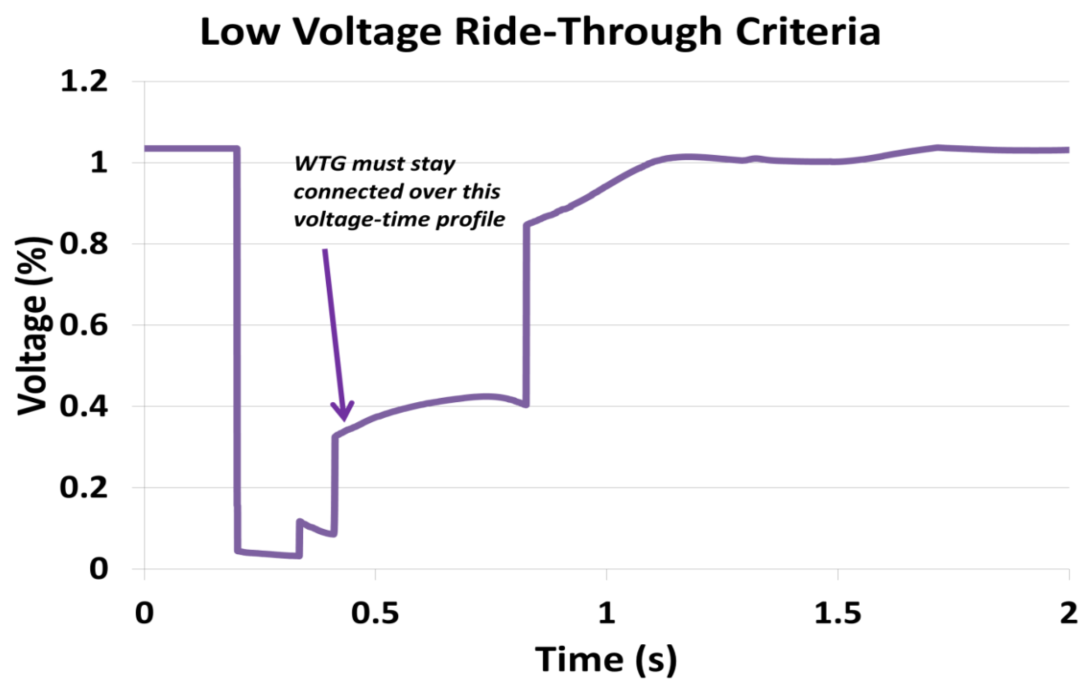


Figure 5.11: LVRT Criteria for Network under Study

5.4.2 New Zealand LVRT Summary and Comparison

Based on the methodology, the system response for the North Island is different than that for the South Island, due to the difference in load composition and contingencies for the region, a separate LVRT criterion for each island is required.

The worst 10 bus results are recorded and averaged on this basis for the LVRT system performance and a safety margin is applied to these profiles to allow for the condition where less motor load is tripped. These results are discussed in the next section.

It was found that the North Island system LVRT performance is worse than that of the South Island. The results for the North Island are compared with existing system operator HVDC and international LVRT criteria in the Figure 5.12 and 5.13 below.

As shown in Figure 5.12, the North Island performance violated the System Operator HVDC criteria after 500ms where the voltage recovery is outside the 0.8 pu voltage requirements. The HVDC criterion is used as a benchmark for these studies because it considers the limitations on distance protection under faulted conditions, the LVRT should not be prolonged so that Zone 3 and Zone 4 distance relays do not operate inadvertently [98, 105].

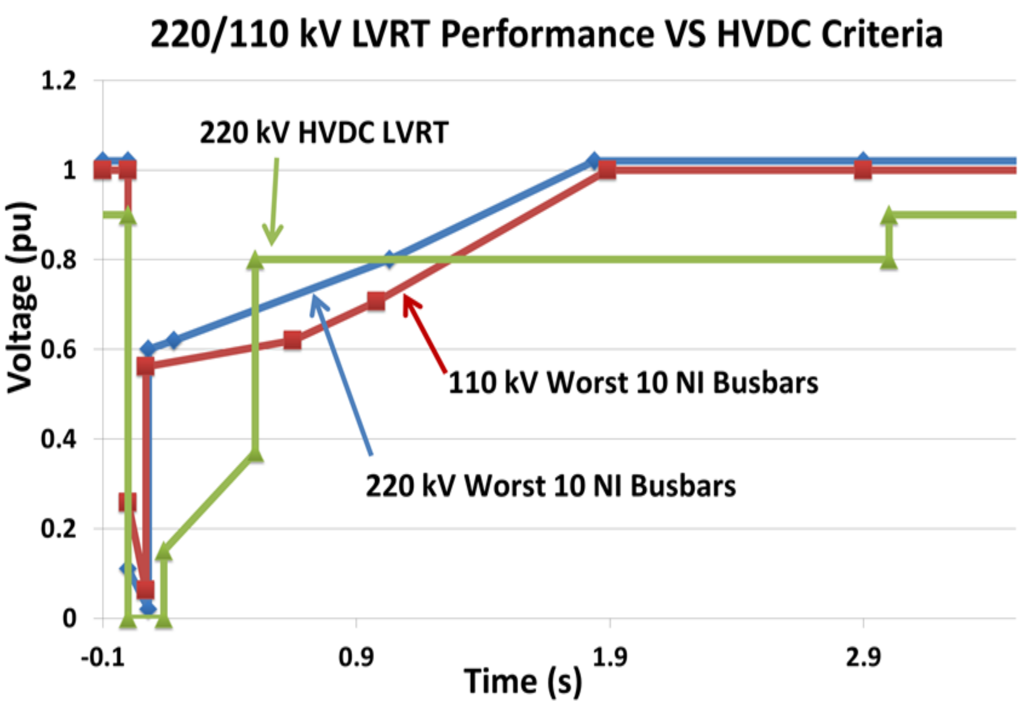


Figure 5.12: Summary and Existing HVDC Transpower Comparison – LVRT

As can be seen from Figure 5.13 the LVRT performance and System Operator HVDC criteria are within the boundaries of many of the international FRT criteria. It is also visible that the LVRT curves are within the AGO2 wind turbine criteria with the exception of the zero voltage periods. It is worth noting that many of the international criteria are applied to highly interconnected transmission systems. This comparison gives us some confidence towards existing Wind Turbine Generator technology to be connected to New Zealand Grid without any major ride-through issues.

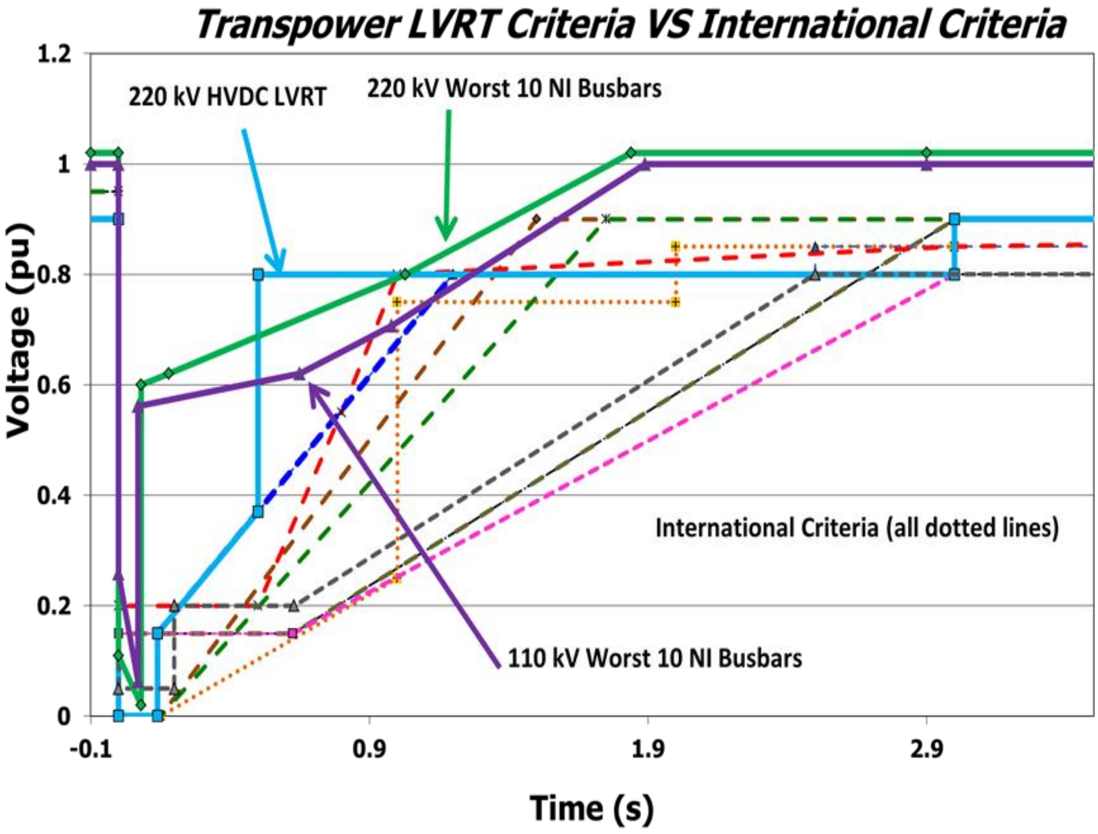


Figure 5.13: International Comparison-LVRT

5.4.3 Final Proposed FRT Envelopes

Based on the considerations, discussed methodology, results and analysis above, a separate FRT criteria or envelope can be developed for North and South Islands due to the difference in LVRT system performance [61].

5.4.3.1 Proposed North Island LVRT Requirement

The FRT envelope proposed for the North Island system is the combination of the existing Transpower HVDC criteria and system performance for the LVRT criteria with margin applied. The profiles are shown in Figure 5.14 [61].

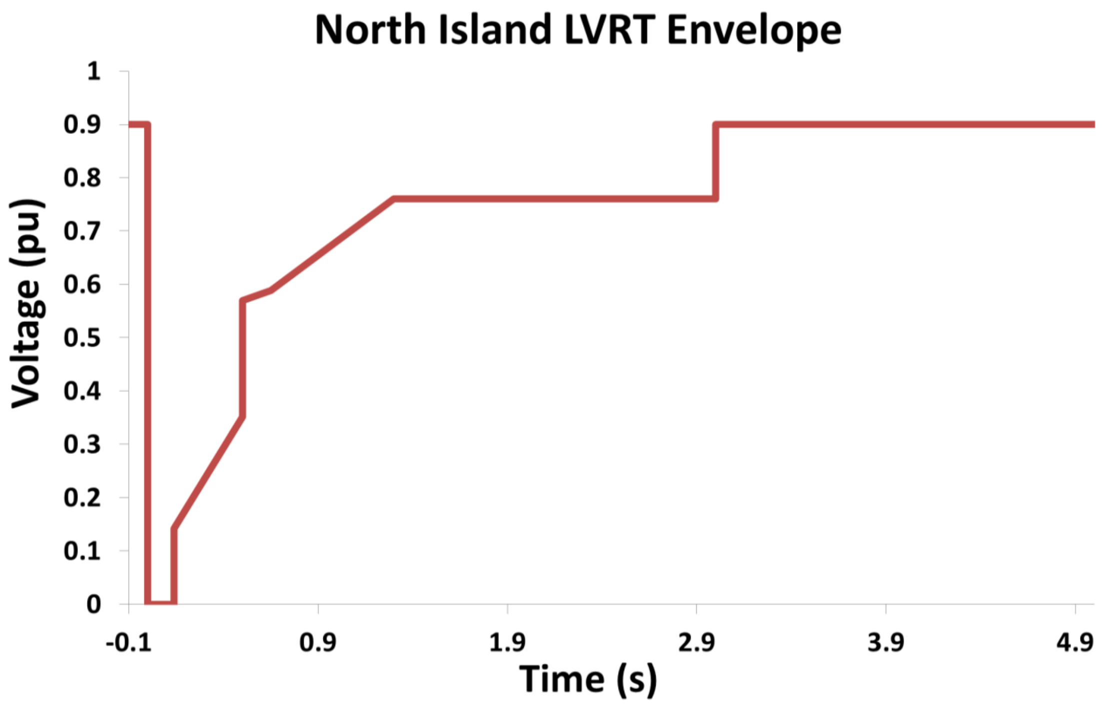


Figure 5.14: North Island LVRT Envelope

5.4.3.2 Proposed South Island LVRT Requirement

The envelope proposed for the South Island system is the existing Transpower HVDC LVRT criteria with margin. The envelope is shown in Figure 5.15 [61].

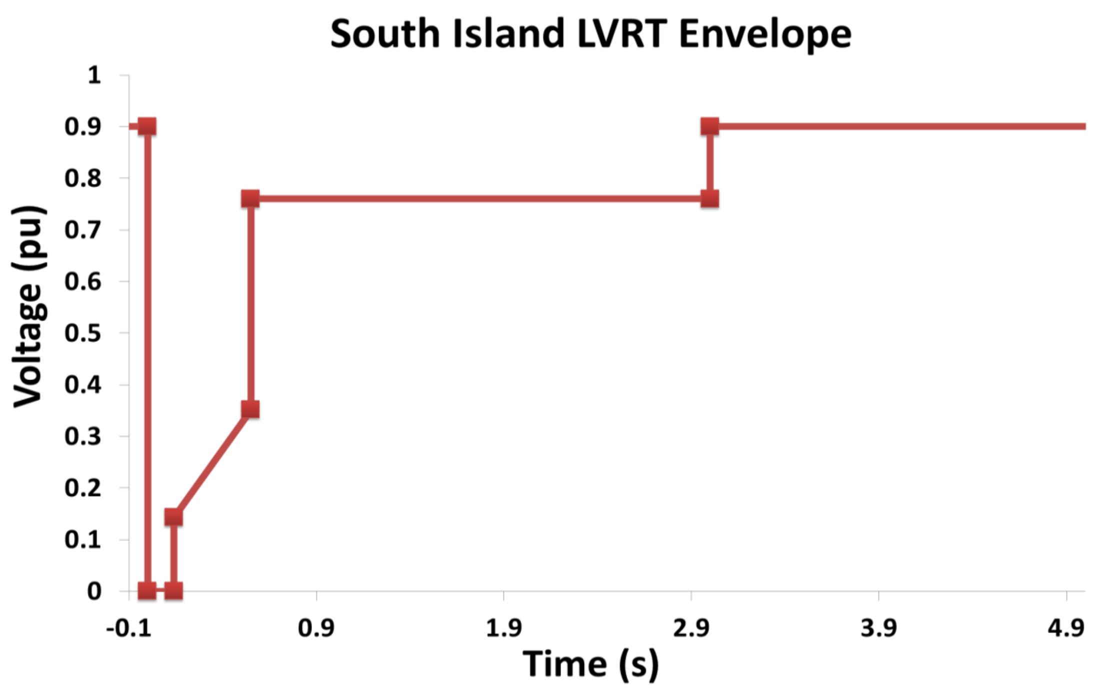


Figure 5.15: South Island LVRT Envelope

5.5 Compliance Tests

Existing Wind farms and generators need to be tested against proposed criteria for compliance; thus it is proposed that the Generator Asset Owner are required to conduct dynamic simulations using the curves and observe the modelled response of the generator. It is also proposed that type testing be performed using laboratory testing on the actual generator or turbine under faulted conditions using a simulated HV bus fault. Necessary and proper data recording is also suggested to be installed on generator site to enable the System Operator to review generator performance for actual system disturbances. The System Operator is in progress of drafting process documentation for the commissioning and testing of large scale wind farms.

5.6 Recommendations and Future Direction

In future, country level criteria may be proposed but it is recommended at this stage that an island based FRT envelope is proposed. It is also proposed that the FRT envelope be reviewed once additional reactive plants are commissioned as it is expected that a common FRT envelope for both islands can be implemented once this has been achieved.

As mentioned earlier the HVRT requirement is currently under review by the regulator, the outcome from this review is expected to be implemented into final FRT criteria for both the North and South Island transmission systems and have not been made part of this thesis due to confidentiality issues.

5.7 Summary

Chapter 5 details the first objective of this research. New Zealand transmission network was selected as a case study to exercise ride-through criteria assessments. This chapter provides a comprehensive review of New Zealand power system from wind integration viewpoint. FRT criteria are required for enabling increasing wind integration scenario for New Zealand network. The establishment of these criteria requires special analysis, data set and other network related aspects to be taken into account. This chapter discussed available wind generator technologies from FRT capability viewpoint and system aspects. A methodology has been proposed and adopted to develop a voltage envelope for the grid. A complete New Zealand grid example has been reported in this chapter which explains the development of FRT criteria for a section of a grid. Further, actual proposed ride-through envelopes for New Zealand North Island and South Island grids have also been presented towards the end of this chapter. This work was carried out in collaboration with Transpower; the Transmission System Operator. The motivation of this work was to explore wind integration protection aspects where FRT criteria development plays an important role for protection clearance times and coordination management. Compliance testing, future improvements, directions and recommendations are also identified.

Chapter 6: Wind Farm Protection

The protection practices for wind farms are not standardized. This chapter firstly reviews the general existing protection practice at wind farms. A brief comparison has been made between conventional generation and wind farm layout to further explore the protection design in each case. The chapter discusses a number of factors effecting fault current or its calculation for different wind generator technologies types as highlighted in previous chapters. In order to investigate possible issues with existing protection schemes in case of a large wind farm, a specific case study representing a weak grid scenario has been established. This case study thereafter is assessed for all the four types of wind generator technologies at the same time. Through dynamic analyses using DIgSILENT® PowerFactory, comparative fault behaviour analyses are achieved. Using results from case study the protection performance of each individual WTG type is investigated. Challenges to wind technology modelling and standardisation efforts are mostly highlighted in introduction and conclusion chapters.

6.1 Conventional Generator Layout

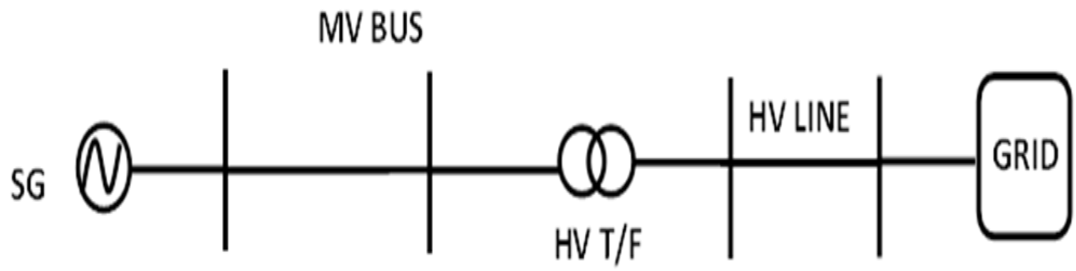


Figure 6.1: Conventional Generation Interconnection with Grid

Figure 6.1 illustrates the philosophy of conventional generator layout and its connection to the Power System. A conventional generator normally generates at a relatively higher voltage level compared to wind farms for instance 11 kV to 15 kV; thus directly connecting to a Medium Voltage (MV) Level bus as shown in Figure. The voltage is further stepped up through a High Voltage (HV) transformer to connect to grid through HV transmission link. The actual arrangement for relatively smaller generation units may vary but large conventional generation units generally follow this arrangement.

6.2 Wind Farm Layout

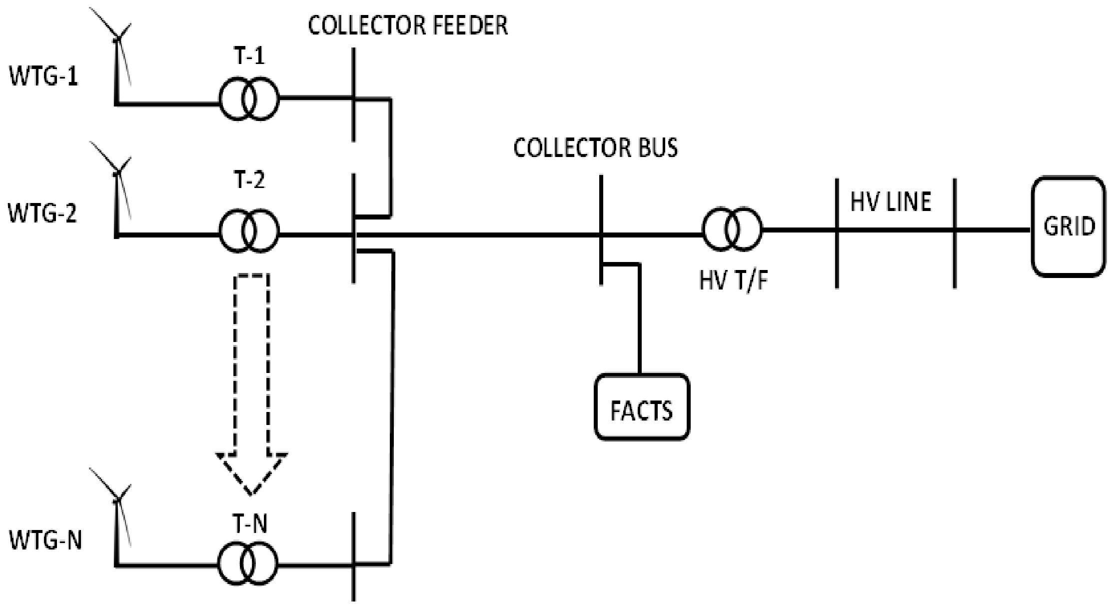


Figure 6.2: Wind Farm Interconnection with Grid

Figure 6.2 illustrates the philosophy of wind farm layout and its connection to the grid. A wind farm comprises multiple wind units varying from a few to hundreds in number. Each WTG normally generates at a relatively lower voltage level compared to wind farms for instance 400 V or 690 V; thus directly connecting to a Lower Voltage (LV) Level bus called collector feeder as shown in Figure 6.2. Each collector feeder may have one or few units connected to it in parallel. The voltage from these collector feeders is then collected to collector bus to achieve aggregated power from all turbines at the same time. Collector Bus voltage is then further stepped up through High Voltage (HV) transformer to connect it to Grid through HV Transmission link. The FACTS devices such as SVCs and STATCOMs are generally connected at the Collector Bus but they may vary in location in real practices. The actual arrangements differ but most of the installed wind farms globally follow this arrangement.

6.3 Wind Farm and Conventional Generation Protection

Figure 6.3 explains the philosophy of conventional generator protection and its protection zones. A large conventional generator is protected through standard protection philosophy of unit generation protection scheme. In the above case it is easier to establish coordination among generator, transformer and transmission protection because of limited or single unit of generation. Conventional generators even have the capability of supplying reactive power and the inertia is also an inherent capability. Because of the reactive support and having higher short -circuit strength they have higher fault ride through capability and they can satisfy almost any FRT criteria established in any part of the world.

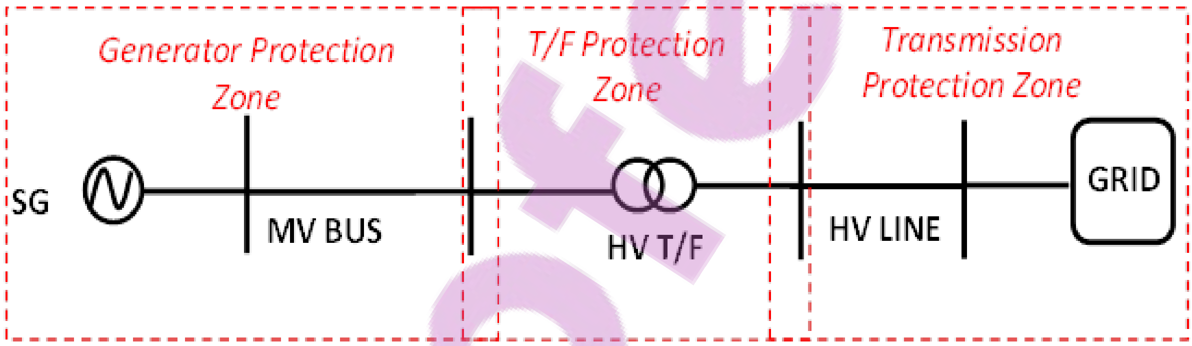


Figure 6.3: Conventional Generation Protection

If wind farms are compared to conventional generators, they will require different and varied protection requirements. Since a single wind farm usually consists of several wind units and these units are connected together to collector bus through collector feeders. Reactive support is also a separate unit and is normally connected to collector bus. The collector bus voltage is stepped up in order to connect to transmission system as shown in Figure 6.4. In this arrangement protection requirements are different than normal conventional generator as each wind unit is provided with generator protection and also has the collector feeder protection. The coordination of transmission protection with entire unit protection configuration requires additional effort and care.

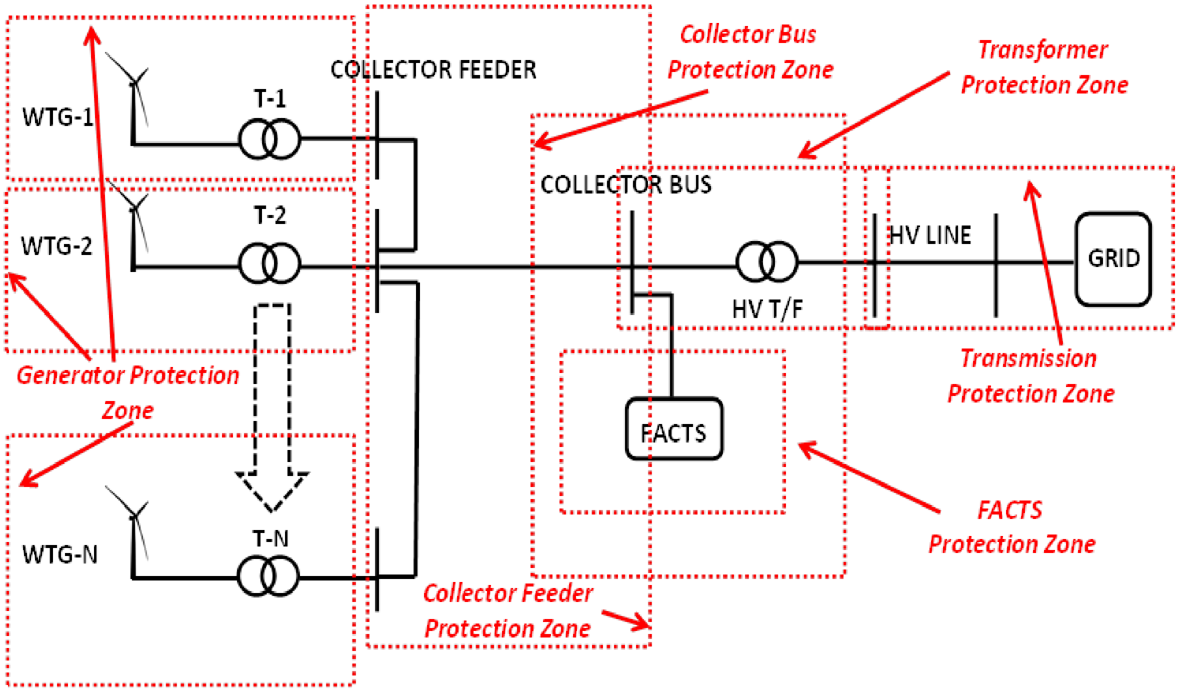


Figure 6.4: Wind Farm Protection

6.4 FRT Criteria and Protection & Control Coordination

In the context of FRT capability, under-voltage and over-voltage protection relays must operate accurately to achieve ride through and ensure safety of the wind farm. The safety of the wind units is also important as wind farm operating on extended envelope requirements cannot afford any malfunctioning of these relays.

In addition to voltage envelope requirement for abnormal operation, grid codes also demand wind farms to operate on extended voltage and frequency limits during normal operation. These requirements have been well defined in some of the grid codes are to be satisfied even at the expense of active power [9]. Robust control design of the wind farm can help achieve these requirements. Not all available technologies meet these requirements, thus requiring additional control blocks, demanding certain protection requirements.

All above mentioned expectations from large wind farms have direct impact on fault response of the wind units while riding through the faults and participating in market services at the same time. Increasing penetration of larger wind farms using different

WTGs raises questions about system protection schemes. The literature review identifies that this aspect requires much more attention. On-going research for large scale wind integration is around standardization of practices followed in transmission systems and exploring new options for control that will support the grid. Normal system operation with wind has been well studied with issues like forecasting, reliability, power quality, transient stability and fault ride through impacts following large scale wind integration [65]. However, there are no standard protection schemes for wind farms, yet available like those available for conventional generation plants. Wind generators collective response has not been discussed much especially under abnormal operations such as grid disturbances and faults.

Reference [106] discusses impacts of distributed generation on protective device coordination but it focuses on distribution system rather than transmission system. In [107, 108] author has analysed the performance of conventional protection schemes used for a 225 MW wind farm and some issues such as disconnection of whole generation in case of fault in single wind generator highlighted. This leads towards investigation and design of new intra-wind farm protection schemes and better coordination strategies for future integrations. Reference [109] discusses the earth fault protection for decentralized wind power plants. Over-current protection based on a particular model and testing facility for Types 1, 2, and 3 wind farms has been discussed but only from modelling validation viewpoint [110] . The importance and necessity of over voltage and over voltage lightning protection has also been identified based on a Chinese case study but not be emphasising over any particular WTG or its protection issues [18] . Some of the potential WTG faults and their effective management through IEC 61850 perspective and control viewpoint is discussed in [19, 111, 112]. In order to assess accurate protection settings, realistic wind farm models are required. These models should closely represent the dynamic behaviour of connected wind farm. Accuracy of the machine model, ability of the model to be used to carry out balanced and unbalanced studies, type of the model based on its differential equation order and accurate transfer functions of the control blocks are essentially required.

There is a need to carry out detailed system short-circuits and fault studies under various operating scenarios. Though short-circuit models for WTGs have been proposed in few publications but standardization of relaying schemes is still a work in progress. These studies require wind farm modelling and all fault calculations and protection relay settings would thereby be influenced by the models. Terminal voltage, stator and rotor current magnitude during a fault are influenced by the model type [46].

The next section presents a case study developed in DIgSILENT® PowerFactory to carry out comparative analyses of dynamic fault behaviour of all four mentioned WTG arrangements from a grid interface perspective. The impacts of each WTG arrangement on protection operation and performance for distance, differential and over-current protection are explored and discussed in detail as the scope of this chapter.

6.5 Case Study

6.5.1 Network under Study

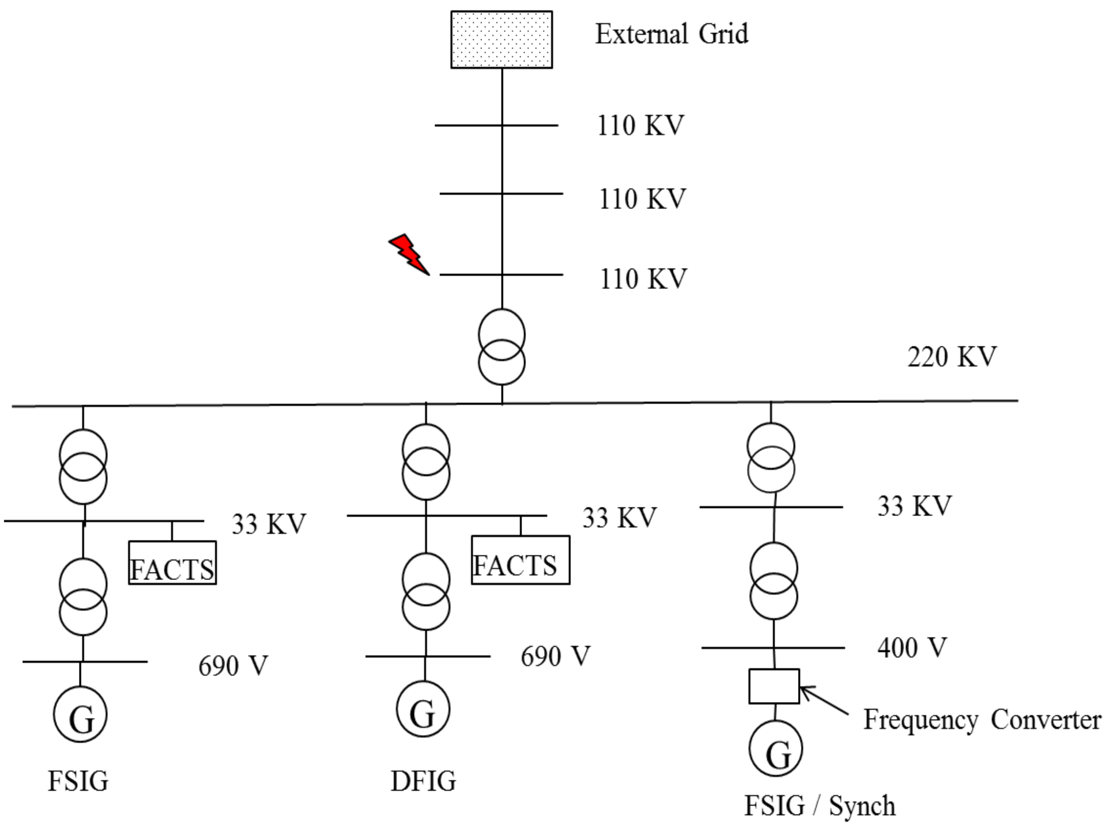


Figure 6.5: Case Study for Comparative Fault Study

Fault current response of WTGs depends on a number of following factors;

- Short-circuit strength of WTG technology;
- Distance of WTG from PCC,
- System protection schemes;
- Voltage level of connection point; and
- System characteristics at that particular network region

For weak system conditions; an individual distant wind farm connected to a high voltage system has been selected as case study in the scope of this chapter. To understand the response of each of the WTG technologies, a case study has been developed to carry out a comparative study for different WTG types. The network used for this case study is shown in Figure 6.5. All the WTG types are connected under same network conditions to provide fair basis of comparison. All the models of this network are developed in DIgSILENT® Power Factory, are lumped aggregated models. A strong external network having large short-circuit strength has been modelled but this has been separated by two long transmission lines. This is an attempt to create a weak network, as there is no conventional generation near the wind farms and the external infinite grid is separated by transmission lines. FSIG (Types 1 & 2) and DFIG (Type-3) wind farms are stepped up to a 0.69/33/220 kV voltage level to connect to Point of Common Coupling (PCC). FSFC (Type-4) is stepped up 0.4/33/220 kV voltage level to be connected to PCC. The voltage is further stepped down for transmission. Network and generators parameters are given as shown in Appendix Table A-1 to Table A-4. However, the system parameters are given in Table A-5 in Appendix A.

6.6 Wind Integration Dynamic Fault Studies

6.6.1 Model Order Impact on Fault Current or Voltage

The model-related difference in the machine short-circuit behaviour is primarily caused by disregarding stator flux transients in the reduced third order model. However, ignoring the term is only suitable for slow variations and control under limited conditions. It is concluded that the 3rd order model should not be used for effective fault analysis. The results of the test cases show that the crowbar protection settings also have significant influence on the DFIG short-circuit model. The short-circuit model is useful for grid operator to determine whether it meets the requirements of recently proposed grid codes. Wherever possible, 5th order model should be used to conclude accurate fault current values. The concept has been discussed in this co-authored publication [67].

6.6.2 Time Step Impact on Fault Current or Voltage

The selection of ideal time step is also a very important factor. If the time step is too short then it might result in some abrupt values within one cycle of the electrical frequency and peak current values obtained through such results may cause protective devices to under-estimate the fault. This may result in inefficient performance of the protective relays. In order to understand the impact of time-step on fault current magnitudes for protection configuration, the Type-3 model as discussed above in this chapter was observed under similar network and fault condition scenario. The time step for this simulation was varied from 0.001 s to 0.01s in a manner illustrated in Figure 6.6.

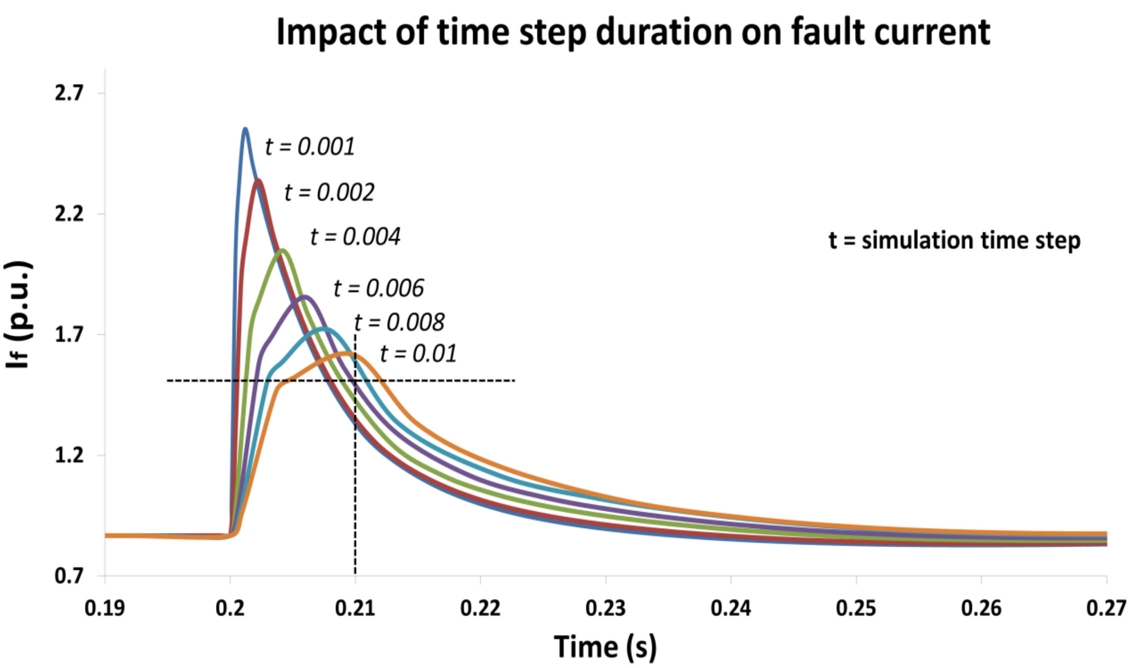


Figure 6.6: Impact of time-step duration on fault current

It could clearly be observed that the peak current is directly dependent on the time-step duration. Protection relays and devices are configured based on these peak short-circuit currents obtained from simulation results. Thus, in order to assess the protection performance, reasonable time-step duration should be selected to improve protection performance. For the above mentioned case study, time-step duration has been selected as t = 0.01s. This is because of the facts that during 10 ms which is half of the electrical frequency cycle, it is very rare that any protection device may detect the fault and fault current would eventually come down to a magnitude shown by crossed dotted lines.

6.6.3Crowbar Impact on Fault Current or Voltage

Besides the model order type, time-step duration, other control within WTG or wind farm may have direct impacts on fault current calculations. Some of the controls have been mentioned earlier in Chapter 2. One of the old and conventional control and protection technique discussed earlier is crowbar resistance insertion on rotor side of Type-3 machine. This technique has its own merits and demerits. While doing the analysis, it is important to identify all the internal controls and protection functions, which could interact with your fault current calculations. To explain this phenomenon, Type-3 (DFIG) based machines having similar network condition and parameters are discussed in Section 6.5.1, a specific scenario was simulated.

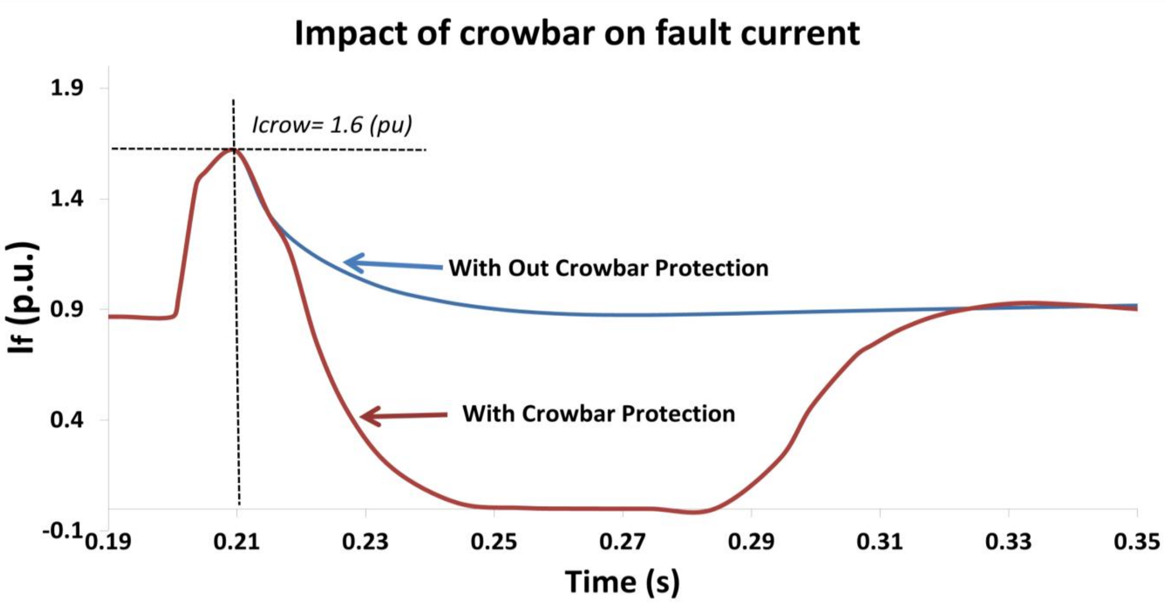


Figure 6.7: Impact of crowbar duration on fault current

This scenario involves enabling and disabling the crowbar protection within the DFIG model. The crowbar protection was set to operate if the fault current exceeded 1.6 (pu) in magnitude. Both the fault current profiles for Type-3 machine have been recorded as reported in Figure 6.7.

From Figure 6.7, it is worth noticing that with crowbar protection the fault current significantly drops down to a negligible value in 2 electrical frequency cycles. In such cases, Type-3 machines may have severe impacts on protection relay operation during the fault. The details about protection performance in scenarios of ‘with crowbar protection’ and ‘without crowbar protection’ have further been explored in the following sections.

6.6.4 Comparative Fault Analysis for WTGs

In this case study, a Three-phase fault on 110 kV busbar has been simulated as indicated in Figure 6.5. The fault duration is 400 ms with zero impedance. The purpose of this dynamic fault study is to understand the behaviours of large wind farms with regard to the WTG technology used. Thus, the resultant fault current and voltage from each generator collector bus have been recorded. To understand the responses from each of the wind generator types, similar fault scenarios have been created for each WTG type, while the wind farm is connected to the same PCC. One type of wind farm is connected at a time. The purpose of developing scenarios of weak and independent connections is to investigate future possibility of having only wind farms connected to PCC, because wind is a resource which is limited to specific parts of geographical regions. If a wind farm of some wind technology is connected to a grid location then it is very unlikely to have conventional generation in the same region. The fault current contribution and positive sequence voltages have been recorded. The results are illustrated as shown in Figure 6.8 to Figure 6.11.

The normal operations of wind generator types have been well understood. These wind farms may not have a direct impact on each other in a case of normal operation. Their interaction in a case of abnormal operation such as a system fault or any frequency event remains unidentified unless that region faces a similar situation. As FRT criteria are in place it becomes very important to investigate these wind farms for system security and voltage stability issues to overcome severe situations through special protection schemes. Since wind farms interactions may also impact the fault response of any particular wind farm to the system, it is essential to understand a standard response of a generator connected independently to a grid. Based on the simulation results, Figure 6.8 represents the pu current and voltage response of Types 1 & 2 WTGs. It is worth noticing that Type-1 & Type-2 are being treated same due to the fact that rotor resistance is fixed during simulation. Figures 6.9 and Figure 6.10 represent similar responses in pu (per-unit) for Type-3 with and without crowbar action, respectively. Figure 6.11 shows the response from Type-4 WTGs.

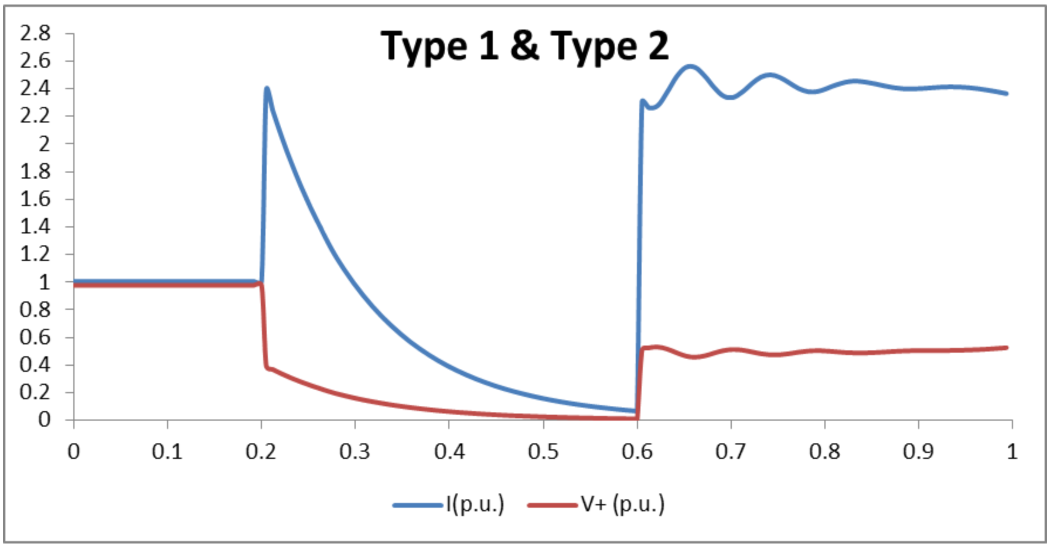


Figure 6.8: Fault Response of Types 1 & 2 (IG) Wind Farms

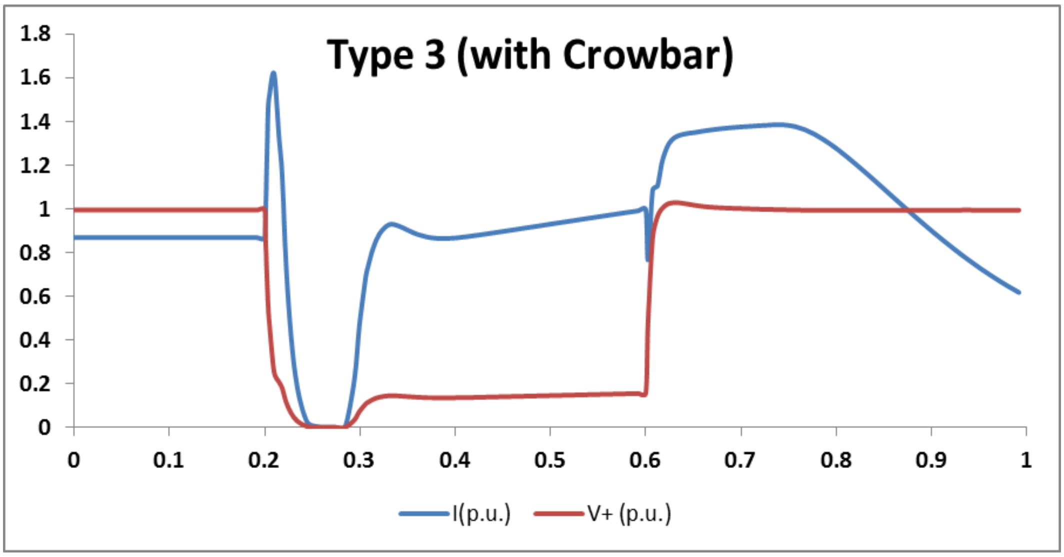


Figure 6.9: Fault Response of Type-3 WTG with Crowbar

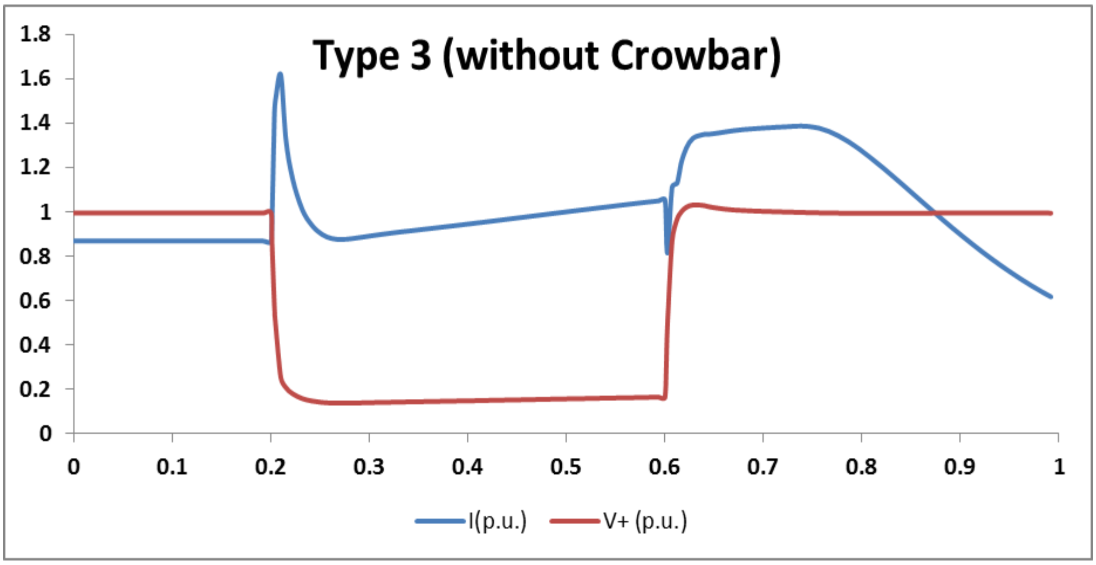


Figure 6.10: Fault Response of Type-3 WTG without Crowbar

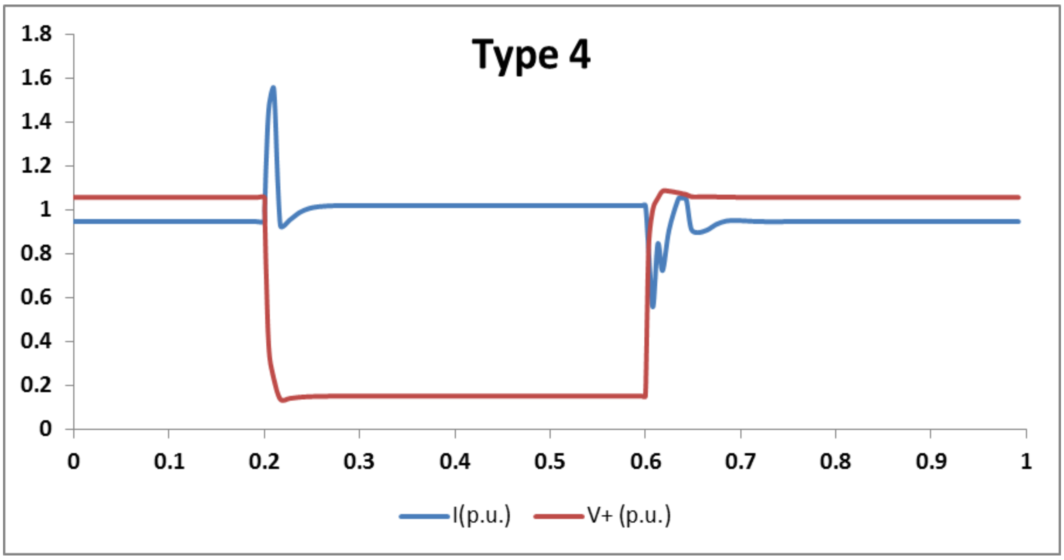


Figure 6.11: Fault Response of Type-4 WTG

6.7 Significance of Results

Based on the results obtained from Figure 6.8 to 6.11, the fault response of each generator type can be approximated as shown in Figure 6.12.

Types1 & 2 WTG have been widely available technologies for large scale wind units and they are normally modelled as a voltage source behind the locked rotor impedance. The response is not ideal as a short-circuit current source. Typically, the induction generator contributes to the initial three-phases short-circuit current at generator terminals fault, supplying balanced short-circuit current that normally is

2~4 times the generator rated current. This short-circuit current quickly decays, and typically may be neglected past few hundred milliseconds (300~400 ms) after the short-circuit inception, depending on the size and design of the induction generator. However, Figure 6.9 shows that initial the short-circuit current is close to 2.5 times the WTG rated current and decays quickly very similar to the typical induction response.

In terms of modelling aspects, Types 1, 2 & 3 WTGs Initially, behave as a voltage source. Their equivalent circuit can be represented as shown in Figure 6.13a. However, after a very short time because of the presence of rotor and grid side converter control action, the response of Type-3 WTG differs from Types 1 & 2 and matches the response of Type-4 WTG which is constant current source response. At that time, the equivalent circuit of Types 3 & 4 may be represented as shown in Figure 6.13b.

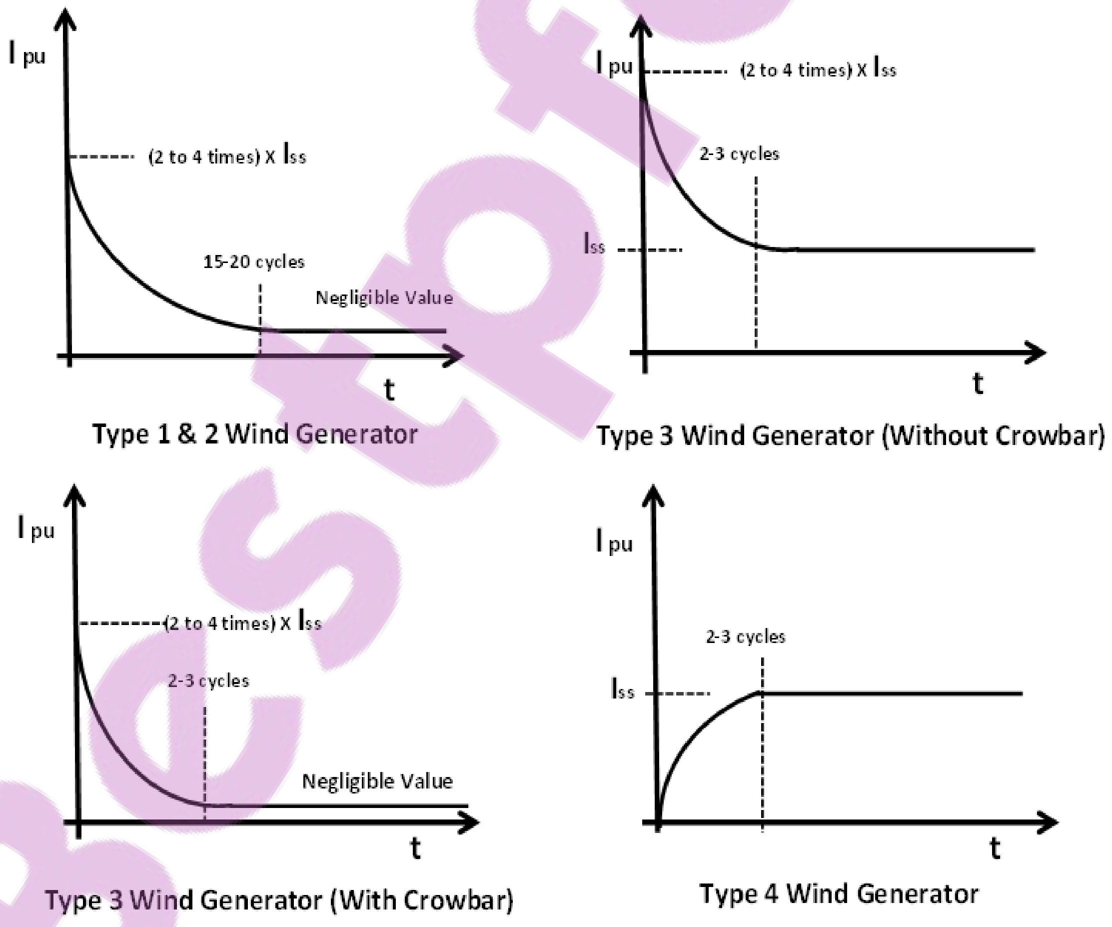


Figure 6.12: Generalized Fault Current Response of Wind Generators

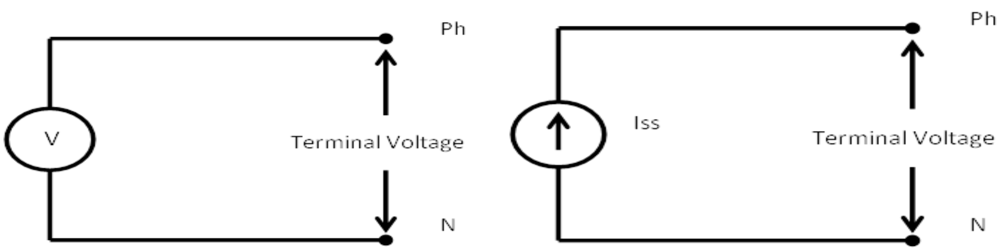


Figure 6.13a: Equivalent Circuit of Types 1, 2 & 3 immediately After Fault

Figure 6.13b: Equivalent Circuit of Types 3 & 4 during the fault

Type-3 WTG transient response quickly decays from the initial short-circuit current of a magnitude of 2~4 times the rated current, as a typical squirrel cage machine, to the limited steady state current value in the range 1~1.5 times the generator rated current (I_{SS}). The decaying time is typically a few tens of milliseconds (40~ 60 ms). After a few cycles these WTGs behave as an ideal current source that supplies continuously balanced constant current to the three-phase short-circuit [109]. WTGs equipped with DFIG type, respond to the above model only if the generator rotor electronic converter is adequately sized or the generator system is technically equipped to withstand the short-circuit current without any additional controls such as crowbar action or any special protection scheme in place to trip DFIG in order to guarantee electronic devices self-protection. However, this may not be true if the DFIG operation is altered by the introduction of crowbar or other control action. If crow bar is activated, Type-3 WTG response matches with Type-2 WTG but fault current decays even faster than Type-2 WTGs. On the contrary, DFIG current response as shown in Figure 6.12 shows that current reaches a much lower value than rated value.

Figure 6.11 shows that Type-4 WTG current builds up to 1.6 times that of steady state current but it is worth noticing that it immediately goes back to steady state value in less than one cycle. This is such a short duration for protection and control activation that can be ignored here. Such a peak could be due to limitations in modelling full scale frequency convertor based WTG. It can also be observed in Figure 6.11 that fault current through FSFC reaches to a steady value very quickly. This response entirely depends on the converter capability and models being used for dynamic studies. Generally, in case of Type-4 WTG, the initial short-circuit current is around 25% of the rated current and this builds up in 2-4 cycles to reach a rated value of constant current (I_{ss}) [109].

The next section onwards focuses on finding possible issues with relay performance for the various protection types. The most commonly used protection type in case of large wind farms are Distance, Differential and Over-current schemes. These schemes have some minimum sensitivity requirements to detect the fault and operate relays. Most of the modern relays require a minimum current magnitude (I_{min}) to carry out these calculations and operate relay. If the current to the relay is lesser than its minimum required value, relay may not operate and fault could remain unattended.

As mentioned earlier, each WTG is connected to the grid with no conventional generation in the vicinity. In addition, the grid is separated by a long transmission network, thus creating the situation of a weak grid. In such a case, there are two possible issues. If a wind unit does not supply enough fault current as expected then relay might not operate. Let us examine each of the protection type and their possible issues for all four WTG types. It is worth repeating that the system is a radial one with a single wind farm feeds the fault. The argument revolves around a relay operation where the minimum required current known as pick up current (I_p) is being fed through WTG only.

6.7.1 Types 1 & 2 WTGs Protection Performance

Distance relays operate based on measured impedance value from relaying point to fault location. These impedances are calculated based on ratios of phase to ground voltages of each phase and phase currents. Initial fault current from Types 1 & 2 WTG is much larger than the rated value so the minimum required or pick up current to operate distance protection is easily achieved; thus, distance relay connected to such wind farms may not have any issues in sensing the fault. However, the fault current decays to a much lower value in a period of few cycles. This means distance relay for Zone 2 and Zone 3 protections may not adequately function.

Differential protection schemes are not used for all types of transmission levels, being used mostly for high voltage lines or some of the critical lines. In case of differential protection, Types 1 & 2 WTG is capable enough to feed in sufficient current to at the initial stages of the fault to get protection activated.

For over-current protection, Types 1 & 2 WTG may easily supply enough fault current to get over-current relay activated and operated. However, the coordination may be the main concern. Normally, over-current protections are used as back up protection, or if used as main protection, they are delayed to coordinate with differential and distance protection relays, resulting in over-current relay waiting for a few hundred milliseconds before the operation. During this waiting period the fault current of Types 1 & 2 WTG may have decayed to a much lower value, causing over-current protection to fail to operate.

With the presence of Flexible Alternating Current Transmission System (FACTS), typically used to improve voltage response, there exist more uncertainties estimating a fault current magnitude of the Types 1 & 2 based wind farms. FACTS devices have some advanced controls which may play a role in achieving fault current response from WTG feeder terminal.

6.7.2 Type-3 WTG Protection Performance

In the absence of crowbar action, distance protection is unlikely to face any issues with Type-3 WTG collective response as the initial current magnitude is large enough to get distance relays operated for Zone-1 protection. After a few cycles, the current response quickly decays to a rated value, capable of achieving Zone 2 and Zone 3 protection activation. Differential protection may not have any problems depending on Type-3 WTG collective response. The initial current should be able to activate the differential protection scheme. However, an over-current protection scheme may face issues due to protection coordination delays and the decaying response such WTGs.

As discussed earlier, this response may be altered through the insertion of a crowbar with the rotor circuit, intentional trips, or any other control/protection action within a WTG. The distance protection, differential protection and even over-current protection may have detection issues if the crowbar is activated. As shown in Figure 6.12, the current response of Type-3 becomes negligible within few cycles as soon as the crowbar action takes place. Either crowbar action is to be delayed or other control strategies used to ensure reliable operation of protection devices. Some turbine manufacturers are employing advanced controls such as AGO2 in VESTAS made turbines. Certain Type-3 WTG may also require FACTS devices having some impact on collective fault current response from collector feeder similar to Type-2 WTG based wind farms.

6.7.3 Type-4 WTG Protection Performance

If protection schemes are solely depending on collective current response of Type-4 WTG, in case of a weak grid situation, then protection operation is an important concern. The initial current response from standard Type-4 WTG is not significant. The fault current magnitude increases within a few tens of milliseconds (30-40 ms) reaching to a value of the rated current magnitude (I_{SS}). If such WTG is not supported through some additional advanced control features then distance, differential and over-current protection schemes are most likely to have functional problems.

With the response shown in Figure 6.11, Type-4 WTG may not be able to supply enough current for Zone-1 protection to operate. Differential protection may also have problems as the fault current may take some time to achieve its rated value, and over-current protection may hardly detect the faults because it is difficult to detect normal and abnormal current magnitudes, with the magnitude of fault current supplied by Type-4 WTG.

Nowadays, it is being claimed that modern Type-4 WTG are far more capable than other wind technologies but these claims are still to be verified through testing and validation for certain fault situations other than simulation platforms. Significant advancement is not achieved in this direction as unsymmetrical and detailed models of Type-4 WTG are still awaited to be available for research and study purpose.

6.7.4 Summary of WTG Protection Performance

On basis of above results, the protection performance of three main schemes against four different WTG technology types has been summarized as shown in Table 6.1 below.

TABLE 6.1: SUMMARY OF PROTECTION PERFORMANCE ISSUES FOR WTG TECHNOLOGIES

WTG Technology	Protection Schemes		
	Distance Protection	**Differential Protection**	**Over-Current Protection**
Type-1& Type-2	May have sensing issues in Zone-2 & Zone-3	No known Issues	May not have issues as main scheme but could have issues as back-up scheme
Type-3	No known Issues	May have issues while crowbar protection is activated	May have issues while crowbar protection is activated
Type-4	May have detection issues for Zone-1 at higher voltages	May have detection issues at higher voltages	May have detection issues for smaller clearance time

6.8 Summary

Chapter 6 reviews existing literature related to wind farm protection and identifies important aspects worth considering for the design of protection for the various WTG types. This chapter discussed the interconnection of wind units to the grid through multiple hierarchies and identifies possible areas where protection system or relays could be installed. Later, in this chapter a case study involving Type-1 to Type-4 type WTGs is carried out, recording the fault current data for each type during a similar fault condition. Results obtained from the mentioned case study, developed in DIgSILENT® PowerFactory, have been utilized to analyse the fault behaviour of four common WTG types. WTG types equivalent short-circuit models presented to form basis of comparative fault behaviour study. The responses have been then generalized to an extent and compared to analyse their impacts on protection operation and performance under a weak grid interconnection. Distance, differential and over-current protection operation and performance have been assessed for each WTG type. This chapter further identifies impacts on fault current because of three major aspects of modelling. These aspects include mechanical model order type, time step, crowbar protection and additional controls. All these aspects have significant impact to achieve the correct current magnitudes for protection relay configuration. Practical challenges and implementation issues identified in this chapter can be addressed by improving cooperation amongst wind generators, transmission system operators and researchers.

Chapter 7: Developing Wind Generator Sequence Network Equivalent Models

With the number of large wind farms in transmission grid approaching a significant level of penetration, the system studies such as load flow and short-circuit studies are becoming complex. One of the first procedural steps while integrating any proposed generation with the power grid is to perform short-circuits analysis of the system with the new proposed generation connected. Such analysis will estimate fault-current values at different buses in the system. The buses near the point of interconnection are likely to experience significantly higher fault currents. These analyses also estimate the capacities of power plant towards supporting the system in case of any system level disturbance or fault. These analyses could then be used to determine whether changes in the relay settings and replacements of circuit-breakers at the most affected buses are required. Short-time ratings of transformers in the vicinity may also need to be checked for safety reasons. This analysis will also determine the ratings of the new equipment installed, along with the new relay-settings, during the integration project.

Not much attention has been given to short-circuit modelling of large wind farms, specifically to DFIG-based wind generators. Reference [29] discusses the limitations and capabilities of the existing standard models commonly available for wind farms. The impact of fault current models of DFIG-based wind farms on protection coordination has also been discussed based on model order type in co-authored paper by the thesis author [46]. Short-circuit models of various wind generator types have been compared and discussed from fault current perspective but DFIG and full convertor based generators have not been given much attention and detail from equivalent impedance viewpoint [30]. Short-circuit currents for stator winding are compared for DFIG-based wind farms from generator rating viewpoint; however, it lacks a generic view to solve short-circuit studies for large DFIG-based wind farms through fault impedance [31].

With the rapid increase of large wind farms connected to the transmission networks, there is a need in the industry for characterization of different wind turbine topologies with regard to short-circuit behaviour. Hence, there is a need to develop simplified yet realistic short-circuit models for various wind turbine types.

The symmetrical component representation is an effective way to represent an unbalanced system by using positive, negative, and zero sequence impedances seen from the fault point. In a conventional power system, most generators are synchronous generators and their short-circuit models are well documented [113, 114]. Wind turbine generators (WTG), especially DFIG and full convertor, behave differently both in electrical and mechanical characteristics compared to conventional synchronous machines. While most of the system faults are unbalanced in nature, some of the newer wind technologies have not been modelled for unbalanced dynamic studies. It is still awaited to get unbalanced models from turbine manufacturers to validate generator models using real fault data of power systems which is normally unbalanced in nature. The models can be validated and tested against various dynamic studies if recorded data can be made available from wind generators. It is a challenging task to get data from wind generators to carry out such system level studies especially due to commercial sensitivity. In order to perform wind farm inter-connection studies, it is necessary to have well understood and effective short-circuit models of wind farms that are widely accepted by transmission and generation stakeholders. These models will also enable to quickly assess the performance of new technology applications such as control modifications or impact of dynamic reactive sources (e.g. SVC/STATCOM) during disturbances.

The objective of this investigation/study is to propose a technique of formulating the Sequence Network Equivalents (SNE) of a wind turbine and/or wind farms widely used for conventional studies. An aggregate DFIG-based wind farm model is built in DIgSILENT® PowerFactory [70]. The dynamic model is used to perform transient analysis during fault conditions. The objective of such analysis is to calculate the symmetrical and unsymmetrical short-circuit current injected from the wind farm when a fault occurs at the connection point without short-circuit current contribution from any other source. Sequence voltages and currents are obtained which lead towards calculation of sequence impedances for various fault types under different control and protection scenarios. The equivalent circuit is obtained through a network reduction technique. It can be used to represent the wind farm in future short-circuit calculations in the transmission networks.

This chapter is organized as follows: Section 7.1 discusses the development of DFIG-based wind farm model at a length. Section 7.2 revises the concept of calculation of sequence voltages and currents; the same approach has been used in the course of this work. Section 7.3 describes the test case of planned studies and the results obtained. It is followed by the sequence models achieved and related discussion. The major contribution of this chapter is then finally highlighted and future directions are proposed.

7.1 Development of DFIG-based Wind Farm Model

This section presents details of the working principles and modelling of all components in a DFIG-based wind farm [4, 89, 97, 115]. Amongst all wind turbine concepts, the DFIG is one of the well-used turbines being installed in wind farms worldwide. Various important factors characterizing the responses of DFIG model during grid disturbance are discussed here.

7.1.1 Induction Generator

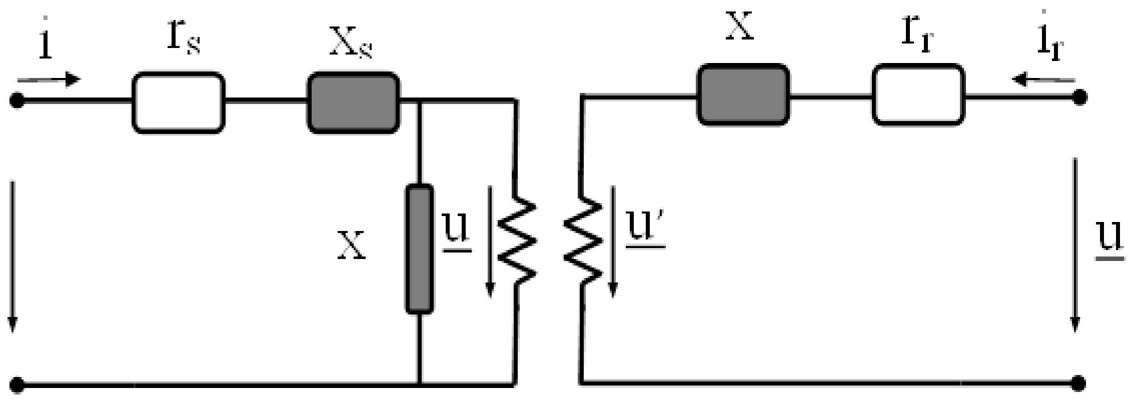


Figure 7.1: Equivalent circuit of the DFIG

Figure 7.1 shows the equivalent circuit diagram of a DFIG. For most stability studies, induction generator models usually consider rotor-flux transients and mechanics by differential equations but neglect stator-flux transients by reducing stator-voltage equations to arithmetic equations [116]. This means the induction generator model of 5th order, which is able to correctly represent rotor and stator transients, is reduced to its 3rd order model. The model equations of 3rd order can be derived as follows:

$$\underline{\mathbf{u}}_{\mathbf{s}} = \mathbf{r}_{\mathbf{s}}\underline{\mathbf{i}}_{\mathbf{s}} + \mathbf{j}\frac{\omega_{\mathbf{ref}}}{\omega_{\mathbf{n}}}\underline{\boldsymbol{\psi}}_{\mathbf{s}} \tag{1}$$

$$\underline{\mathbf{u}}_{\mathbf{r}} = \mathbf{r}_{\mathbf{r}}\underline{\mathbf{i}}_{\mathbf{r}} + \frac{\mathbf{d}\underline{\boldsymbol{\psi}}_{\mathbf{r}}}{\omega_{\mathbf{n}}\mathbf{dt}} + \mathbf{j}\frac{\omega_{\mathbf{ref}}-\omega_{\mathbf{g}}}{\omega_{\mathbf{n}}}\underline{\boldsymbol{\psi}}_{\mathbf{r}} \tag{2}$$

The flux linkage can be expressed by the following equations:

$$\underline{\boldsymbol{\psi}}_{\mathbf{s}} = (\mathbf{x}_{\mathbf{s}} + \mathbf{x}_{\mathbf{m}})\underline{\mathbf{i}}_{\mathbf{s}} + \mathbf{x}_{\mathbf{m}}\underline{\mathbf{i}}_{\mathbf{r}} \tag{3}$$

$$\underline{\boldsymbol{\psi}}_{\mathbf{r}} = \mathbf{x}_{\mathbf{m}}\underline{\mathbf{i}}_{\mathbf{s}} + (\mathbf{x}_{\mathbf{m}} + \mathbf{x}_{\mathbf{r}})\underline{\mathbf{i}}_{\mathbf{r}} \tag{4}$$

All quantities are expressed in a stator-side per unit system.

7.1.2 Rotor Current Protection

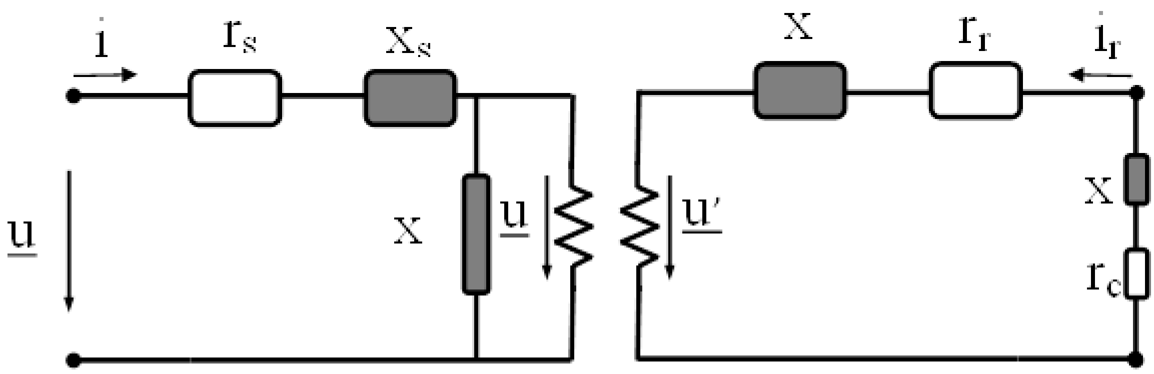


Figure 7.2: DFIG with inserted crowbar protection ($\mathbf{r}_{\mathbf{c}}$ and $\mathbf{x}_{\mathbf{c}}$)

The rotor current protection is specific to DFIG to protect rotor-side converter from high rotor currents in case of nearby faults. This protection scheme is also known as "crowbar protection". When the rotor currents exceed a certain limit, the rotor-side converter is bypassed in order to avoid any damages (see Figure 7.2).

While the rotor-side converter is bypassed, the generator operates as a normal induction generator. Since the speed can be considerably above synchronous speed before a fault occurs or the machine quickly accelerates during a fault, the stalling point of the machine is usually exceeded during a fault leading to higher reactive power consumption [89]. Bypassing the rotor with additional impedance ($\mathbf{r_c}$ and $\mathbf{x_c}$ in Figure 7.2) shifts the stalling point to a higher speed value and reduces the machine's reactive power consumption. This mode of operation can be considered in the rotor-voltage (2) and the rotor flux-linkage equation (4) as follows:

$$\underline{\mathbf{0}} = (\mathbf{r_r} + \mathbf{r_c})\underline{\mathbf{i}}_\mathbf{r} + \frac{\mathbf{d\underline{\psi}_r}}{\mathbf{\omega_n dt}} + \mathbf{j}\frac{\mathbf{\omega_{ref} - \omega_g}}{\mathbf{\omega_n}}\underline{\boldsymbol{\psi}}_\mathbf{r} \quad (5)$$

$$\underline{\boldsymbol{\psi}}_\mathbf{r} = \mathbf{x_m}\underline{\mathbf{i}}_\mathbf{s} + (\mathbf{x_m} + \mathbf{x_r} + \mathbf{x_c})\underline{\mathbf{i}}_\mathbf{r} \quad (6)$$

The crowbar protection is usually removed after a pre-defined time.

7.1.3 Turbine Control

A generic wind turbine model for stability studies based on a Maximum Power Tracking (MPT) strategy [89] can be implemented according to Figure 7.3. When the rotor frequency is below $\boldsymbol{\omega}_{\mathbf{max}}$, active power is regulated according to the MPT characteristic that defines the maximum power depending on the shaft speed as power reference of the power controller. When the maximum shaft speed is reached, the active power set point remains constant and the pitch angle control system (see Figure 7.4) starts acting driving the shaft speed back to the maximum permitted value [89].

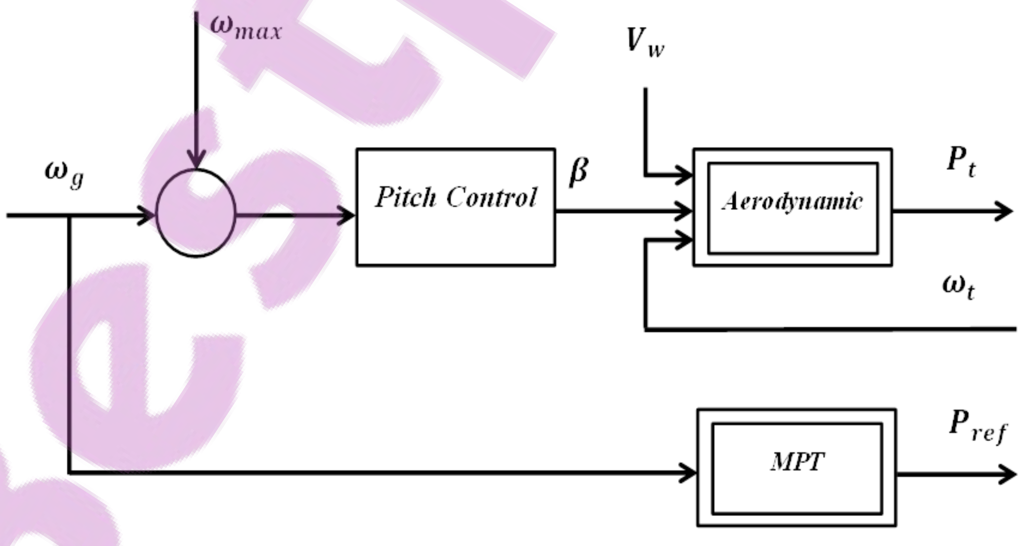


Figure 7.3: Generic wind turbine model

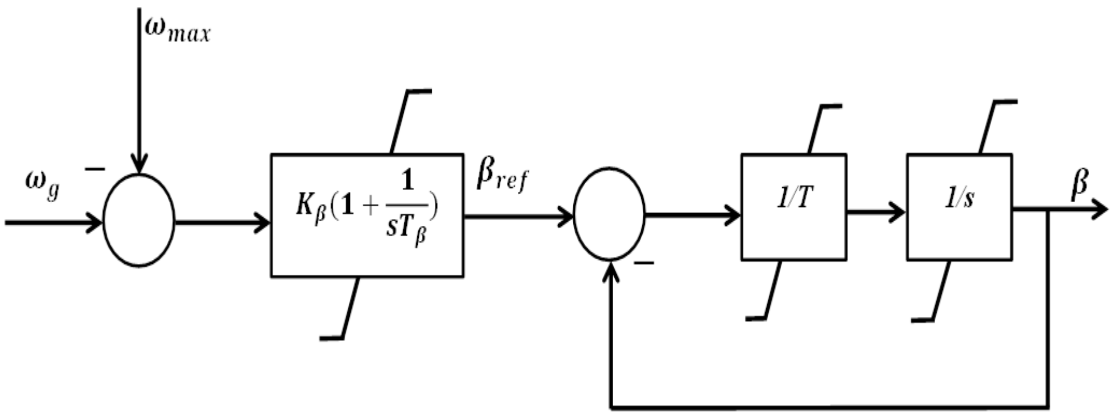


Figure 7.4: Generic model of the pitch control system

The speed reference is calculated from the actual generated electric power (inverse MPT characteristic). The generator is driven at optimal speed. In case when $\mathbf{P_{max}}$ is reached, the actual power is regulated to $\mathbf{P_{max}}$ by pitch angle control. It is to be noted that wind fluctuations are not considered in the context of this study.

7.1.4 Rotor-side, Grid-side Converters and Controls

The rotor- and grid-side converters are self-commutated converters which are usually set-up by six-pulse bridges.

The rotor-side converter operates in a stator-flux d-q reference frame that decomposes the rotor current into an active power (q-axis) and a reactive power (d-axis) component. The active and the reactive component of the rotor current are regulated by a faster inner control loop. The current set-point is defined by a slower outer control loop regulating active and reactive power (see Figure 7.5).

The grid-side converter controller operates in an AC-voltage d-q reference system. The control scheme of the grid-side converter is very similar to the rotor-side controller scheme. A fast inner control loop regulates active and reactive components of the grid-side converter currents. The DC-voltage is regulated by a slower outer control loop defining the q-current set point to a pre-defined value. The set point of the d-axis component can be used for optimum reactive power sharing between the generator and the grid-side converter or simply kept to a constant value [89].

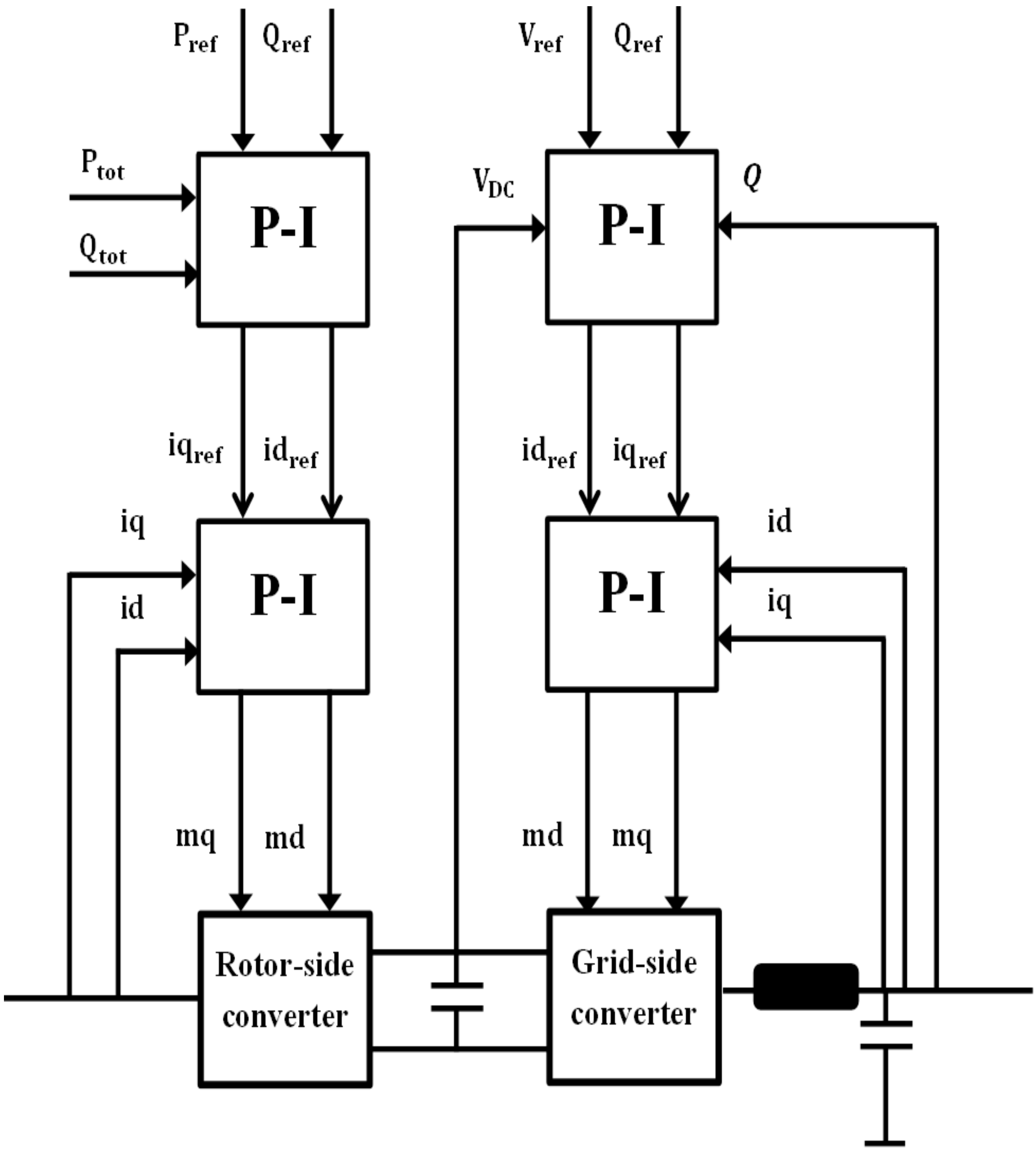


Figure 7.5: Electrical control-scheme of the DFIG

7.2 Proposed Formulation using Sequence Components

The short-circuit models to be developed are positive, negative and zero sequence equivalents as shown in Figure 7.6 with conventional notations.

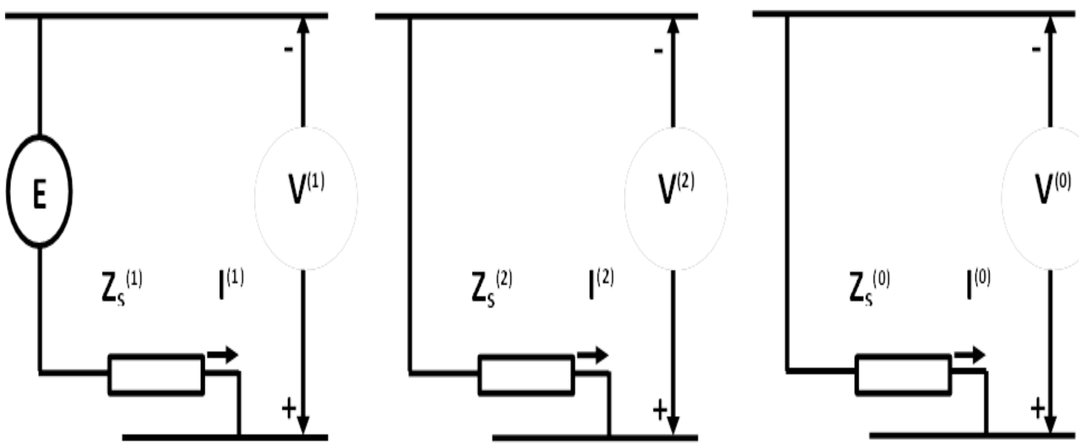


Figure 7.6: Deriving fault models

It is assumed that before a fault, only positive sequence current is injected in the circuit. The pre-fault values of '$\mathbf{V}^{(1)}$' and '$\mathbf{I}^{(1)}$' are $\mathbf{V_L}$ and $\mathbf{I_L}$ respectively, and the positive sequence fault values are $\mathbf{V_F^{(1)}}$ and $\mathbf{I_F^{(1)}}$ respectively. The equation describing the pre-fault condition can be written as:

$$\mathbf{E} = \mathbf{V_L} + \mathbf{Z_S^{(1)}}\mathbf{I_L} \tag{7}$$

The equation describing the post-fault condition is:

$$\mathbf{E} = \mathbf{V_F^{(1)}} + \mathbf{Z_S^{(1)}}\mathbf{I_F^{(1)}} \tag{8}$$

Subtracting (8) from (7), we get

$$\mathbf{V_L} - \mathbf{V_F^{(1)}} = \mathbf{Z_S^{(1)}}(\mathbf{I_F^{(1)}} - \mathbf{I_L}) \tag{9}$$

$\mathbf{V_L} - \mathbf{V_F^{(1)}}$ and $\mathbf{I_F^{(1)}} - \mathbf{I_L}$ are changes, respectively, in positive sequence bus voltage and positive sequence bus current due to fault. Denoting these changes by $\Delta\mathbf{V}^{(1)}$ and $\Delta\mathbf{I}^{(1)}$, (9) can be rewritten as:

$$\mathbf{Z_S^{(1)}} = \frac{\Delta\mathbf{V}^{(1)}}{\Delta\mathbf{I}^{(1)}} \tag{10}$$

Similarly, the negative sequence and zero sequence Thevenin impedances can be found using (11) and (12).

$$\mathbf{Z}_{\mathbf{S}}^{(\mathbf{2})} = -\frac{\mathbf{V}_{\mathbf{F}}^{(\mathbf{2})}}{\mathbf{I}_{\mathbf{F}}^{(\mathbf{2})}} \tag{11}$$

$$\mathbf{Z}_{\mathbf{S}}^{(\mathbf{0})} = -\frac{\mathbf{V}_{\mathbf{F}}^{(\mathbf{0})}}{\mathbf{I}_{\mathbf{F}}^{(\mathbf{0})}} \tag{12}$$

In order to derive the models in Figure 7.7, the pre-fault and fault values of $\mathbf{V}$ and $\mathbf{I}$ at the connection point are obtained through DIgSILENT® PowerFactory simulations. The models implemented capture the mechanical as well as electrical characteristics of wind turbine units, interfaces, controls and protections, if any. The Thevenin impedances from fault waveforms at point of coupling are then calculated using (10)-(12).

For short-circuit analysis at the transmission level, it is not practical to model the wind farm in detail. A set of procedures can be developed to include the effect of a newly installed wind farm on the protection settings. They are summarized below:

It is assumed that wind speed and capacity factor and other mechanically related quantities remain constant which is reasonable during the time-frame for this technique. A detailed wind farm model which includes exact representation of the collector system (e.g. wind turbines, pad mount transformers, cables and overhead lines) is developed.

An equivalent wind farm model can be developed using one or a few wind turbines with rescaled power capacity. The techniques can be found in existing literature [117-122].

Equations (10)-(12) are used to obtain the equivalent positive, negative and zero sequence impedances of the wind farm during different fault types.

The wind farm is represented as a voltage source and a series impedance with the corresponding $\mathbf{Z}_{\mathbf{S}}^{(\mathbf{1})}$, $\mathbf{Z}_{\mathbf{S}}^{(\mathbf{2})}$ and $\mathbf{Z}_{\mathbf{S}}^{(\mathbf{0})}$. The substation transformer can be included in the equivalent impedance if the measurements are taken at the connection point. However, it is not included in the equivalent impedance when the effect of different transformer connection types on the contribution of the wind farm to the fault level at the transmission network is studied.

7.3 Case Study

7.3.1 Model Description

The first simulation setup is shown in Figure 7.7. The wind farm is directly connected to the external transmission grid. It consists of 99 X 2 MW DFIG Figure 7.7 also illustrates the load-flow results when the DFIG is operating at rated power.

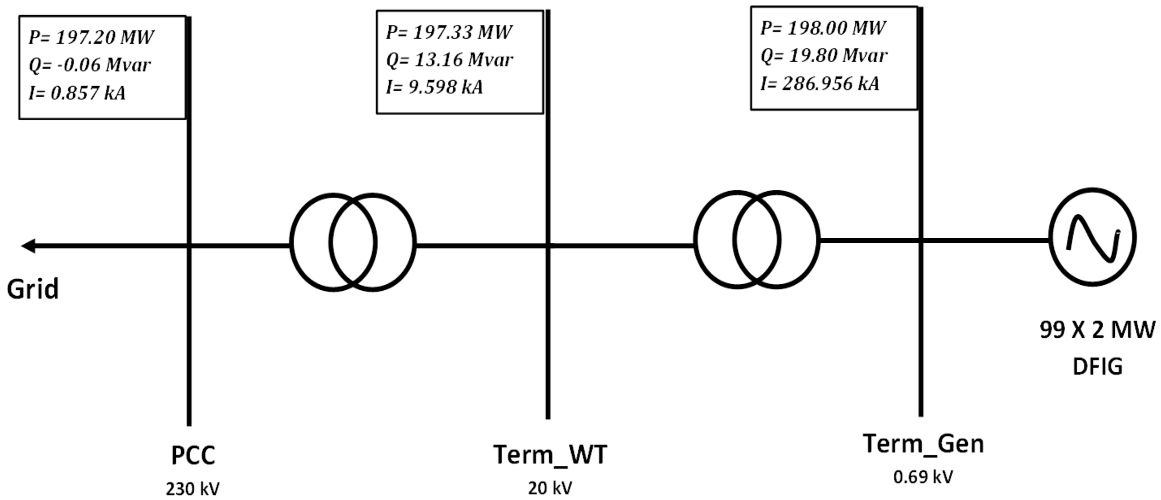


Figure 7.7: Simulation setup of a DFIG-based wind farm

7.3.1.1 Model Validation

The above DFIG wind farm model is a generic DIgSILENT® PowerFactory build-in model for induction machine and rotor and grid side convertors. The related DFIG machine and turbine data are given in the Appendix as in Table A-6. For the validation purposes of an unbalanced model type some measurements data is required. Due to confidentiality issues, there was no practical data available for such type of study. However, the validation could still be carried out through comparing the static short-circuit currents and comparing their theoretical relationship as shown from Equation (14) & (15).

The Symmetrical and Unsymmetrical fault currents of various faults can be represented as following:

For Three-Phase Fault:

$$\left|I_{fL}\right|_{3\phi} = |E|/|Z_1| \qquad (13)$$

Where:

$\left|I_{fL}\right|_{3\phi}$= Three Phase Fault Current

$|E|$= Line to Line Voltage Magnitude

$|Z_1|$= Positive Sequence Impedance

<u>For Single-Phase-Ground Fault:</u>

$$\left|I_{fL}\right|_{1\emptyset} = \frac{3|E|}{|Z_0+2Z_1|} \quad (14)$$

Where:

$\left|I_{fL}\right|_{1\phi}$= Single Phase Fault Current

$|Z_0|$= Positive Sequence Impedance

When faults are father away from the source, $\left|I_{fL}\right|_{1\emptyset} < \left|I_{fL}\right|_{3\emptyset}\ if\ Z_0 > Z_1$. When faults are closer to the source, $\left|I_{fL}\right|_{1\emptyset} > \left|I_{fL}\right|_{3\emptyset}\ if\ Z_0 < Z_1$.

<u>For Two-Phase Fault:</u>

$$\left|I_{fL}\right|_{2\emptyset} = \frac{\sqrt{3}}{2}\frac{|E|}{|Z_1|} \Rightarrow \left|I_{fL}\right|_{2\emptyset} = 0.866\left|I_{fL}\right|_{3\emptyset} \quad (15)$$

Where:

$\left|I_{fL}\right|_{2\phi}$= Two Phase Fault Current

TABLE 7.1: FAULT CURRENTS FROM SIMULATIONS UNDER STATIC FAULT ANALYSIS

Fault Type	**$I_k^{''}$ (kA)**		
	a	**b**	**c**
3-ph	2165.17	2165.17	2165.17
2-ph	0	1875.09	1875.09
1-ph ground	2613.59	0	0

The fault currents of the Term_Gen obtained through simulation are shown in Table 7.1. Three types of short-circuit are applied to the generator terminal (i.e. Term-Gen) and the maximum fault current at the bus bar is determined.

The maximum currents,$\mathbf{I_k^{''}}$ for three-phase and two-phase faults are 2165.17 **kA** and 1875.09 **kA**, respectively. In order to validate the model fault current relationship the fault currents were found to exactly follow the relation illustrated as in Equation (15). It is also worth noticing that $\mathbf{I_k^{''}}$ of single-phase-ground fault appears to be higher than the three-phase fault. This is quite sensible as short-circuit is applied closer to the generator/ supply. In reality, most faults occur farther away from the supply or generator. The value of the fault current for single phase decreases due to presence of impedance in the short-circuit pathway.

7.3.2 Test Scenarios

7.3.2.1 Test Scenarios for Dynamic Studies

Details about the test case system are given in Table A-5 & A-6 in Appendix A.

In this section, three different faults are analysed using the simulation setup shown above. Detail of each case is provided below:

- Three-phase short-circuit (3P)
- Double-phase short-circuit (2P)
- Single-phase to ground fault (1P)

For all the above fault types, different control and protection scenarios are also developed as given below:

- Fault With Crowbar Protection & With Rotor Current Controller (WCPWRC)
- Fault With Crowbar Protection & Without Rotor Current Controller (WCPWORC)
- Fault With Out Crowbar Protection & Without Rotor Current Controller (WOCPWORC)

TABLE 7.2 : COMPLETE TEST SCENARIOS

Scenario / Fault Type	**Single-phase to Ground**	**Double-phase SC**	**Three-phase SC**
With Crowbar Protection & With Rotor Current Controller	1PWCPWRC	2PWCPWRC	3PWCPWRC
With Crowbar Protection & With Out Rotor Current Controller	1PWCPWORC	2PWCPWORC	3PWCPWORC
With Out Rotor Current Controller & With Out Rotor Current Controller	1PWOCPWRC	2PWOCPWRC	3PWOCPWRC

The test case considers the short-circuit behaviour of the DFIG when the fault is created at $\mathbf{t = 1.00\ s}$ at bus "Term_Gen" as shown in Figure 7.7. Crowbar protection is disabled after $\mathbf{t = 0.06\ s}$ duration of its activation. The short-circuit clearance time is $\mathbf{110\ ms}$ for all the simulated fault cases. The results are presented as combination of fault types as shown in Table 7.2.

7.3.3. Fault Analysis & Results

7.3.3.1 Balanced Fault

A three-phase balanced short-circuit is initiated at the DFIG generator terminal. The voltage magnitude, voltage angle, current magnitude and current angle are recorded for all assumed scenarios for three-phase fault as mentioned in Table 7.2. Figure 7.8 illustrates the line voltages of the DFIG under three-phase short-circuit fault. The $\mathbf{110\ ms}$ three-phase short-circuit is applied at $\mathbf{1\ s}$ and the crowbar is removed after $\mathbf{0.06\ s}$ of its activation. All the phase angles information for line voltages are presented in Figure 7.9. Figure 7.10 and 7.11 illustrates line current magnitude and phase information for same fault scenarios. Looking at the current magnitudes, the response could be divided into four stages as illustrated in Figure 7.12. Stage I is pre-fault period. Stage II is regarded as the time immediately after the fault before crowbar protection operates. Stage III is regarded as period after crowbar activation and Stage IV is the post-fault response. The current response does not need to be similar to the one shown in illustration; however, the number of stages remains the same. In Stage III, the DFIG behaviour is regulated by the crowbar circuit.

7.3.3.2 Unbalanced Faults

During unbalanced faults (i.e. Single-phase to ground and Double-phase short-circuit), all the sequence components will be presented. As the DFIG generator windings are in "D" connection type so there is no zero sequence component observed. The division of response in four stages is also valid for unbalanced fault types as given in Figure 7.12. Figure 7.8 to Figure 7.11 represent line voltage magnitudes, line voltage phase angles, line current magnitudes and line current phase angles for unbalanced faults, respectively. The crowbar is activated as the rotor current exceeds 1.3 (pu). The fixed duration of crowbar is the same as balanced faults (i.e. $\mathbf{0.06\ s}$). It is to be noted that crowbar is not available in all scenarios. Apart from “1PWCPWRC” scenario, crowbar operates in all the other cases where it is enabled.

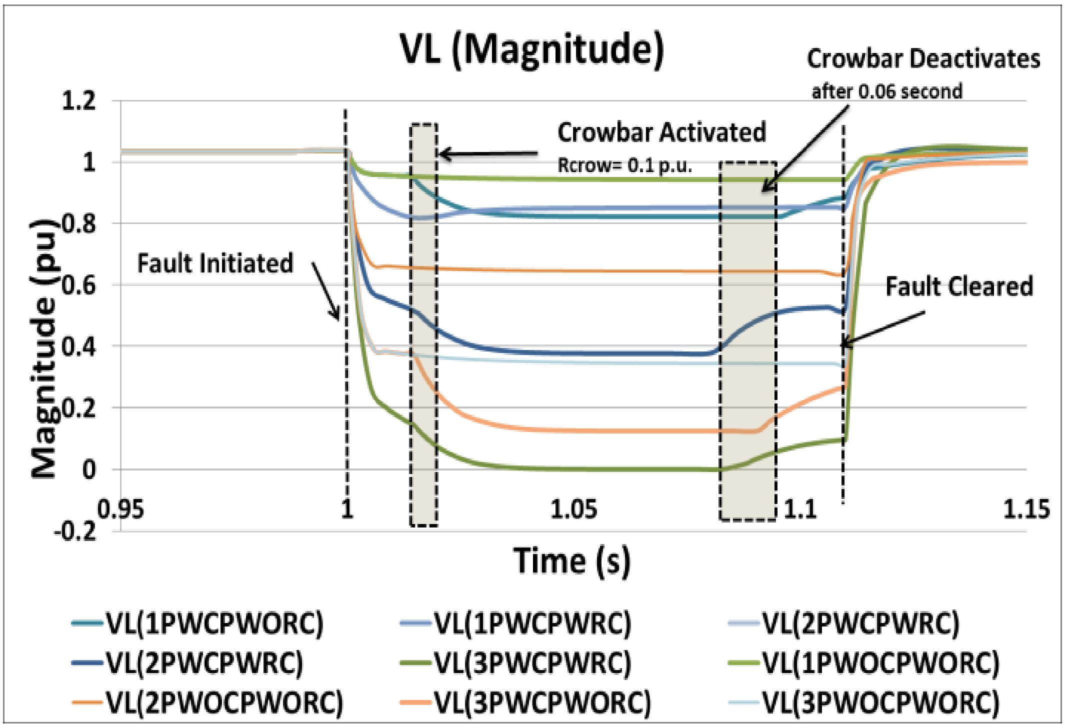


Figure 7.8: Line to ground voltage magnitude

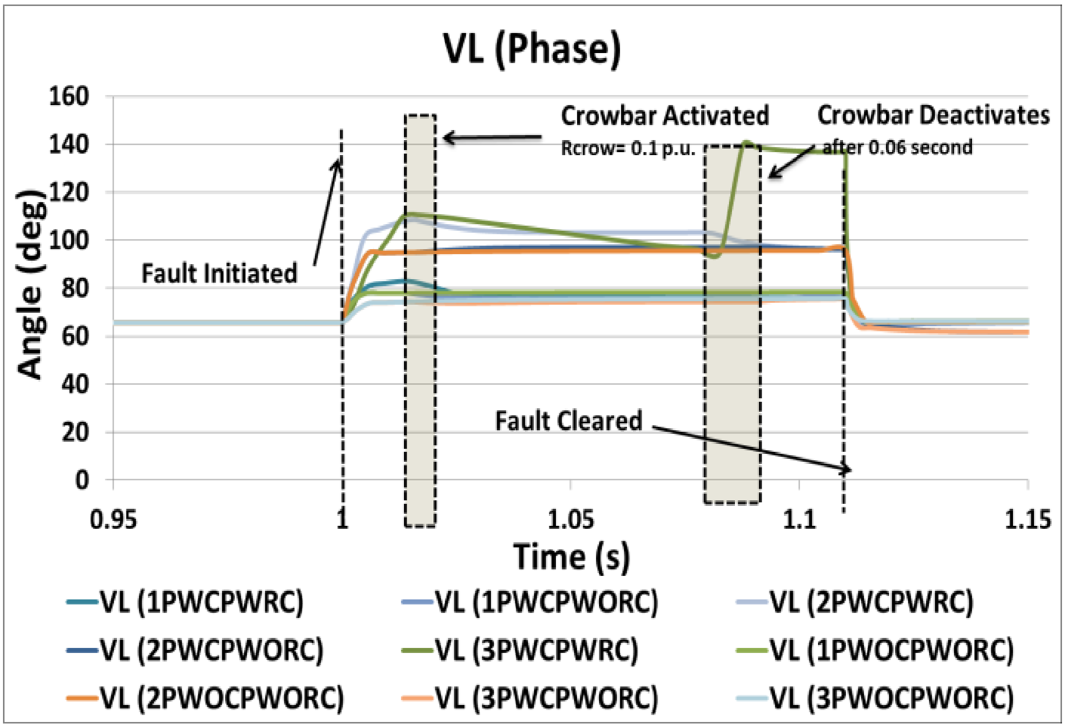


Figure 7.9: Line to ground voltage phase

The purpose of recording and presenting all these voltages is to give a relative idea about fault voltage and current response of DFIG during different scenarios. However, these recorded values are to be used to calculate positive, negative voltage and current in per unit values in order to achieve Thevenin Sequence Network Equivalents for DFIG-based wind farms.

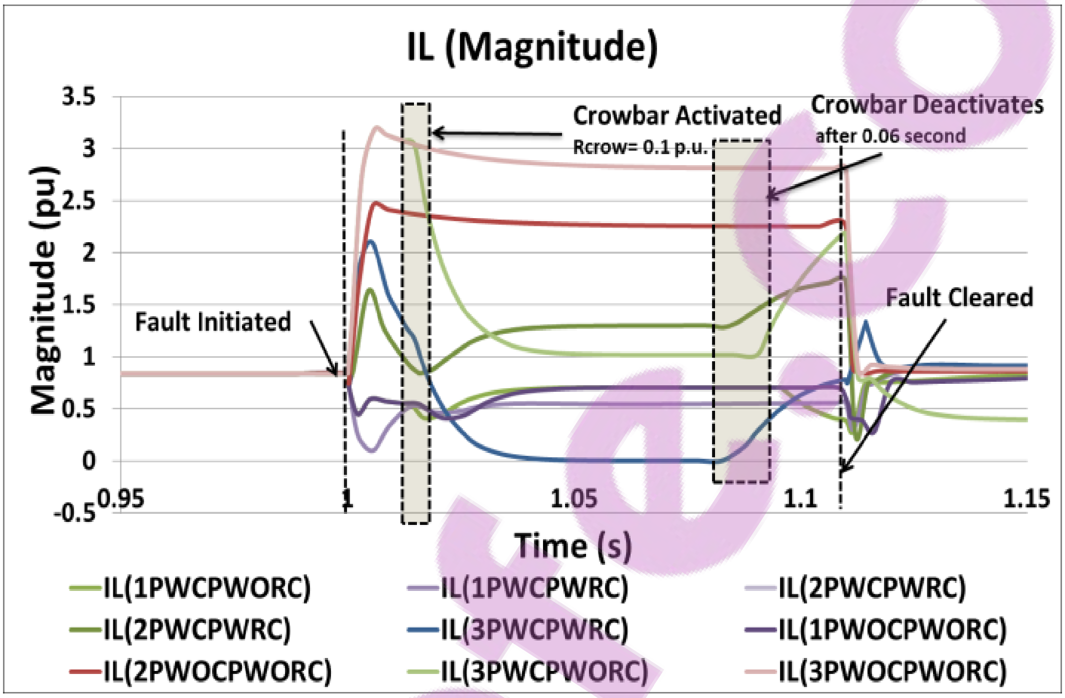


Figure 7.10: Line to ground current magnitude

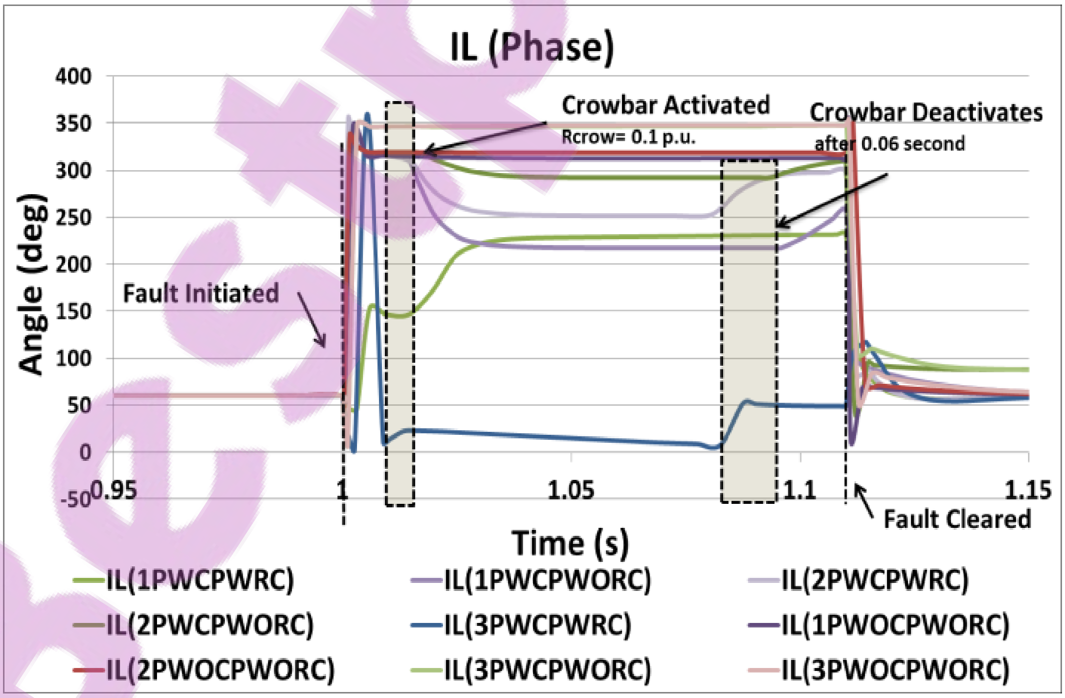


Figure 7.11: Line to ground current phase

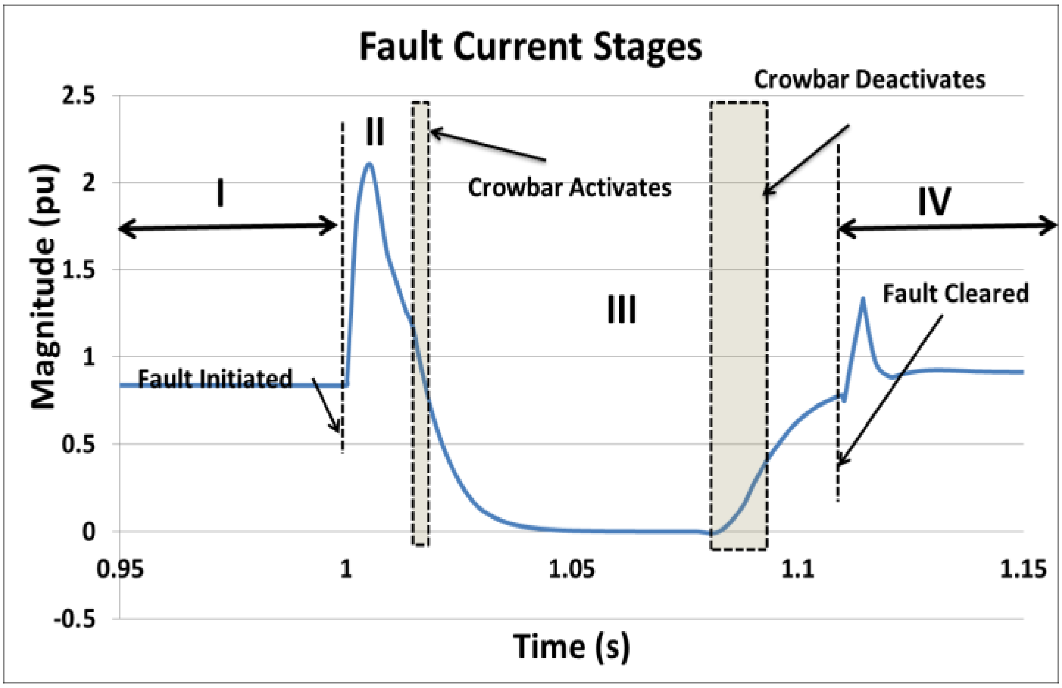


Figure 7.12: Fault characteristics DFIG-based large wind farms

7.3.3.3 Sequence Voltages

Positive sequence voltages along with their phase angles and negative sequence voltages along with their phase angles are calculated based on results obtained in the earlier stage and are shown in Figure 7.13 to Figure 7.16.

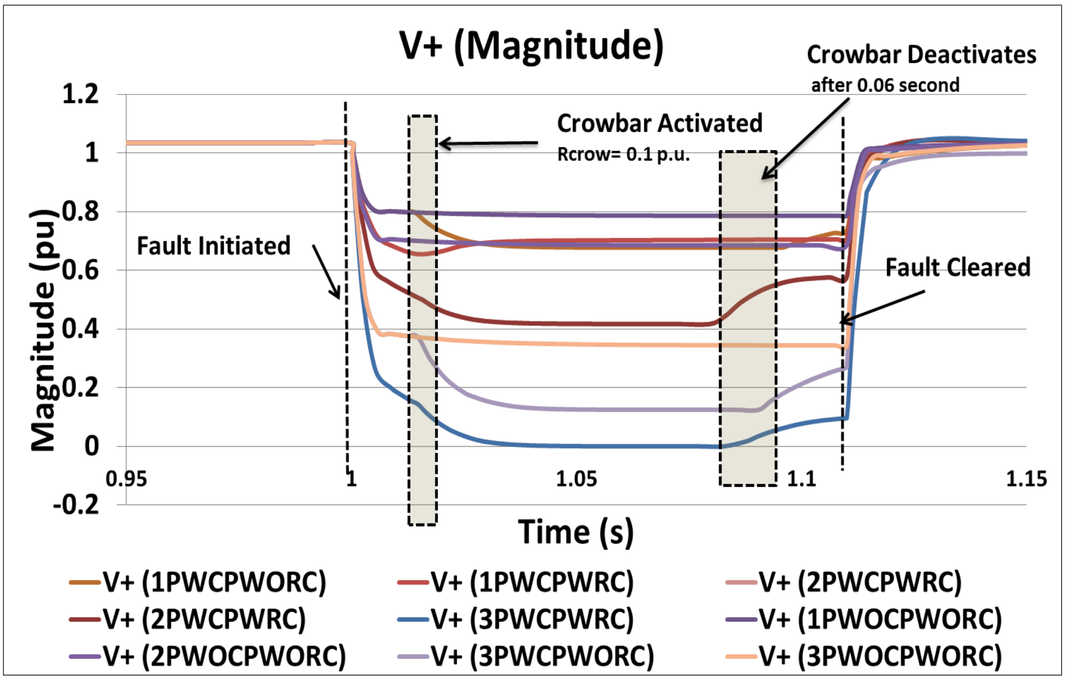


Figure 7.13: Positive sequence voltage magnitude

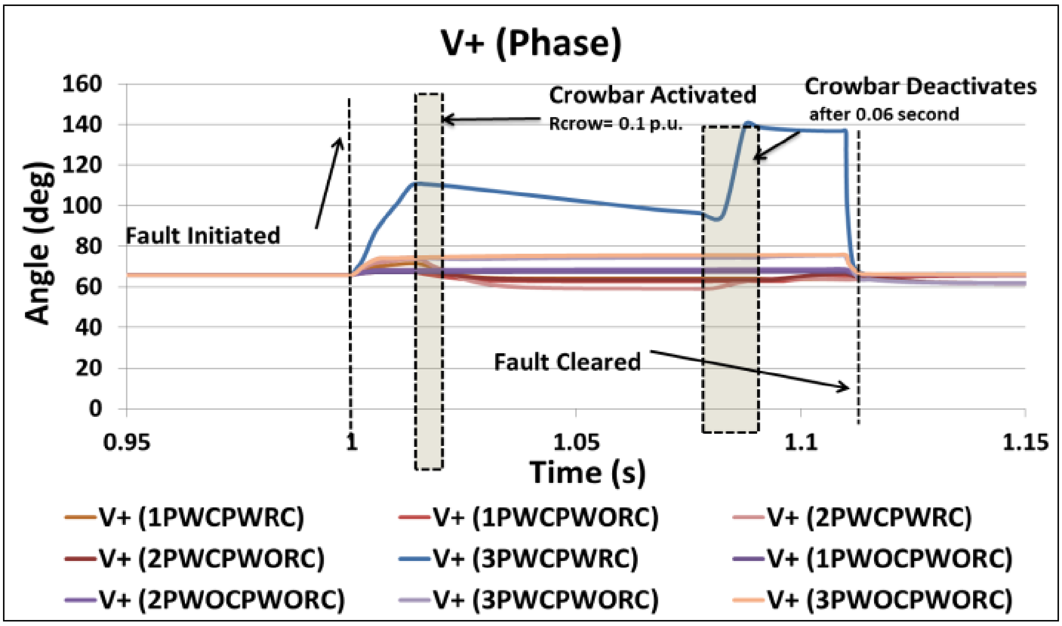


Figure 7.14: Positive sequence voltage phase

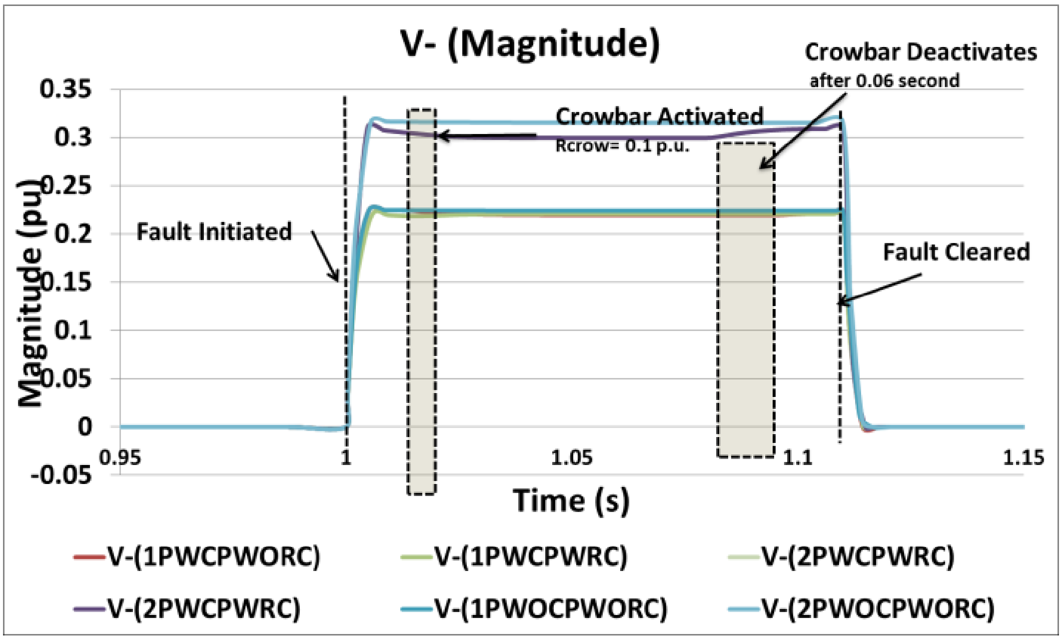


Figure 7.15: Negative sequence voltage magnitude

One thing which could be observed from the given graphs is that the presence of crowbar protection and rotor controller has impacts on the positive sequence voltages. This is because both controls are activated for balanced network and contribute towards the positive sequence components. The negative sequence voltage (magnitude and phase angle) seem to be unaffected by any protection or control action. The fault voltage magnitude is a reflection of the severity of the fault. The three-phase faults are the most severe one which are followed by two-phase faults and single-phase faults.

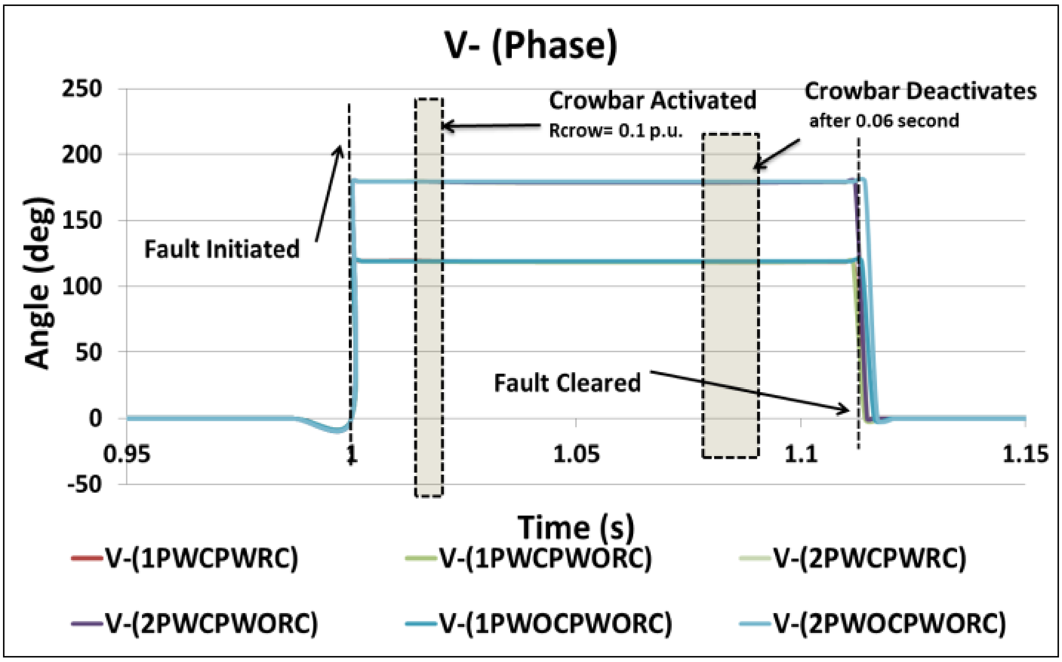


Figure 7.16: Negative sequence voltage phase

7.3.3.4 Sequence Currents

Positive sequence current magnitudes along with their phase angles and negative sequence current magnitudes along with their phase angles are calculated based on results obtained in the earlier stage and are shown in Figure 7.17 to Figure 7.20.

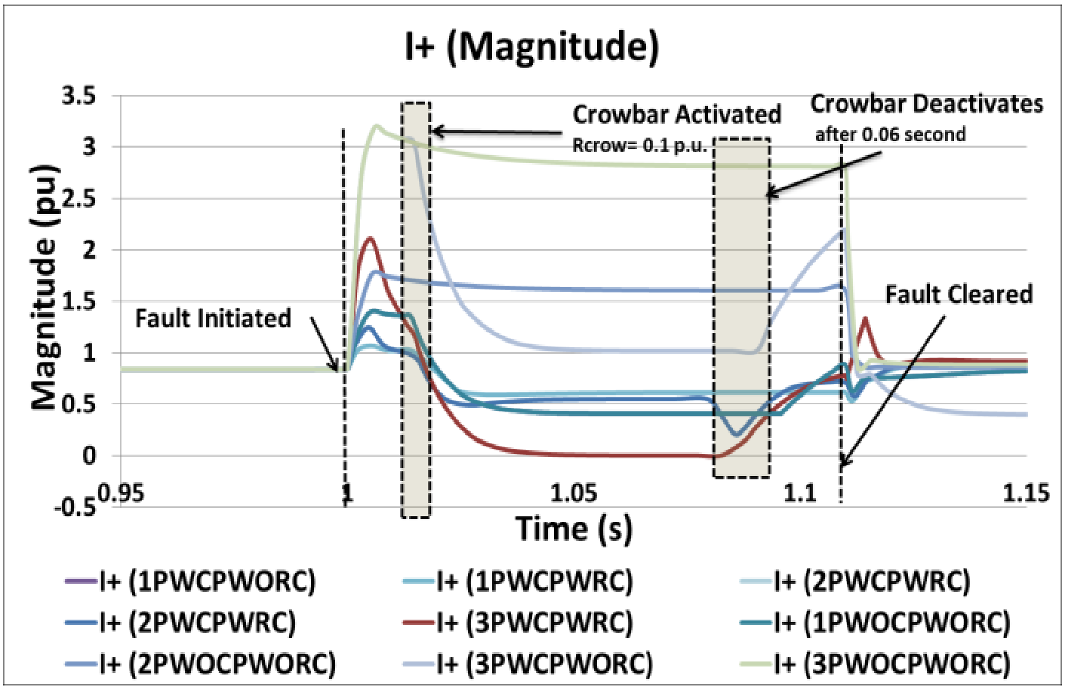


Figure 7.17: Positive sequence current magnitude

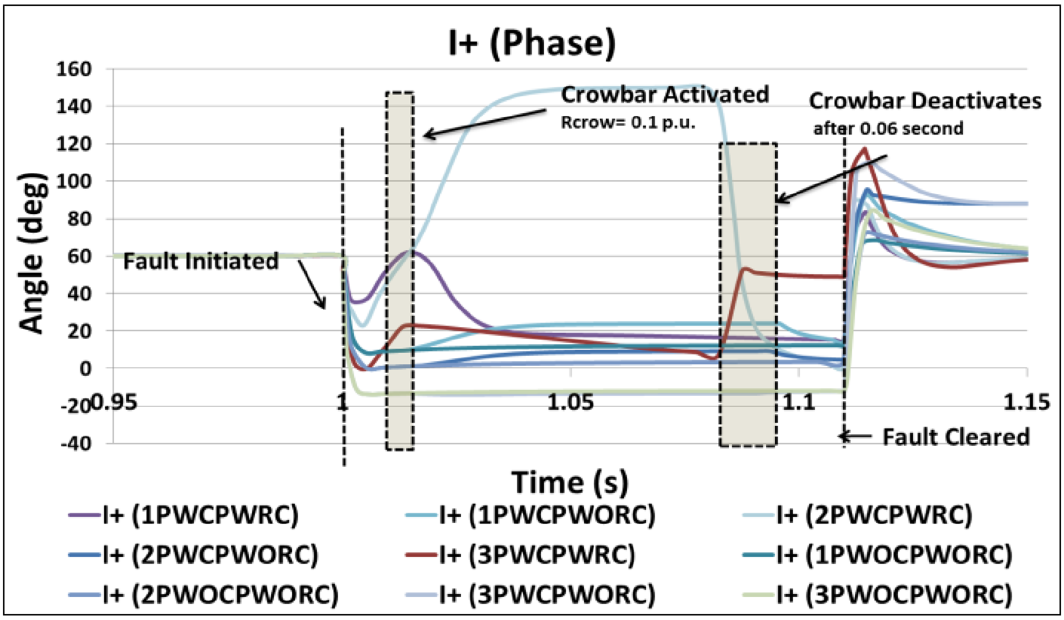


Figure 7.18: Positive sequence current phase

As discussed above, the presence of crowbar protection and rotor controller has impacts on the positive sequence voltages so as on positive sequence currents. Similarly, negative sequence currents are nearly constant during the fault for not being affected by any protection and control action due to their balanced nature. This characteristic of negative sequence component is very important and has been used to derive some of the important conclusions for Thevenin SNEs for DFIG-based large wind farms.

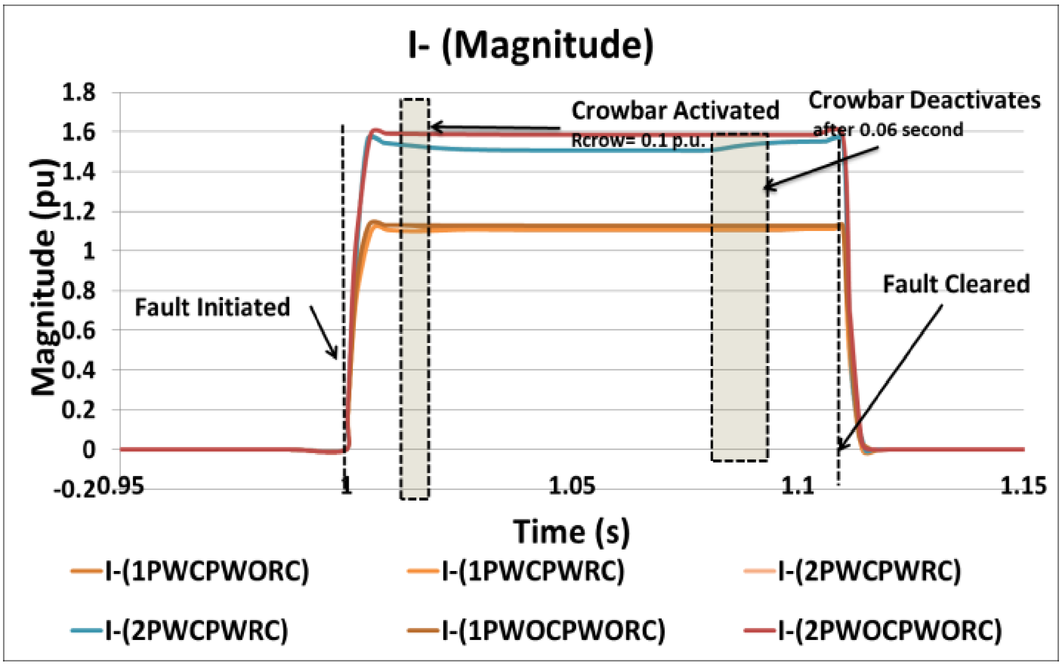


Figure 7.19: Negative sequence current magnitude

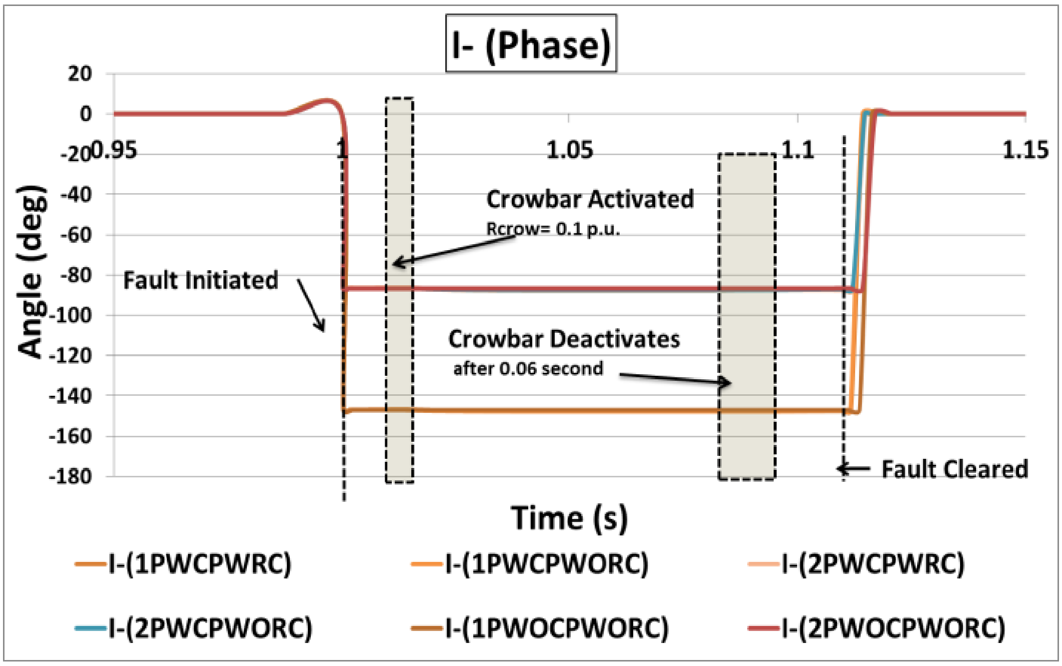


Figure 7.20: Negative sequence current phase

7.3.3.5 Sequence Impedance

From the evaluation of sequence voltages and sequence currents, the calculation of sequence impedance is achieved through formulation discussed in Section 7.2. Equations (10)-(12) are used to evaluate the positive, negative and zero sequence impedances.

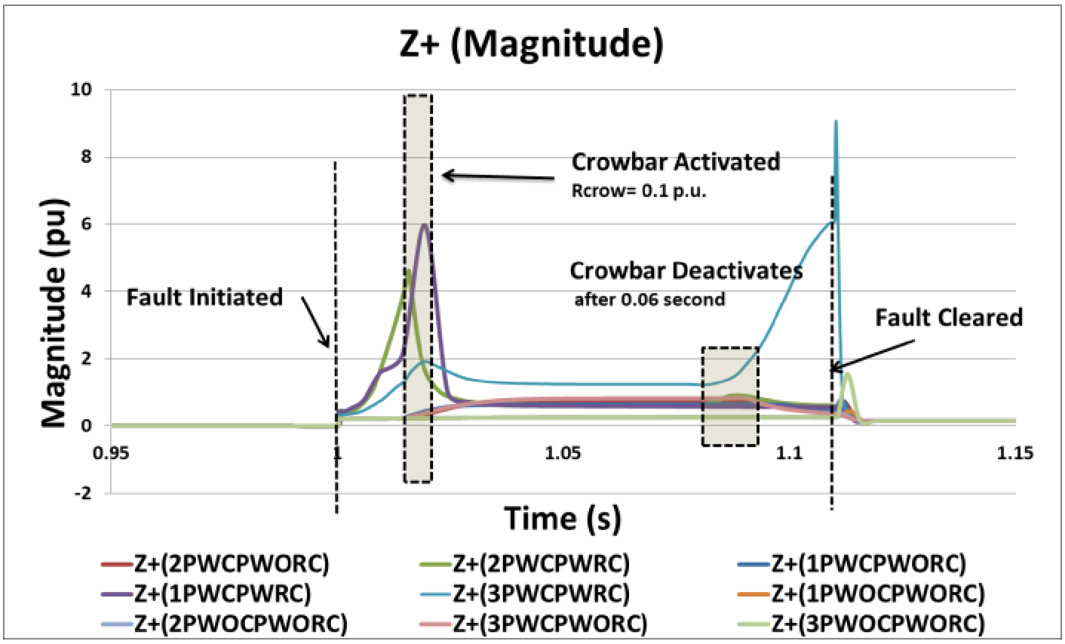


Figure 7.21: Positive sequence impedance magnitude

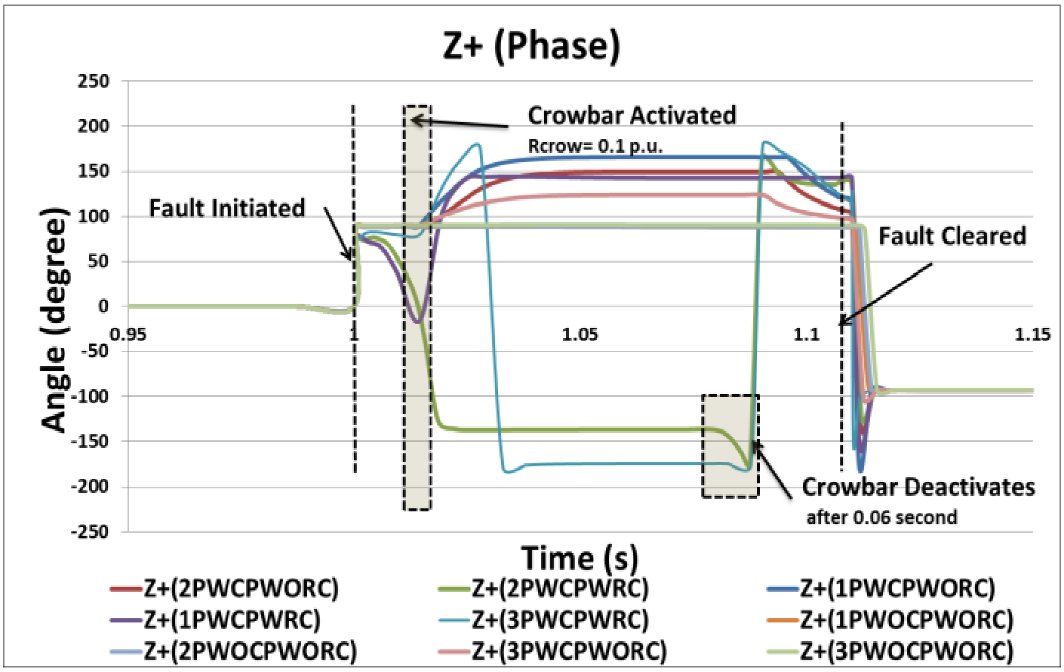


Figure 7.22: Positive sequence impedance phase

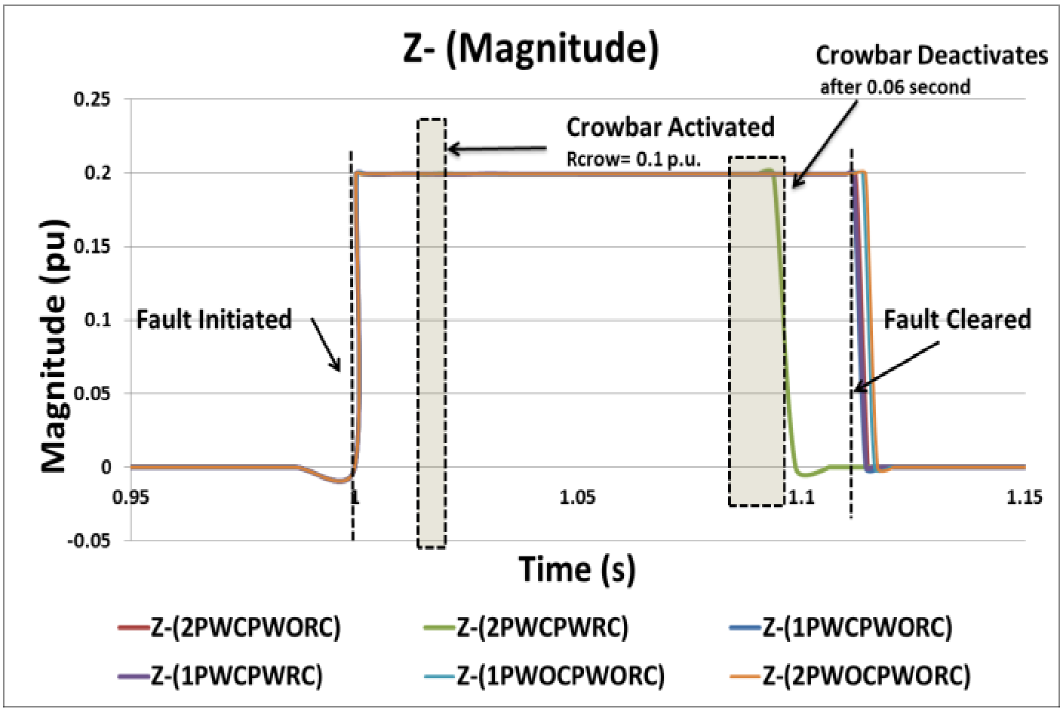


Figure 7.23: Negative sequence impedance magnitude

The resulted positive and negative sequence impedances are presented in Figure 7.21 and Figure 7.23. However, phase angle information is illustrated in Figure 7.22 and Figure 7.24.

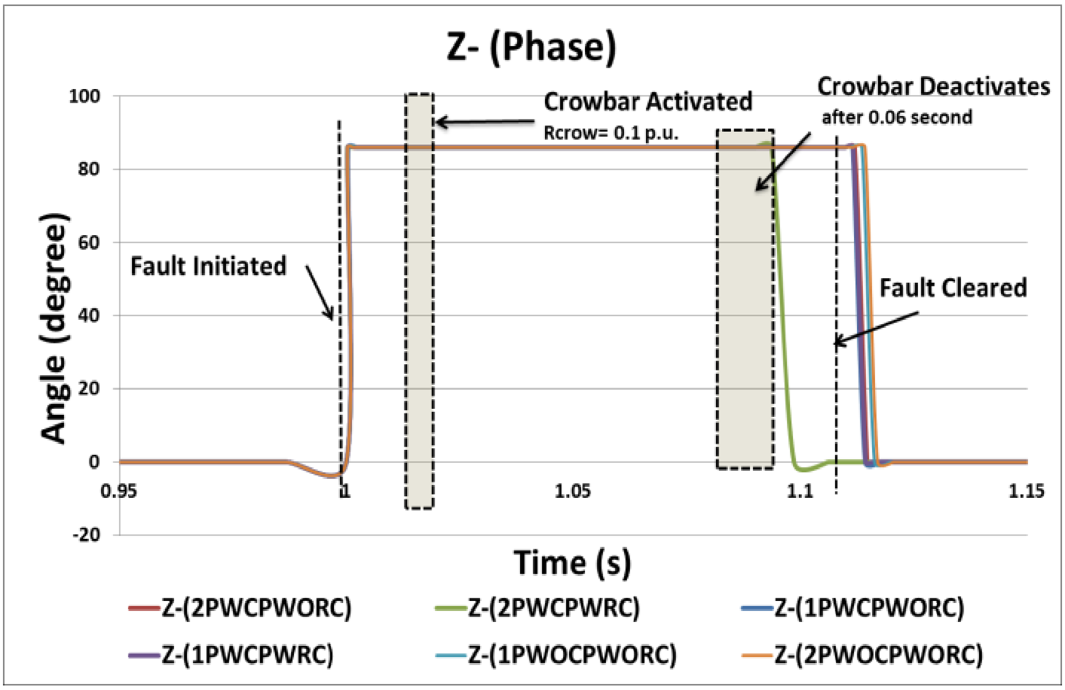


Figure 7.24: Negative sequence impedance phase

7.4 Discussion and Significance of Results

In order to quantify and represent the impedances in sequence networks, Table 7.3 lists the sequence equivalent impedances calculated from sequences impedances obtained in Figure 7.21 to Figure 7.24 for all fault types presented in previous sections. Based on information summarized in Table 7.3, the following conclusions could be inferred:

Negative sequence impedance value remains same no matter what control or protection actions are activated. Thus, negative sequence could be regarded as basic characteristic of any DFIG-based wind farm for short-circuit or fault studies. Positive sequence impedance value is dependent upon rotor current controller settings and the application of crowbar protection.

In the presence of rotor current controller, the positive sequence impedance tend to increase exponentially to keep rotor current and active as well as reactive powers in specified limits but as soon as the rotor current exceeds crowbar activation limit, the rotor circuit is modified and positive sequence impedance value goes back to normal. However, the direction of current flow changes which leads to negative values of resistances in positive sequence impedance.

TABLE 7.3: THEVENIN EQUIVALENT SEQUENCE IMPEDANCE DURING DIFFERENT FAULT TYPES

$Z_S^{(1)}$	Scenario	Stage II	Stage III
		Before t=1.015s	After 1.015 s
3-ph	3PWCPWRC	0.0746+ 0.3103j to 0.1932 + 1.3115j	-1.2287 – 0.1220j
	3PWCPWORC	0.205j to 0.218j	-0.4540 + 0.6795j
	3PWOCPWORC	0.205j to 0.260 j	0.260j
2-ph	2PWCPWRC	0.0872+ 0.3814j to 3.1945 + 0.7420j	-0.4516 – 0.4264j
	2PWCPWORC	0.205j to 0.233j	-0.6425 + 0.3805j
	2PWOCPWORC	0.205j to 0.255j	0.255j
1-ph-G	1PWCPWRC	0.0890 + 0.4044j To 1.2444+ 0.9792j	-0.4606 + 0.3542j
	1PWCPWORC	0.205j to 0.229j	-0.6195 + 0.1569j
	1PWOCPWORC	0.205j to 0.226j	0.26j
$Z_S^{(2)}$	All Cases	0.1985j	
$Z_S^{(0)}$	All Cases	Nil	

In the absence of both rotor current controller and crowbar protection, the positive sequence impedance remains roughly the same as the negative sequence impedance. This would help establish sequence networks equivalent for DFIG-based wind farm under minimal control actions.

Based on the results obtained in Table 7.3, the Sequence Network Equivalents for DFIG-based wind farms can be approximated as shown in Figure 7.25. Smaller values and minor differences have been ignored.

It can be said that sequence impedance equivalents of the DFIG-based wind turbine may be achieved under certain conditions. These networks could be used to estimate short-circuit current values for DFIG-based wind farms. These sequence networks equivalent models may provide the protection engineers an estimated value with calculated margin of error for steady-state and dynamic fault current values for existing and future wind farms. However, the exact impacts of rotor controller on sequence impedance still need to be investigated. Those impacts are modelled in Figure 7.25 as a dependent current source.

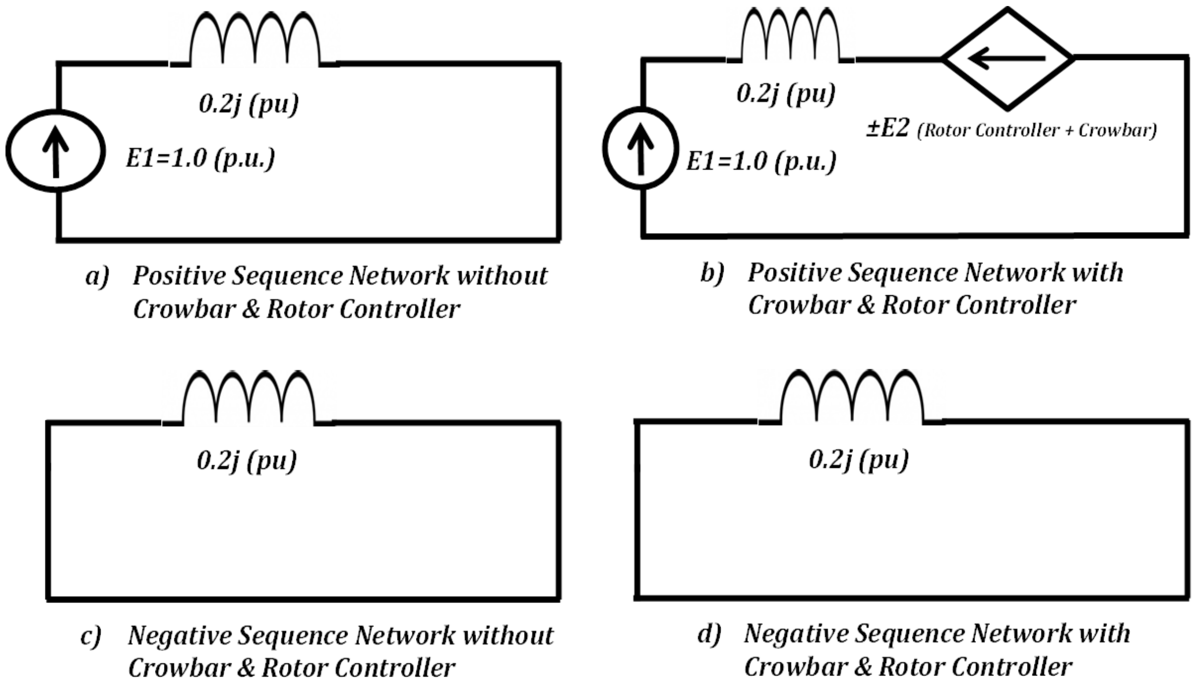


Figure 7.25: SNEs for DFIG-based Large Wind farm

In practice, a three phase winding produces normal rotating field because of a positive sequence set of currents, while an opposite direction field is produced due to a negative sequence set, whereas an oscillating field is produced due to a zero sequence set and it does not rotate between phase windings. These phenomena could be measured or detected through sequence filters, forming the basis for the design of protective relays. The following observations can be made based on the above case study;

- Positive sequence components are not much reliable for protection relay design of wind farms as the sequence components of voltage and current are not reliable. These components are influenced by the positive sequence control of rotor current controller and as well as crowbar protection. These components could also be modified by any other controls offered by modern wind farms such as advanced PQ controllers or Maximum Power Tracking (MPT) controller.

- Negative sequence components seem to be far more reliable and constant. These components vary in magnitude and phase for each fault type but negative sequence component of the impedance remains constant. This value seems to be reliable and could be utilized for designing protection relays and schemes for the wind farms. The challenge is however sensitivity and also verification of the above from actual tests.

Thus, it could be deduced that negative sequence components of impedance could be treated as reliable indicators of disturbance or fault. The above Figure 7.25 and Table 7.3 also confirm the same for the design of protective relays for large wind farms to detect the fault.

7.5 Summary

This chapter proposes a simple method of evaluating the Sequence Network Equivalents (SNE) for a large DFIG based wind farm. These equivalents can represent the wind farm in future short-circuit calculations in the transmission networks. It is shown that the sequence impedances especially in unsymmetrical fault conditions are able to capture the wind generator characteristics for balanced as well as unbalanced events. The simulation results suggest that positive sequence impedances depend on fault type, crowbar controller and rotor controller actions. It remains nearly constant if these control actions are disabled or not activated. However, the negative sequence impedance is more insensitive in all cases. It is concluded that the negative sequence impedances can serve as an indication of the contribution of wind generator contribution during the fault. Future enhancements and detailed validation of SNE for wind generators can provide accurate models for short-circuit studies for each type of wind generator.

Chapter 8: Conclusion

This main motivation of this doctoral thesis is to comprehensively address large scale wind integration in power system particularly during abnormal grid operating conditions. Though realistic case studies was used to illustrate the performance assessment for wind farms for New Zealand transmission grid, the concepts and techniques developed in this research can be applied universally.

Review of detailed literature carried out initially pertaining to large scale wind integration included; global wind penetration levels; grid code requirements; fault ride-through capability of WTGs; New Zealand electricity industry and its wind integration experience; and, system/special protection requirements.

Subsequently, following three areas were identified as main research requirements:

- Detailed research was needed towards robust ride-through criteria development methodology from a transmission viewpoint.
- A detailed assessment was required to quantify the level of fault current contribution from each WTG type to help improve existing protection schemes in the context of higher level of penetration especially for weak grid interconnection scenarios.
- An analytical framework or method was missing to estimate fault currents for convertor based WTGs such as DFIGs. A need existed to come up with a technique that will help quantify equivalent impedance to estimate fault current contribution from these wind farms.

New Zealand has been selected as a case study to carry out fault ride-through criteria development. This thesis provides a comprehensive review of the New Zealand power system prior to doing so. The establishment of FRT requires specialized analysis, data set and other network related aspects to be taken into consideration. This research assessed existing wind generator technologies from a FRT capability viewpoint, and system aspects and the methodology has been proposed to be considered and adopted for New Zealand to develop a voltage envelope for its grid. Further, actual proposed ride-through envelopes for New

Zealand North and South Islands' grids have been presented. This part of the work was carried out in collaboration with Transpower; Transmission System Operator. These criteria have been compared with other existing global standards. In the context of wind integration protection studies, FRT criteria play an important role during protection coordination. Future improvements, directions and recommendations were also identified.

Existing literature related to wind farm protection, identifying important aspects for the design of protection for various WTG types, has been reviewed. WTG types have been illustrated and equivalent short-circuit models presented to form the basis of a comparative fault behaviour assessment. Results obtained from case studies; developed in DIgSILENT® PowerFactory have been utilised to analyse the fault behaviour for four common WTG types. Their responses have been discussed comparatively to analyse their impacts on protection operation and performance under a weak grid interconnection situation. Distance, differential and over-current protection operation and performance have been assessed for each WTG type. Impacts on fault current because of wind farm model order type, time-step duration and additional controls within wind farms are also identified. All these aspects have significant impact in achieving the correct current magnitudes for protection relay configuration. A summary of the performance of three different protection schemes against four different WTG types is presented in section 6.7.4. Practical challenges and implementation issues identified in Section 6.8 need to be addressed by improving cooperation between wind generators and transmission system operators.

A simple method of evaluating the Sequence Network Equivalent (SNE) for large wind farms was proposed in Section 7.5 It is shown that the sequence impedances, especially during unsymmetrical fault conditions, are able to capture the wind generator characteristics, controls and protections for balanced as well as unbalanced events. The simulation results suggest that the positive sequence impedances depend on fault type, crowbar controller and rotor controller actions. It remained nearly constant if these control actions are disabled or not activated. However, the negative sequence impedance was not impacted by unit control in all cases. Thus, it can be inferred that the magnitude of negative sequence impedances could serve as robust indication for wind generator contribution during grid faults.

Future enhancements and detailed validation of SNE for wind generators could be used to provide accurate models for short-circuit studies for each type of wind generator. These can then be used to represent the wind farm for short-circuit calculations for planning studies.

8.1 Main Contributions

The main contributions of this research are as follows:

- Development of ride-through criteria methodology and identification of the role of protection schemes on FRT criteria.
- Assessment of fault current and voltage levels for available WTG technology types and identification of possible protection performance issues for large wind farms.
- Development of technique to propose a new method to identify minimum fault impedance for convertor based WTGs through a symmetrical component method.

8.2 Significance of the Contributions

This research helps better understand the responses from various WTG technologies in terms of voltage and current levels during the abnormal transmission grid operating conditions. Fault ride-through criteria and their interdependence on protection clearance times; fault current behaviour of wind farms and the impacts on protection design; and estimation of positive sequence impedance to calculate fault current contributions, are the three main outputs delivered through this research.

Investigation on FRT criteria development provides a pathway for utility companies to develop their own FRT criteria factoring necessary considerations identified in this thesis. Understanding fault current response from WTGs helps to formulate guidelines for relay manufacturing companies as well as transmission companies, to deal with identified protection performance issues. Estimation of the symmetrical component based impedance model for a wind farm whose control model is not known; can be of great value during utility planning processes. These planning processes help finalise larger investments for grid upgrade plans.

The contributions from this research could also inspire towards development of better control and protection techniques by wind turbine-generator manufacturers.

8.3 Challenges

With rapid advancements in control and integration aspects of wind technology, research on large scale wind integration issues is topical. Due to commercial sensitivities, sufficient literature related to some of the modern wind turbines and generators are not readily available. Standardisation of a mechanical model type of wind farm is also an on-going challenge. Different simulation packages use different model types and it is challenging to compare results derived using different packages. This generates more confusions and uncertainties while dealing with simulation and validation results. For this research, the author has primarily used RMS simulations using DIgSILENT® PowerFactory. Most of the system faults are unbalanced in nature but some of the newer wind technologies have not been modelled for unbalanced dynamic studies. Public access is a challenge for unbalanced models from turbine manufacturers to help validate generator models using real fault data, normally unbalanced in nature. The author in this work has used all generic/standard models available with the simulation platform. There is a strong assumption that using standard models does not have any impact on the standard fault response of WTG types. However, proprietary controls offered by each manufacturer may alter the response slightly in terms of current, voltage and power injection during the fault. This will need to be verified in future.

Another challenging task is the data acquisition from WTG owners/operator. This is needed for the models to be validated and tested against various dynamic studies and can be made possible if recorded data is made available. During the course of this research, the author tried unsuccessfully to acquire real data from wind generator operators. Therefore, to illustrate the concepts developed in this research the author has used data extracted from case studies developed using simulation platform. In future as wind farms become more commonplace, like traditional generation, this challenge is expected to disappear and standardised methods for integration control and protection will emerge.

8.4 Future Work

Future directions identified that can be built upon this research are:

1. Investigation on High Voltage Ride-through Criteria
2. Development of national level FRT criteria for HVDC interconnected grid.
3. Investigation and validation of protection performance of wind generators using real data.
4. Validation of Symmetrical Network Equivalent models through real data.
5. Identification of the role of reactive compensation or Flexible AC Transmission Systems (FACTS) devices on fault current levels and protection performance of wind farms.

Appendices

Appendix A

TABLE A-1: PARAMETERS FOR FSIG AND DFIG GENERATORS

Parameter	Representation	Value
Rated Voltage	V	0.69 kV
Rated Power	Pm	2 X 20 MW
Rated Power Factor	pf	0.8799
Efficiency	η	98%
Nominal Frequency	fm	50 Hz
Nominal Speed	Nm	1485 rpm
No. of Pole Pairs	N	2
Stator Resistance	Rs	0.00889 pu
Stator Reactance	Xs	0.1
Rotor Resistance	Rr	0.1022388 pu
Rotor Reactance	Xr	o.1017394 pu
Magnetizing Reactance	Xm	3.1198 pu
SVC Rating	Q	23 MVAR

TABLE A-2: PARAMETERS FOR DFIG CONVERTER

Parameter	Representation	Value
d-Axis Current Gain	Kd	0.05
d-axis Time constant	Td	0.013
q-Axis Current Gain	Kq	0.05
q-axis Time constant	Tq	0.013
Max Rotor Current for Crowbar	MaxIr	1.3 pu
Crowbar Bypass Time	Tbypass	0.06 s
Additional Rotor Crowbar Resistance	Ra’	0.1 pu

TABLE A-3: PARAMETERS FOR FSFC

Parameter	Representation	Value
Rated AC Voltage	Vac	0.4 kV
Rated DC Voltage	Vdc	1 kV
Rated Power	Pm	40 MVA
Short-circuit Impedance	Zsc	10%
Copper Loss	Pc	120 kW
AC Voltage Set point	Set Vac	1.05 pu
DC Voltage Set point	Set Vdc	1.00 pu
Chopper Rating	Ich	40000 A
Reactive Power Limits	+/- Q	+/- 0.4 pu

TABLE A-4: PARAMETERS FOR SYNCHRONOUS

Parameter	***Representation***	***Value***
Rated Voltage	V	33 kV
Rated Power	Pm	40 MW
Power Factor	Pf	0.8
Bus Type	Type	PV
Reactive Power Rating	Qm	20 Mvar
Bus Voltage	Vb	1.05 pu
Nominal Frequency	fm	50 Hz
d-axis Syn. Reactance	Xd	2 pu
q-axis Syn. Reactance	Xq	2 pu
Transient Reactance	Xd'	0.3 pu
d-axis Sub transient Reactance	Xd''	0.2 pu
q-axis Sub transient Reactance	Xq''	0.2 pu
Leakage Reactance	Xl	0.1 pu
Acceleration Time Constant	Ta	10s

TABLE A-5: NETWORK PARAMETERS

Parameter	***Representation***	***Value***
Max. Short-circuit Power	Sk'' max	9999 MVA
Min. Short-circuit Power	Sk'' min	150 MVA
Reactance to Resistance Ratio	X/ R	10
Resistance Ratio	R0/R1	0.1
Reactance Ratio	X0/X1	1
Impedance Ratio	Z2/Z1	1
Acceleration Time Constant	Ta	9999 s

TABLE A-6 SYMMETRICAL COMPONENT CASE STUDY DFIG PARAMETERS

Parameter	***Value***
Rated Mechanical Power	2000 kW
Rated Reactive Power	0.2 Mvar
Efficiency at nominal Operation	98%
Nominal Frequency	50 Hz
Nominal Speed	1485 rpm
No of Pole Pairs	2
Inertia:	100 kgm2
Stator Resistance	0.0088 pu
Stator Reactance	0.1 pu
Mag. Reactance	3.12 pu

TABLE A-7: NORTH ISLAND CONTINGENCIES

Region	***Contingent events***	***Condition***
Northland	HEN-SWN-1	TUV
	MDN-MPE-1	TUV
Auckland	OTA-PEN-5 or 6	TUV
Upper North Island	OTC G1	TUV
	HLY G5	TUV
	HLY-OTA-2	TUV
	OHW-OTA-1	TUV
	HLY-DRY-1(committed upgrade)	TUV
	WKM-BRH (committed upgrade)	TUV
Waikato	HAM-WKM-1	TUV
	ARI-HAM-1 or 2	TUV
	BOB-HAM-1 or 2	TUV
	HAM-WHU-1 or 2	TUV
	HLY-TWH-1	TOV
BOP	OHK-WRK-1	TUV
	ARI-KIN1 or 2	TUV
Hawke's Bay	RDF-WHI-1	TUV
	FHL-RDF-1 or 2	TUV
Taranaki	SPL G1	TOV
	BRK-SFD-3	TUV
	HWA-WVY-1	TUV
Central North Island (Bunnythorpe)	BPE-MTR-OKN-ONG	TUV
	TKU-WKM-1 or 2	TUV
	BPE-WDV	TUV
	MGM-WDV-1	TUV
	SFD-TMN-1	TUV
	BPE-TKU-1 or 2	TUV
Wellington	BPE-TWC-LTN-1	TUV
	Pole 2	TOV
	HAY-TKR-1 or 2	TUV
	HAY-UHT-1 or 2	TUV

TABLE A-8: SOUTH ISLAND CONTINGENCIES

Region	**Contingent events**	**Condition**
Nelson/Marlborough	ISL-KIK-2 or 3	TUV
	BLN-KIK-1	TUV
	KIK Statcom (committed upgrade)	TOV
West Coast	IGH-RFN-ATU	TUV
	HOR-ISL-1 or 2	TUV
	COL-OTI-2	TUV
Upper South Island	ASB-TIM-TWZ-1 or 2	TUV
	ISL-TKB	TUV
Otago / Southland	CYD-CML-TWZ-1 or 2	TUV
	CYD-CML-TWZ-1 or 2 -CB fail event	TUV
	Pole 2	TOV
	TWI pot line	TOV
	INV-ROX	TUV
	GOR-ROX-1	TUV
	BAL-BWK-HWB-1	TUV

APPENDIX B

New Zealand North Island Power System Network Model

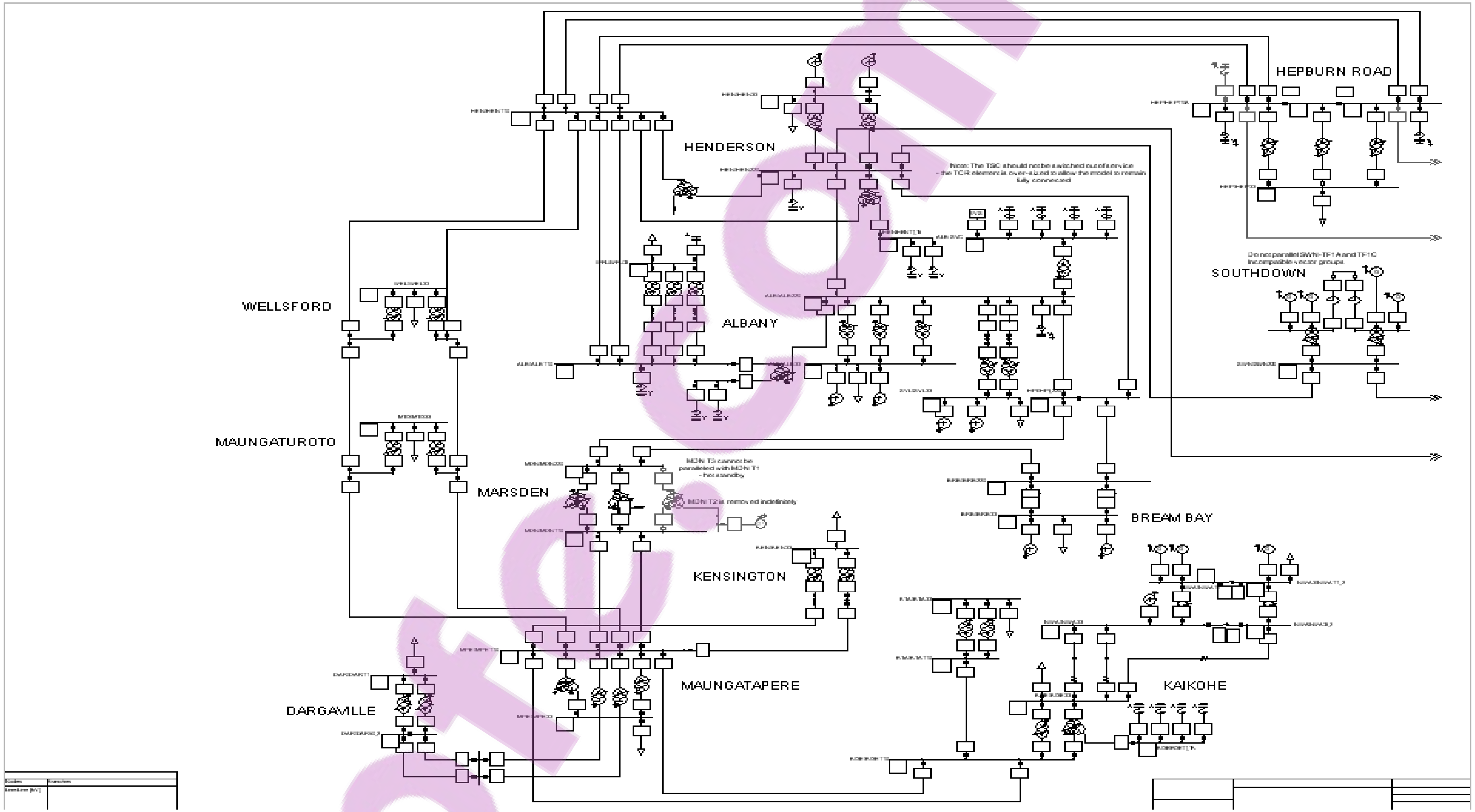
This appendix is a reference to the New Zealand North Island Power System (NIPS) network models in DIgSILENT® PowerFactory. The dynamic models of the NIPS are based on asset capability information provided by asset owners. In many cases, the dynamic models have not been validated against recent test results. In addition, information for some parts of the dynamic models is not available, and these elements have been modelled under a certain set of assumptions. Generic models have been applied for some wind generation technologies. These generic models do not represent the details of the controls of any particular wind turbine manufacturer. Table B-1 provides the load flow results on the complete NIPS model.

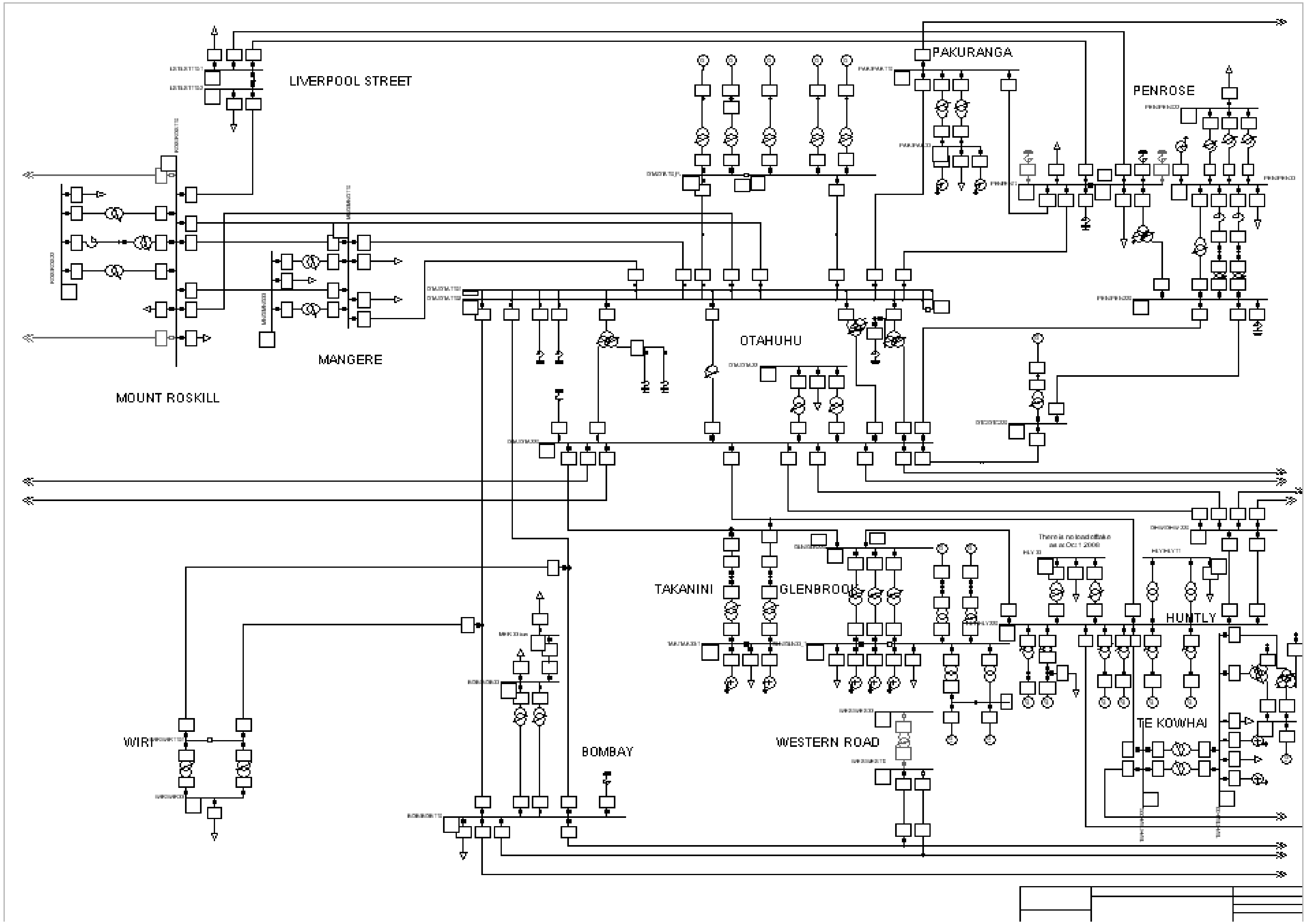
TABLE B-1: LOAD FLOW OF THE NIPS MODEL

Item	MW	MVAr
Generation	3546.9	523.1
HVDC	-688.0	294.0
Load	4187.6	808.9
Losses	137.3	364.2
Capacitors	0.0	-944.1
Reactors	0.0	0.0

Note: the negative load flow (i.e. -688MW) indicates the power is flowed from the South Island power system to the North Island power system through the HVDC line.

DIgSILENT® PowerFactory NIPS Snapshot

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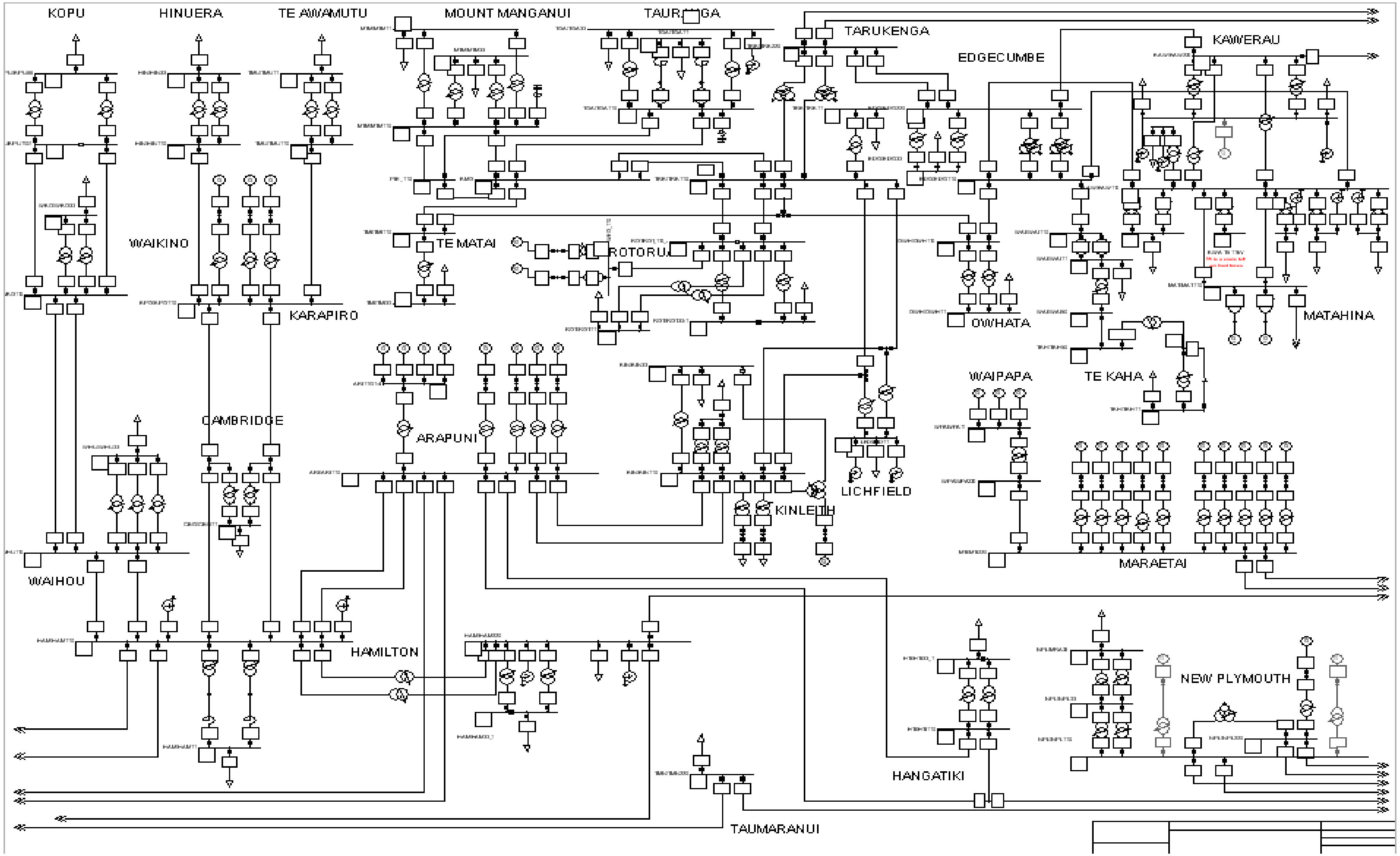
PAKURANGA
PENROSE
MANGERE
MOUNT ROSKILL
OTAHUHU
TAKANINI
GLENBROOK
HUNTLY
TE KOWHAI
WIRI
BOMBAY
WESTERN ROAD
There is no load offtake as at Oct 1 2008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ROTORUA
KARAPIRO
OWHATA
MATAHINA
WAIPAPA
TE KAHA
CAMBRIDGE
ARAPUNI
LICHFIELD
KINLEITH
MARAETAI
WAIHOU
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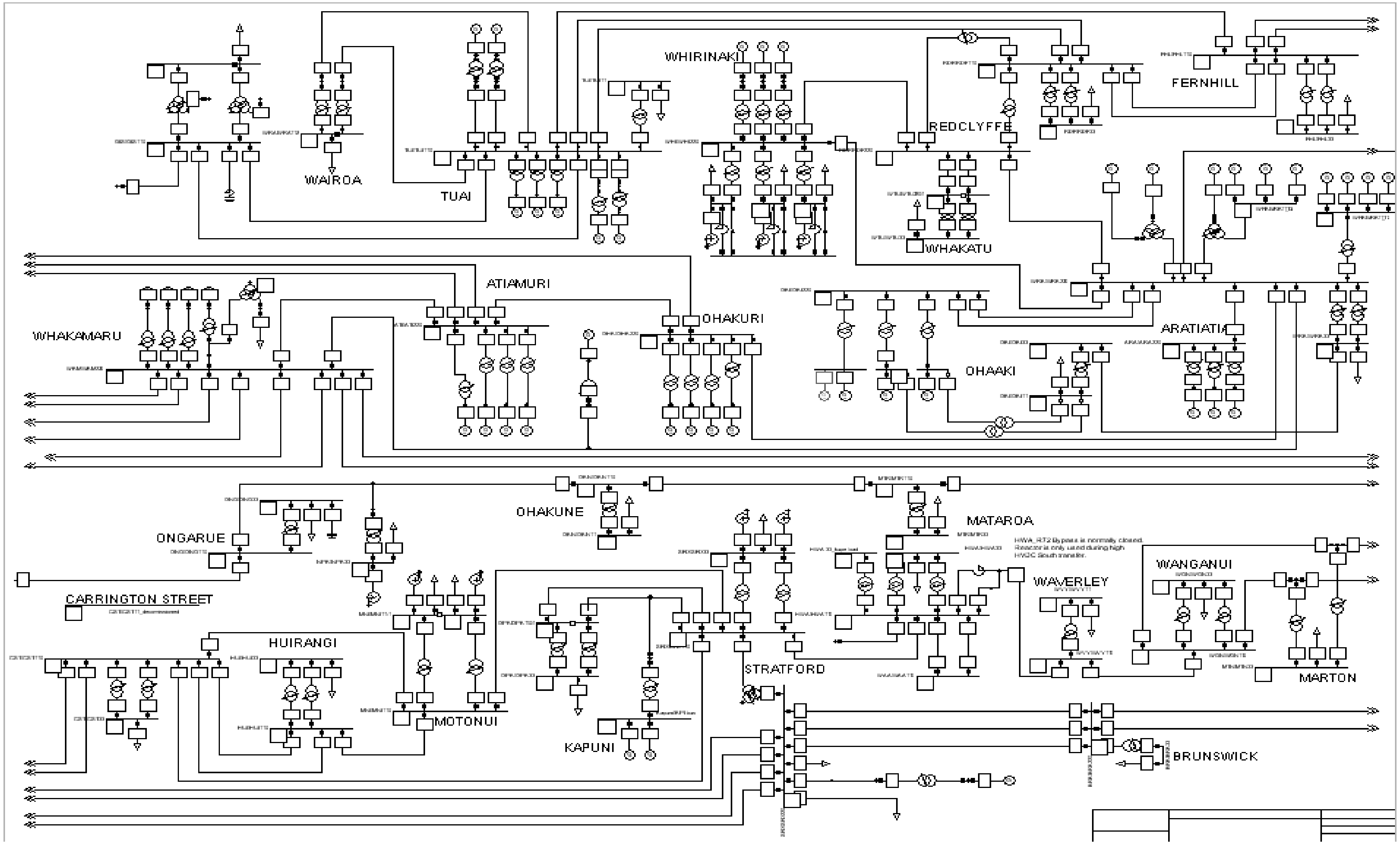
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WHAKATU
WHAKAMARU
ATIAMURI
OHAKURI
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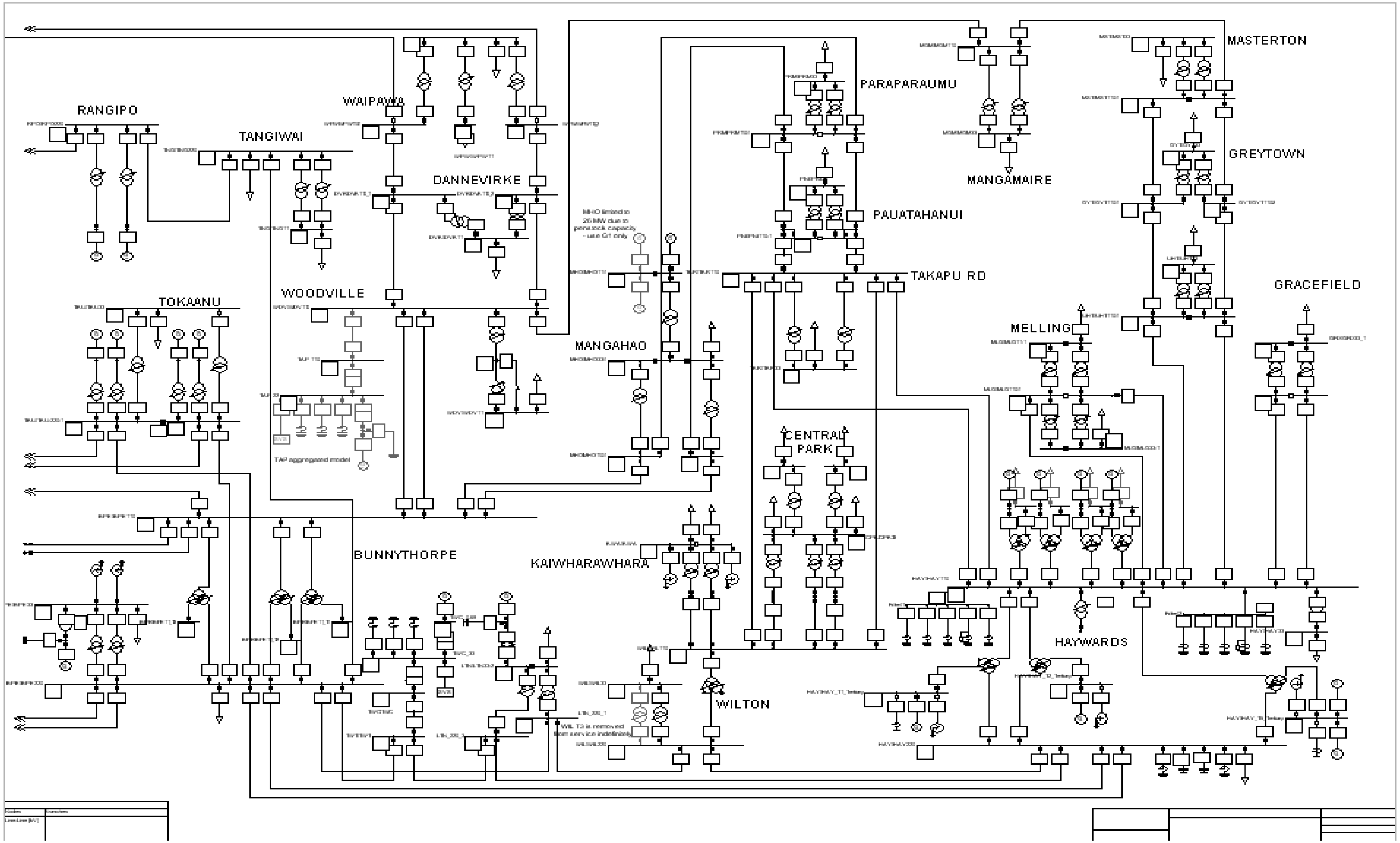
ARATIATIA
ONGARUE
OHAKUNE
MATAROA
CARRINGTON STREET
HUIRANGI
MOTONUI
KAPUNI
STRATFORD
WAVERLEY
WANGANUI
MARTON
BRUNSWICK
HWA_RT2 Bypass is normally closed.
Reactor is only used during high
HVDC South transfer.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WAIPAWA
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TOKAANU
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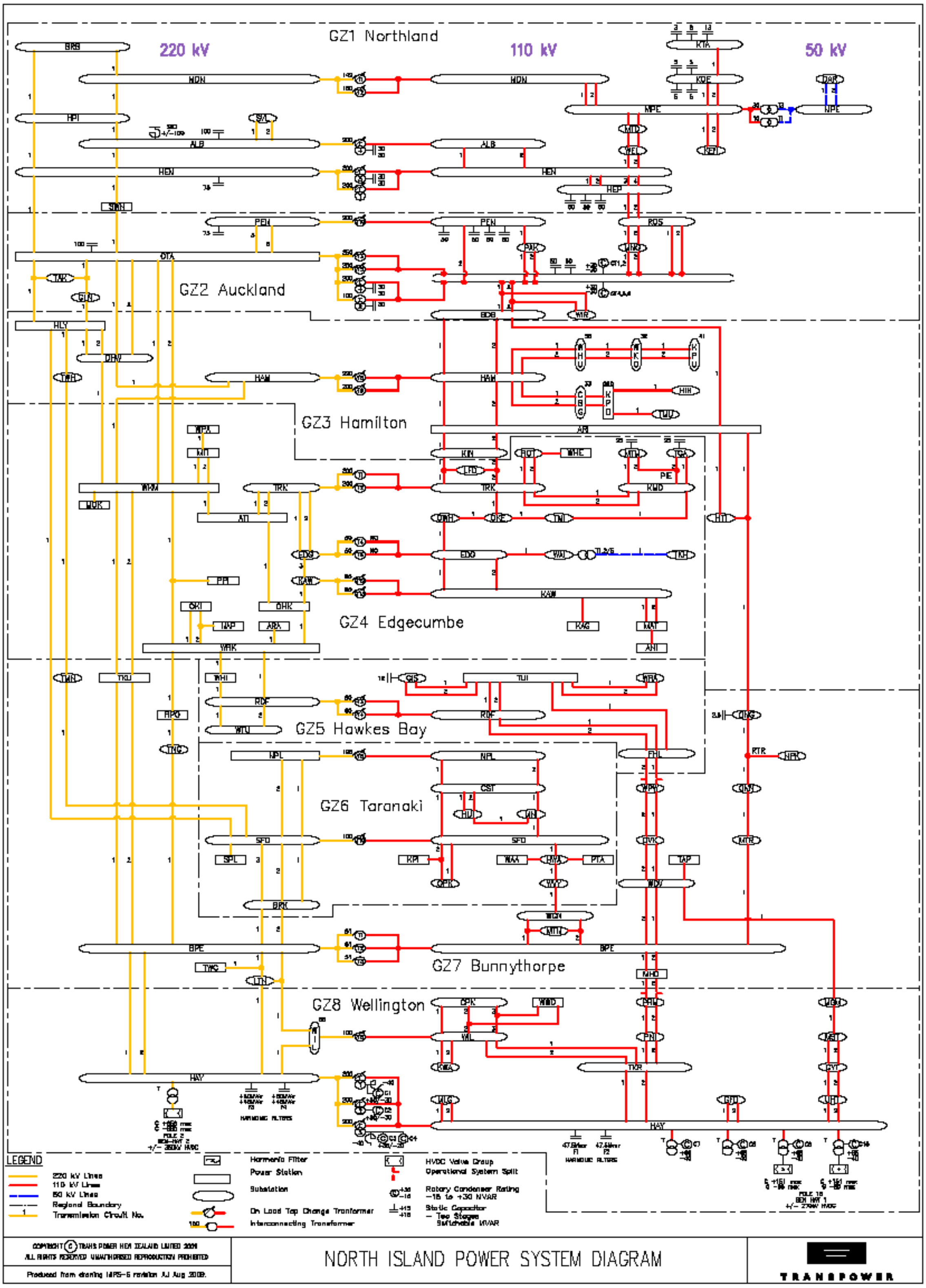
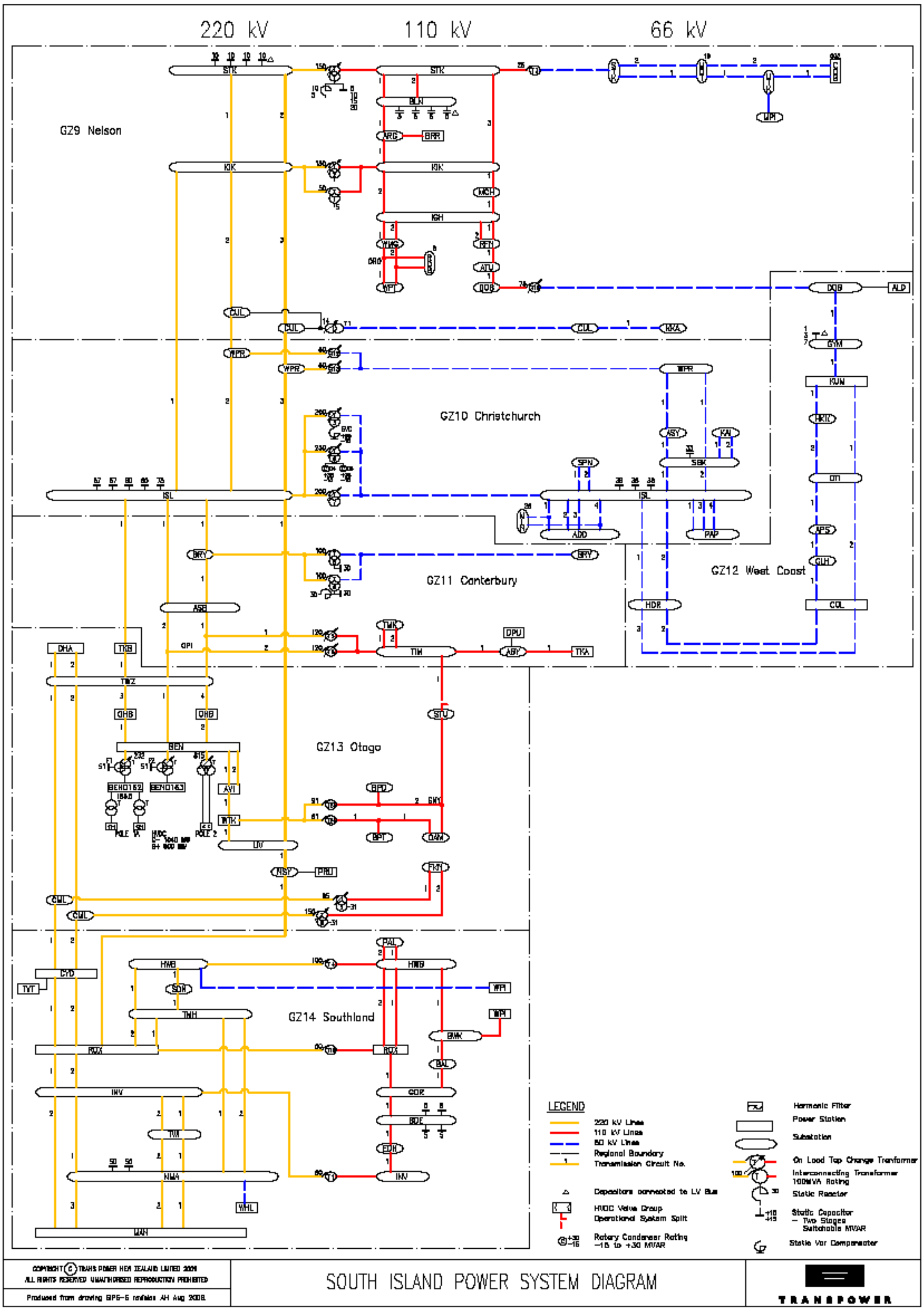
PARAPARAUMU
PAUATAHANUI
TAKAPU RD
CENTRAL PARK
MANGAMAIRE
MASTERTON
GREYTOWN
GRACEFIELD
MELLING
HAYWARDS
TAP aggregated model

North Island Power Systems Diagram



South Island Power Systems Diagram



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