Generator Fault Ride Through (FRT) Investigation

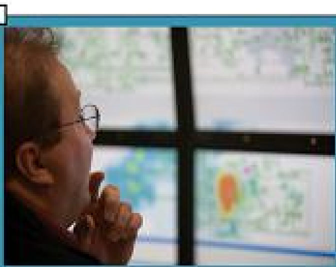
Stage 1

Literature Review

GEN FRT: S1

Feb 2009

TRANSPOWER



SYSTEM OPERATOR

Keeping the energy flowing

Version	Date	Change
1	26 Jan 2009	Draft
2	04 Feb 2009	Final

	Position
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Executive Summary

Introduction

The New Zealand power system frequently experiences voltage and frequency disturbances that are different to those experienced on large well-interconnected continental power systems around which ride through capability has been designed. In New Zealand, generation will not only be required to remain connected during low voltages during and following faults, connection will need to be maintained during frequency excursions following the loss of large generating units or HVDC transfer into the receiving island and also during high voltages and high frequencies following the loss of the HVDC link. At present there are no technical requirements for generator voltage ride through capability.

This project aims to formulate voltage ride through (VRT) requirements for all generation connected to the New Zealand power system. One outcome will be the determination of ***voltage-duration profile(s)*** or a ***voltage-duration envelope*** for the New Zealand power system. The System Operator would be responsible for operating the power system within the voltage-duration profile. Generation and other system plant would be expected to remain connected for voltages within the voltage duration profile and not have a detrimental effect on the ability of the System Operator to maintain system voltage within this envelope/profile. The specification of such a requirement will allow generators to incorporate these performance requirements in the design of generation installations and provide a benchmark for manufacturer type testing and commissioning testing. The requirement for additional dynamic reactive support would be identified by comparing generator capability against the VRT requirement.

It is expected that the outcome of this investigation will provide VRT requirements for incorporation into the Electricity Governance Rules (EGRs). Factors relevant to the development of a VRT requirement such as international grid codes, New Zealand power system issues, fault types and locations, performance of protection systems and the low voltage ride through capability of connected plant are examined.

Stage 1 Conclusions

For stage 1 of the project, background documentation associated with the Transpower network including protection operation and clearance times, indicative voltage-time durations and existing planning requirements are documented. In addition international grid code requirements and the ability of wind generators to ride through faults are reviewed.

Woodville 110 kV post-fault voltage studies indicate that although the VRT profile specified for HVDC equipment may be suitable to capture voltage drops following 220 kV faults, it will not be suitable to describe the requirements following 110 kV faults.

From 220 kV HVDC protection settings and the indicative Woodville 110 kV post-fault voltage studies, it is clear that the voltage observed on the 220 kV network and the 110 kV network could be significantly different due to the different protection philosophies employed. Key voltage-time markers for the 220 kV network can be extracted from main (1^{st} and 2^{nd} main) and circuit breaker fail (CBFail) protection operation times. For the 110 kV network voltage-time markers include main (zone 1 and 2) and back up protection. The data points upon which an initial voltage-duration profile can be based are given below.

Undervoltage Criteria

220 kV voltage-duration profile to capture the following points:

- 220 kV voltage is likely to drop to 0% for 0.12 s following a 220 kV fault
- 220 kV total fault clearance time 0.35 s following a 220 kV fault
- 220 kV voltage to recover to 40%-80% following 220 kV fault clearance
- 220 kV voltage to recover to 80% within 0.5 s
- 220 kV voltage to recover to 90% within 1-3 s

110 kV voltage-duration profile to capture the following points:

- 110 kV voltage is likely to drop to 0% for 0.2 s following a 110 kV fault
- 110 kV voltage may recover to 10%-60% following a 110 kV fault and an initial zone 1 (0.2 s) clearance
- 110 kV voltage may recover to 40%-80% following final 110 kV fault clearance by zone 2 or back up protection
- Zone 2 & back up protection clearance times vary
  - 0.35 s for circuits with protection signalling
  - 0.60 to 1.0 s for circuits without protection signalling
- 110 kV voltage may recover to 90% within 4-6 s.
  - 110 kV back up protection operation up to 4-6 s

Overvoltage Criteria

Initial recovery overvoltage criteria can be based on the grid planning guidelines [4] and international standards.

- 220 kV and 110 kV voltage may rise to 1.3 pu following a fault until special Protection Schemes operate to reduce voltage within a time period of 0-200 ms
- Voltage may recover to 1.2 pu in less than 0.5 s following action of Special Protection Schemes
- Voltage will recover to below 1.1 pu in less than 1 s

The DC Hybrid Link Project [9] indicates that voltage may rise to 1.43 pu, when the pre-fault voltage is 1.1 pu in the region of the HVDC link. High overvoltages (above

1.3 pu) may also be observed in Southland following the loss of a pot-line at Tiwai, or in areas with large capacitor bank installations such as Islington and Kaitaia following a network fault. Generation wishing to connect in regions where pre-fault voltage is high, close to HVDC terminations (Haywards and Benmore), Southland (Tiwai) or Islington/Kaitaia, may need to be able to comply with the more onerous overvoltage criteria given below.

- 220 kV and 110 kV voltage may rise to 1.43 pu following a fault until Special Protection Schemes operate to reduce voltage within a time period of 0-200 ms.

- Voltage may recover to 1.32 pu - 1.2 pu in less than 0.5 s following action of Special Protection Schemes.

- Voltage will recover to below 1.1 pu in less than 1 s.

Following a review of fault ride-through requirements of other countries and indicative voltage-durations at the Woodville 110 kV bus following network faults, it is expected that a Low Voltage Ride Through (LVRT) profile for 220 kV busbars will compare well with voltage-time profiles specified by other Transmission System Operators (TSOs). However voltages expected at 110 kV busbars may remain low for extended periods of time particularly following faults on circuits that do not have protection signalling and are reliant upon extended zone 2 fault clearance times.

This review indicates potential issues for:

- DFIG wind generators with regard to compliance with some international grid codes.

- DFIG wind generators connected to the 110 kV network riding through remote faults with zone 2 fault clearance times > 0.2 s.

- Wind generators with Full Scale Frequency Converter (FSFC) connected to the 110 kV network riding through remote faults with zone 2 fault clearance times > 0.8 s.

- Capability of wind generators to ride through overvoltages experienced on the New Zealand power system.

System Operator wishes to avoid developing a profile based solely on protection settings that may be present on certain circuits that would lead to over-demanding voltage duration profiles. Similarly the development of a ride through requirement that does not reflect the connection voltage to which a generator is connected or may wish to connect to may also seem over-demanding.

Stage 1 Recommendations

This report recommends the development and introduction of a VRT requirement in the EGRs. A requirement should specify a voltage-duration profile as a means to measure and compare power system performance and plant (load and generator) fault ride through capability. The development and validation of a voltage-duration profile for the New Zealand power system should be based on dynamic studies. Generator active power should be restored with a minimum gradient and/or to a defined output level within a specified time. It is recommended that stage 2 of the project should develop the requirement for generator active power recovery.

It has been found necessary for studies to be undertaken to determine a suitable voltage-duration profile for the New Zealand power system simulating response following 220 kV, 110 kV and 33 kV fault studies. Consideration should be given to defining a range of VRT profile(s) for generators wishing to connect to the 220 kV network and another for those wishing to connect to voltage levels of 110 kV and below with differing levels of protection.

With limited VRT capability it may be necessary to improve the fault clearance times on sections of the transmission network. Although the System Operator is aware that technical issues associated with main and backup protection coordination, plus the potential cost of upgrades to the transmission system protection and protection signalling systems may make extensive improvements impractical. The flexibility of protection settings in the region before requiring generators to comply with a more onerous VRT requirement.

The following clarifying statements as to the application and purpose of the voltage duration profile should accompany the voltage-duration profile.

- The System Operator would be responsible for maintaining power system voltage within a specified post-fault voltage-duration profile.
- Generation and other system plant would be expected to remain connected for voltages within the voltage-duration profile
- Generation should not have a detrimental effect on the ability of the System Operator to maintain system voltage within this profile.
- The VRT standard applies to the voltage at the high voltage side of the generating plant step-up transformer, not at the generator terminals.
- The standard can be met by the performance of the generators or by installing additional equipment (e.g. SVC, etc) within the generating facility.
- The standard does not apply to faults that would occur between the generator terminals and the high voltage side of the generator step-up transformer.
- Generators may be tripped after fault initiation if this action is intended as part of a Special Protection Scheme.
- In the event that existing and new generators do not meet the voltage ride through requirements the generator may be required to apply for a dispensation under this rule.

1 Introduction

1.1 Project Overview

The Electricity Commission of New Zealand has initiated the Generator Fault Ride Through Investigation to determine a suitable Voltage Ride Through (VRT) requirement for incorporation into the Electricity Governance Rules and Regulations (EGRs).

The project has two stages:

1) Literature Review / Data Collection

2) Power System Dynamic Studies

    a. Recommendation of changes to the EGRs to incorporate a Voltage Ride Through (VRT) requirement for generators connected to the New Zealand power system.

Stage 1 reviews existing grid planning criteria, protection requirements, previous ride through studies, international standards and the ability of generators to meet VRT criteria.

Stage 2 will involve dynamic simulations to develop and verify the suitability of a voltage envelope for the New Zealand power system and determine a Voltage Ride Through (VRT) characteristic that should be met by generators wishing to connect to the New Zealand power system. This work will culminate in a specification of a Generator Voltage Ride Through requirement for incorporation into the Electricity Governance Rules and Regulations.

The scope of work can be found in Appendix A.

Overall Project Objective:

To determine a suitable requirement for incorporation into the Electricity Governance Rules and Regulations (EGRs).

1.2 Background

The New Zealand power system frequently experiences voltage and frequency disturbances that are different to those experienced on large well-interconnected continental power systems around which ride through capability has been designed. In New Zealand, generation will not only be required to remain connected during low voltages during and following faults, connection will need to be maintained during frequency excursions following the loss of large generating units or HVDC transfer into the receiving island and also during high voltages and high frequencies following the loss of the HVDC link. At present there are no technical requirements for generator Voltage Ride Through capability.

This project aims to formulate Voltage Ride Through (VRT) requirements for all generation connected to the New Zealand power system. One outcome will be the determination of ***voltage-duration profile(s)*** or a ***voltage-duration envelope*** for the New Zealand power system. The System Operator would be responsible for operating the power system within the voltage-duration profile. Generation and other system plant would be expected to remain connected for voltages within the voltage duration profile and not have a detrimental effect on the ability of the System Operator to maintain system voltage within this envelope/profile. The specification of such a requirement will allow generators to incorporate these performance requirements in the design of generation installations and provide a benchmark for manufacturer type testing and commissioning testing. The requirement for additional dynamic reactive support would be identified by comparing generator capability against the VRT requirement.

It is expected that the outcome of this investigation will provide VRT requirements for incorporation into the Electricity Governance Rules (EGRs). Factors relevant to the development of a VRT requirement such as international grid codes, New Zealand power system issues, fault types and locations, performance of protection systems and the low voltage ride through (LVRT) capability of connected plant are examined.

1.2.1 Short Circuit Faults

The occurrence and removal of short circuit faults will result in momentary voltage sag experienced across the entire power system. Protection relays are employed to detect short circuit faults and act to isolate faults in an effective and responsive manner to reduce the impact of the fault. Delays in removing faulted assets can result in the disconnection of generating units from the power system following loss of synchronism or through the action of protection systems. Similarly it is critical for all generators to remain connected during fault recovery. A long persistent severe fault or the inability for generation to ride through a fault could result in the disconnection of large amounts of generation and result in system collapse.

1.2.2 Current Obligations

The System Operator has two obligations with regard to voltage:

- manage steady state system voltages within quality targets under normal conditions and post contingency, and

- avoid cascade failure during voltage excursions.

The performance requirement for fault ride through capability is that the generator must meet the requirements of the EGRs, including assisting the System Operator to meet the PPOs, in the event of a fault. This includes remaining in service in the event of an external fault (i.e. a fault on either the transmission or distribution network external to the generator station) and returning to the pre-fault MW output rapidly after fault clearance. Generator stations may require additional dynamic voltage control in order to be able to meet this requirement.

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

1.2.3 Voltage-Duration Profile

In general, fault ride through requirements are defined by the voltage-duration profiles. For illustration purposes an example profile is shown in Figure 1.

Each point on the profile (ie the heavy black line) represents a voltage level and an associated time duration which connected generating units or power park modules must withstand or ride through. The profile is not a voltage-time response curve obtained by plotting the transient voltage response at a point on a transmission system or user system to a disturbance.

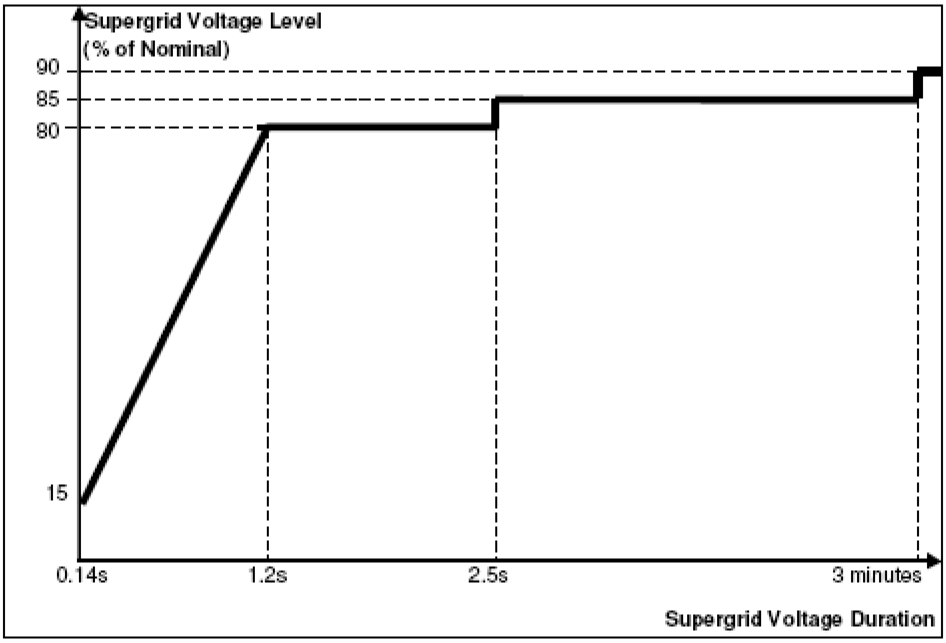

Figure 1:- Example voltage-duration profile for low voltage fault ride through [1]

1.2.4 Impact of wind generation

The New Zealand power system is not tightly meshed and does not have very high short circuit levels. Most short circuit power is supplied by synchronous generating units connected to the power system. Wind generation technologies may provide less short circuit power capability than synchronous generating units. The consequence of introducing wind generation into the power system is that some synchronous generating units will be displaced. Reduced system short circuit power reduces the power system's ability to support system voltage during short circuit faults. In addition wind generation may be in an area that is remote from the displaced synchronous generation. This will further reduce system short circuit power and the power system's ability to support system voltage during short circuit faults.

The deterioration of dynamic voltage performance as a direct result of wind generation can severely affect the ability of generation (including wind generation) to remain connected to the power system. The ability of the wind generation fleet in New Zealand to ride through power system frequency and voltage disturbances will ultimately affect the integration of large scale wind generation into the New Zealand power system.

The intrinsic characteristic of wind generation technologies such as Fixed Speed Induction Generators (FSIG) may worsen voltage sag by absorbing large amounts of reactive power from the grid after the fault is removed prolonging system voltage recovery time. This may result in instability in power system operation. Improvements in wind generation technologies led to the development of Doubly Fed Induction Generator (DFIG) and Full Scale Frequency Converter (FSFC) technologies that have a better dynamic voltage performance as compared to the FSIG technology. The faster and more agile power electronic control with inbuilt low voltage ride through capability enable DFIG and FSFC wind generation technologies to be less susceptible to system faults.

The analysis of WGIP: Investigation 9 [2] indicates that high amounts of wind generation using FSIG technology could cause voltage collapse following severe power system faults at times of light loading. The risk of voltage collapse can be reduced by installing dynamic reactive support devices at the wind farms or by limiting the amount of FSIG wind generation at times of light load. The “Discussion” section of WGIP investigation 9 is presented in Appendix 4 for reference purposes.

2 The New Zealand Power System

2.1 Simulated Faults

Transmission 2040 Grid Planning guidelines state that the power system should remain stable for the following fault types: [3] [4]

- a sudden disconnection of any plant including a generating unit;
- a 3-phase fault on a circuit close to a substation cleared in main protection clearance time by opening the circuit breakers at each end of the circuit to disconnect the circuit;
- a single-phase to earth fault on a circuit cleared by the back-up protection operation of the circuit breakers at each end of the circuit;
- a 3-phase fault on a transformer followed by disconnection of the transformer
- a single-phase to earth fault on any circuit cleared by circuit breaker failure protection of the relevant back-up circuit breakers;
- a 3-phase fault on a bus section cleared by the bus zone protection operation of all circuit breakers connected to the faulted bus section; and
- a single-phase to earth fault on a circuit close to a substation cleared in main protection clearance time by opening the circuit breakers at each end of the circuit and reclosing on fault with subsequent reopening of the circuit breakers at each end to disconnect the circuit.**

Transpower may also examine the following disturbances in order to assess the impact of the events, but they may not necessarily have an influence on investment decisions:

- a 3-phase fault on a circuit close to a substation cleared in main protection clearance time by opening the circuit breakers at each end of the circuit and reclosing on fault with subsequent reopening of the circuit breakers at each end to disconnect the circuit;**
- a 3-phase fault on any circuit cleared by circuit breaker failure protection of the relevant back-up circuit breakers; and
- a 3 phase fault on a circuit cleared by the back-up protection operation of the circuit breakers at each end of the circuit.

** The impact due to this disturbance may be reduced by altering the auto-reclose time to a longer delay

2.2 Use of Auto-Reclosing CBs

Auto-reclose enables circuit breakers to automatically close a set number of times following a circuit fault in order that service can be quickly restored following a temporary fault [3]. The following is a summary of the auto-reclose sequence:

1) The circuit protection starts the reclose sequence when it issues a trip.

2) The auto-reclose relay waits a while, the “dead time”, for the fault to clear.

3) At the end of dead time, auto-reclose sends a close command to the circuit breaker.

4) The auto-reclose then waits a while, the “reclaim time”, before getting ready to perform the sequence again (Transpower schemes are self resetting).

The dead time is typically 1 second on Transpower transmission circuits. Longer dead times are found where older CB’s are installed, typically 2 seconds but may be up to 3 seconds. Dead line charge and synchronisation check schemes often have longer dead times typically 4.5 s to 10 s on 220 kV. The reclaim time is typically 10 s or 15 s on Transpower transmission circuits.

A number of feeder circuit breakers have multi-shot auto-reclose, commonly 2 shot but can be 3 shot. These schemes often have 10 second dead times and 60 second reclaim times.

Automatic reclosing may be employed on all transmission lines to enhance security. However, the system must be planned such that the system is stable without re-closure. The system must also be tested for stability with unsuccessful operation of the auto reclosing facility. If studies show that fast reclosure onto a fault makes the system unstable, the dead time may be increased sufficiently to make the system stable. Alternatively, auto-reclose may be enabled for a single-phase fault and disabled for a 3-phase fault.

Auto-reclosing at line terminals that are in electrical proximity to turbine-generators may subject them to excessive shaft torque and winding stresses with resultant loss of service life. These effects should be evaluated before auto-reclosing is applied.

Auto-reclosing a region (with only one substation or group of substations) connected to the main transmission grid through a single circuit with no generators or limited generation in the region can cause voltage and/or frequency disturbances. There is a possibility of sustained low voltage or even voltage collapse depending on the type of load and the amount of load. These effects should be evaluated fully before applying auto reclosures.

2.3 Protection & Fault Clearance Times

2.3.1 Protection

Generally Transpower policy and protection philosophy is to provide on:

220 kV Transmission circuits

- Duplicate main (on branches, eg. line, transformer, cap bank)

- Line VT's
- Single main on busses (busbar protection)
- Local circuit backup ("high speed" backup)
- Main protection target fault clearance time of 120 ms
- Fault clearance times of 0.3 s to 4 s (and above) may be observed if fault is not cleared within the 120 ms target and/or unforeseen events occur due to switching and changes in network topology.
- Distance protection
- Line differential protection with signalling
- Overcurrent (CBFail)
- Directional Earth Fault (DEF)
- Directional Comparison Earth Fault is with signalling (DCEF)
- Auto-reclose (synchronisation check, dead line charge)

110 kV & 66 kV Transmission circuits

- Main and back up protection (although some parts of the system lack back up)
- Bus VTs, some circuits have line VTs
- Main protection target fault clearance time of 200 ms, however this is typically 0.5s-1s in many parts of the New Zealand network
- Fault clearance times of 0.3 s to 4 s (and above) may be observed if fault is not cleared within the 200 ms target and/or unforeseen events occur due to switching and changes in network topology
- Directional Earth Fault (DEF) and Directional Comparison Earth Fault (DCEF) on most lines. Signal aided tripping common in urban areas and where the terrain or concrete poles make discriminative fault clearance a problem.
- Pilot wire sometimes found on urban lines
- Simple overcurrent and earth fault protection may exist on radial transformer feeders
- Busbar protection and local circuit backup applied where needed, although there are exceptions (ISL 66, WIL110, HAY110)

2.3.2 Fault Clearance Times

Where the exact fault-clearing times are not known Transpower adopt the following "target" fault clearing times as default values [3] [4].

- Main protection for 220 kV circuits: 120 ms
- Main protection for 110 kV circuits: 200 ms
- Main protection for 66 kV circuits: 200 ms
- CB failure time: 350 ms
- Auto-reclose time: 1.5 s

Reference [4] states that fault ride through capability is required for main and back-up clearance of faults on supply buses and feeders. This is often the most onerous fault location for fault ride through as the fault duration is typically very long compared with faults on the transmission system, even though the voltage depression is often less severe. Reference [4] states that for the 2040 planning assessment the actual fault clearing times will be used plus and engineering margin to allow for changes in protection settings as they are reviewed and reset as a result of system developments and changed circuit loadings.

- Back-up protection for 220 kV circuits: approx. 350 ms
- Back-up protection for 110 kV circuits: 350 ms to 6 s dependent upon site

The target fault clearance time for main protection on 220 kV and 110 kV circuits is 120 ms and 200 ms respectively. In the event that main protection fails to clear the fault, back up protection is relied upon. For the 220 kV network back-up protection is set to operate in approximately 350 ms. The 220 kV network is equipped with protection signalling and back-up signalling. On 110 kV circuits the operation of zone 2 protection, back-up protection and protection signalling (if present) results in a wide range of possible fault clearance times, typical zone 2 protection clearance times are indicated below.

- Zone 2 protection for 110 kV circuits: approx. 350 ms with signalling
- Zone 2 protection for 110 kV circuits: 0.6 to 1 s without signalling or signal failure
- Zone 2 protection for 110 kV circuits: historically up to 1.2 -1.5 s (although protection is rarely set to this now)

It is important to realise that due to the nature of the New Zealand network, the varying degree of circuit protection employed; fault characteristics; the use of parallel circuits; the operation of network splits and Special Protection Schemes; unforeseen switching events; and changes in network topology, fault clearance times of up to 6 s may result.

2.4 Special Protection Scheme (SPS)

There are generally two types of Special Protection Schemes, overload schemes and runback schemes. Some of the main Special Protection Schemes on the Transpower system are listed in Table 1.

SPS Name	***Description***
Blenheim (BLN)	The loss of one (BLN) circuit may cause the remaining circuit to become overloaded. The SPS removes the remaining circuit from service. The introduction of a third circuit provides additional supply to the BLN therefore reducing the frequency of operation of this SPS.
Bombay (BOM)	Currently Disabled - SPS protects 110 kV circuits into Auckland during times of low generation.
Haywards overload scheme (HAY)	Planned Scheme.
Hawera automatic bus splitting scheme (HWA)	The HWA bus is split following HWA-WVY circuit overloads, HWA T1 off-loaded (taken out of service) to prevent backfeed.
Islington-Springston (ISL-SPN)	Following the loss of one ISL-SPN circuit, and subsequent failed reclose attempt, SPS opens breakers to disconnect the SPN busbar from the network.
Kaitimako/Tauranga/ Mount Maunganui (KMO/TGA/MTM)	The loading on circuits supplying MTM and TGA is monitored. Should a fault occur on one of the circuits and require the circuit to be taken out of service, the remaining circuits will overload. SPS scheme operates to regulate distribution of power flow on the remaining circuits.
Mangamaire (MGM) overload tripping (WDV-MGM-MST)	During HVDC south transfer, power flow on 110 kV circuits is monitored. Should circuits become overloaded breaker at MGM opens to limit flow on 110 kV lines. Other fault scenarios on the 100 kV circuits may lead to momentary loss of supply to MGM as the status of breakers at either side of the MGN bus change.
Tokannu 220 bus splitting scheme (TKU220)	During periods of high HVDC north transfer, the loss of a circuit from Tokannu may cause local circuit overloads. The overload of TKU-WKM-1/2 circuits will activate the Tokannu 220 kV bus splitting scheme. Splitting the bus will regulate flows on the remaining circuits and remove overloads.
Cobb Runback	During high generation from Cobb, the loss of one of the Cobb circuits will require Cobb generation to be run back to alleviate loading on the remaining Cobb circuit.
Coleridge Runback (COL)	Loss of one COL-HOR circuit results in dynamic instability of the Coleridge AVR. Coleridge generation is run-back to remove instability.
Manapouri Runback (MAN)	Following loss of a Manapouri circuit and overloads detected on the remaining circuits, Manapouri generation is runback. Since the introduction the SPS, Manapouri substation has been changed from a 2 to 3 bus system therefore reducing the frequency of operation of this SPS.
Maraetai (MTI) Runback	Following loss of a MTI-WHM circuit MTI generation may be run back to remove overloads on the remaining circuit.
Te Apiti Runback (stage 1) and intertrip (stage 2) Scheme (TAP)	Following overload of the BPE-WDV-1/2 and/or MGM-WDV circuits TAP generation is runback.
Whareroa Runback and intertrip (WAA)	Following overload of the HWA–SFD and/or HWA-WVY circuits WAA generation is runback.

Table 1: Special Protection Schemes (SPS)

Following the loss of a circuit on the Transpower system, remaining circuits may exceed stated capability. Generation local to the overload may be required to run-back to remove the circuit overload. Alternatively an intertrip scheme may be put into place to change the network connectivity in order to remove the overload condition. The action of Special Protection Schemes takes place within the period of voltage recovery following fault clearance.

Special Protection Schemes may not be enabled at all times. Schemes can be enabled at certain times of the day/night, times of the year (summer/winter) or under certain network operating conditions.

2.5 Protection Problems

There are power system and protection issues that may lead to longer than expected fault clearance times. The key issues associated with the New Zealand system are listed below. A brief description of the issues and the local network areas affected is provided in the following sub-sections.

- High resistance faults
- Weak infeeds / back feeds
- Unearthed systems
- System configuration changes (splitting buses, tying buses)
- Loss of signalling
- Defeating discrimination (parallel feeders/multi-feeder towers)

2.5.1 High resistance faults

High resistance faults will result in a reduction in fault current and increase in fault voltage compared to solidly connected earth faults.

2.5.2 Weak infeeds / backfeeds

Weak infeeds are when parts of the system have difficulty in providing a strong source of infeed during fault conditions. These present problems for protection to act in a fast, positive and selective manner compared to when system conditions are stronger. Weak infeeds may exist because the system impedance restricts the fault current. Alternatively, the system is/becomes supplied from a weaker source of generation (e.g. wind farm generation such as Te Apiti and Tararua wind farms).

Backfeeds may exist under fault or load condition and are often another source of weak infeed. Backfeeds normally occur when the system has undergone or is undergoing a re-configuration from either a planned or unplanned action.

2.5.3 Unearthed systems

Transpower does not intentionally operate an unearthed power system, where a system becomes unearthed automatic (protection) or manual (operator) intervention is required. Transpowers earthing system is normally provided by solid or resistively earthed star points or by an earthing transformer.

2.5.4 System configuration changes

When the system is reconfigured this may result in buses that are normally tied to become split and/or normally split buses may become tied. This may cause protection to behave in an unexpected manner or not at all for certain faults.

2.5.5 Loss of signalling

Protection signalling is typically used on the following types of protection: direct intertrips, line differential, pilot wire and distance protection (acceleration and blocking schemes). Following the loss of signalling, protection systems may not operate correctly. The detection of loss of signalling and/or the operation of co-ordinated back up protection is relied upon to clear the fault.

2.5.6 Defeating discrimination

Non-unit protection (overcurrent and earth fault) is set up to grade under defined system configurations. When the system configuration is changed the protection grading may be compromised and lead to unwanted protection operations and more widespread trippings.

2.6 Examples of Network Faults and Protection Operation

2.6.1 Three-phase fault clearance

There are relatively few examples of three phase-faults on the New Zealand power system. Those that do occur are generally extremely serious and often result in loss of supply.

The plot in Figure 2 shows the current and voltage plots for a 33 kV fault at Stoke following a cable fault at a circuit breaker terminal. The fault is initially a single phase fault that becomes a 2-phase and then a 3-phase fault, which is subsequently cleared 1.88s after initial fault inception, fault clearance is not shown on the plot.

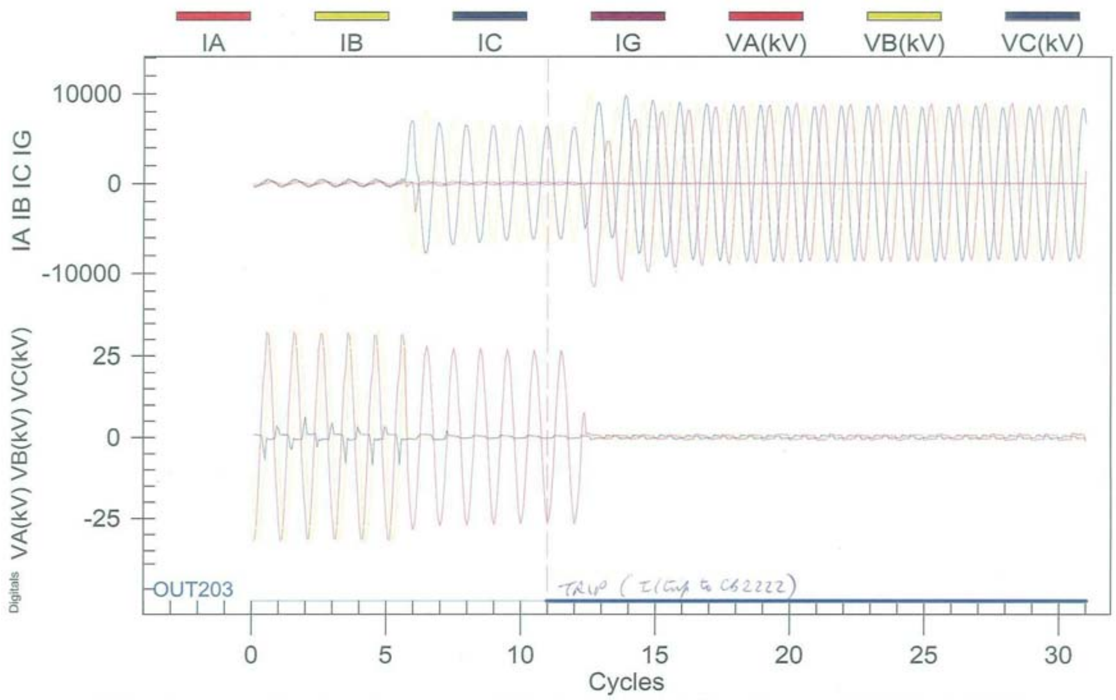

Figure 2:- Example of a 33 kV three-phase fault

The following description of the fault explains the development of the 3 phase fault and demonstrates the action of protection to clear the fault.

On 20 November 2008 at 09:42 a blue-phase-to-earth fault occurred on a cable termination of Stoke circuit breaker 2248. This circuit breaker is the bus-tie breaker that connects the Stoke indoor 33kV switchboard to the 33kV outdoor switchboard via three pairs of underground cables (two cables per phase). One of the blue-phase cables failed to ground in the termination box of Stoke circuit breaker 2248 at a point between the current transformers and the circuit breaker contacts. Initially the fault current in the blue-phase cables (as recorded by the CT's and SEL351S relay on CB2248) was 200A for 0.94s. Then the fault developed into a yellow-blue fault of 7000A in yellow and blue cables for 0.14s. Finally it became a 3-phase fault of 9000A in the cables for 0.8s. Total fault duration was 1.88s.

Once the fault had escalated to yellow-blue, there was enough fault current to allow bus zone protection on indoor Bus B2 to pick up and operate correctly to trip circuit breaker 2248. After Stoke circuit breaker 2248 tripped, fault current was then fed only from the outdoor bus to the fault location. This tripped Stoke circuit breakers 512 and 432 on phase time overcurrent protection to finally clear the fault completely.

B-phase 33 kV voltage was severely depressed throughout the fault duration; Y and B phases were severely depressed during the Y-B period and all three phases were depressed when the fault was 3-phase.

65 MW of load was lost from Stoke for 63 minutes due to this fault.

2.6.2 Single-phase fault clearance / High Resistance fault

Single phase phase-faults are a more likely event on the New Zealand power system. High resistance faults and lack of protection signalling will delay fault clearance.

The plot in Figure 3 shows the current and voltage plots for a 66 kV single phase fault on the west coast of the south island. The fault is a high resistance single phase fault, fortunately protection signalling is present and the fault it cleared approximately 320 ms after initial fault inception, fault clearance is shown on the plot.

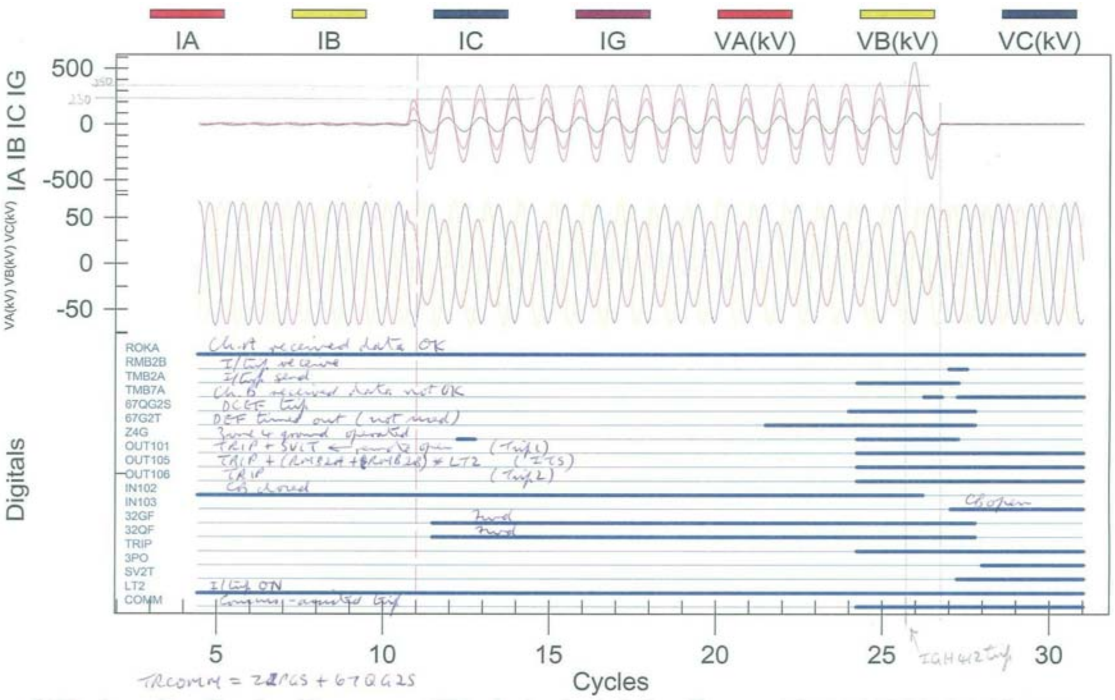

Figure 3:- Example of a 66 kV high resistance single-phase fault

On 28 July 2008 at 10:55 a red-phase-to-earth fault occurred on the west coast of the South Island. The fault current in the red-phase was 230A for 0.3 s sufficient for protection to operate and open Inangahua circuit breaker 412, an inter-trip signal triggers the operation of a second circuit breaker to clear the fault completely. Total fault duration was 0.32 s.

During the fault, voltage on the red phase fell to approximately 72% of nominal. Following operation of Inangahua circuit breaker 412 and prior to fault clearance, voltage fell to approximately 52% of nominal.

It is important to note that in the event of inter-trip signal failure or the lack of protection signalling installed on the circuit, a low voltage of 52% of nominal would have been observed for up to 4 s before protection cleared the fault.

2.6.3 Single phase fault with auto-reclose

An example of a single phase fault clearance times is given in Table 2.

Fault:	1-ph fault on Bunnythorpe-Haywards cct 1 (BPE-HAY-1) 220 kV	
Notes:	------	
Clearance time:		
	Distance 1 and 2, Zone 1 BPE	
	Distance 1, Zone 1 HAY	
	Distance 2, signal aided protection HAY	
	Total backup clearance time	***73 ms***
Auto-reclose:		
	Successful auto-reclose	***1100 ms***

Table 2: Example of fault clearance following single phase fault on BPE-HAY

The corresponding HABConnect data is shown below:

52	2008Nov27 09:28:40	BPE	742	CB CB POS OPEN
73	2008Nov27 09:28:40	HAY	592	CB CB POS OPEN
1073	2008Nov27 09:28:41	HAY	592	CB CB AR2 OPERATED
1140	2008Nov27 09:28:41	BPE	742	CB CB POS CLOSED
1188	2008Nov27 09:28:41	HAY	592	CB CB POS CLOSED

2.6.4 Operation times of back-up protection

Table 3, Table 4 and Table 5 give examples of back-up fault clearance times on the New Zealand power system.

Fault:	3-ph fault at Waipawa (WPW) on WDV-DVK-WPW-2	
Assume:	No Woodville (WDV) 110 kV local circuit backup protection, circuit breaker failure at Woodville.	
Fastest backup clearance time:		
	Zone 3 distance protection at Bunnythorpe	3000 ms
	110 kV circuit breaker opening time	100 ms
	110 kV Protection operating time	20 ms
	Total backup clearance time	***3120 ms***

Table 3: Example of back-up fault clearance following fault at Waipawa (WPW)

Fault:	3-ph fault at Ongarue (ONG) on ONG-OKN	
Assume:	No Ohakune (OKN) 110 kV local circuit backup protection, circuit breaker failure at OKN72.	
Fastest backup clearance time:		
	Zone 4 distance protection at Bunnythorpe	3000 ms
	110 kV circuit breaker opening time	100 ms
	110 kV Protection operating time	20 ms
	Total backup clearance time	***3120 ms***

Table 4: Example of back-up fault clearance following fault at Ongarue (ONG)

Fault:	3-ph fault at Waverly (WVY) on WGN-WVY	
Assume:	No Wellington (WGN) 110 kV local circuit backup protection, circuit breaker failure at Wellington.	
Fastest backup clearance time:		
	Zone 4 distance protection at Bunnythorpe	3000 ms
	110 kV circuit breaker opening time	100 ms
	110 kV Protection operating time	20 ms
	Total backup clearance time	***3120 ms***

Table 5: Example of back-up fault clearance following fault at Waverly (WVY)

2.7 Motor Recovery and Undervoltage Relay

Transpower studies for transmission upgrades into the Upper South Island have indicated that typical demand side induction motors that survive the initial fault inception will stay connected if the motor **terminal** voltage is above 0.5 pu in 0.5 s, and ramps to 0.9 pu in 5 s. The typical undervoltage relay on these motors is set to 0.8 pu for 4 s [5].

2.8 Synchronous Generator Relay Settings

High flux density levels (and overexcitation) will result from overvoltage, underfrequency or a combination of both. Overexcitation or V/Hz relaying is used to protect generators and transformers from excessive magnetic flux density levels.

There are three common protection schemes currently employed for V/Hz relaying in the industry. These schemes are the:

- single-level, definite-time;
- dual-level, definite-time; and
- inverse-time.

Inverse-time relays provide the optimal protection and operational flexibility since they co-ordinate better with the operational limits of the equipment. Figure 4 shows a typical scheme using both inverse-time and definite time relays. Figure 5 shows a typical dual-level definite-time scheme.

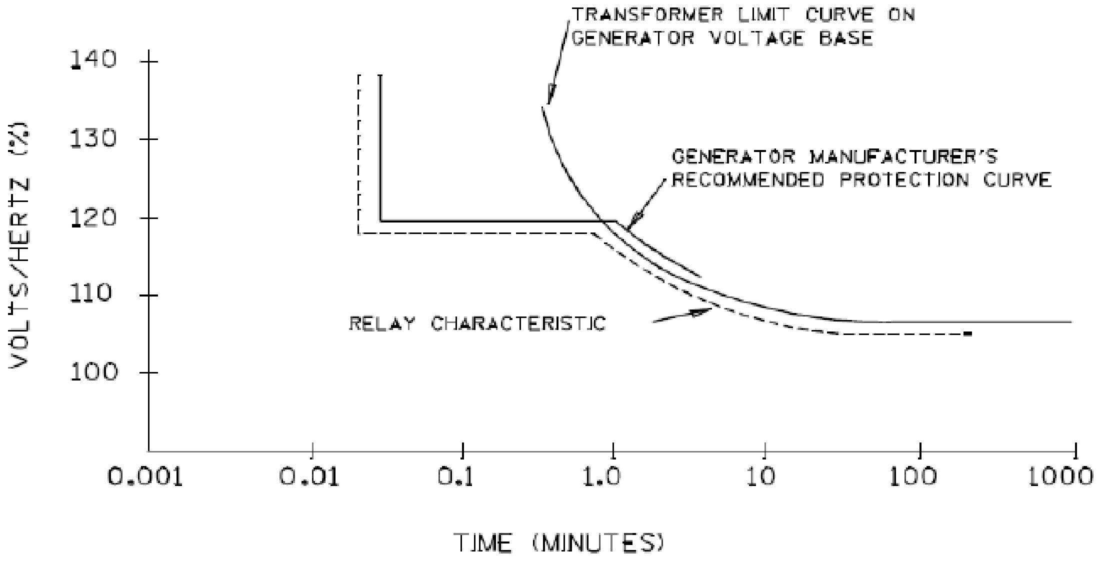

Figure 4:- Example of Setting for Inverse-Time V/Hz Relay with Fixed-Time Unit [6]

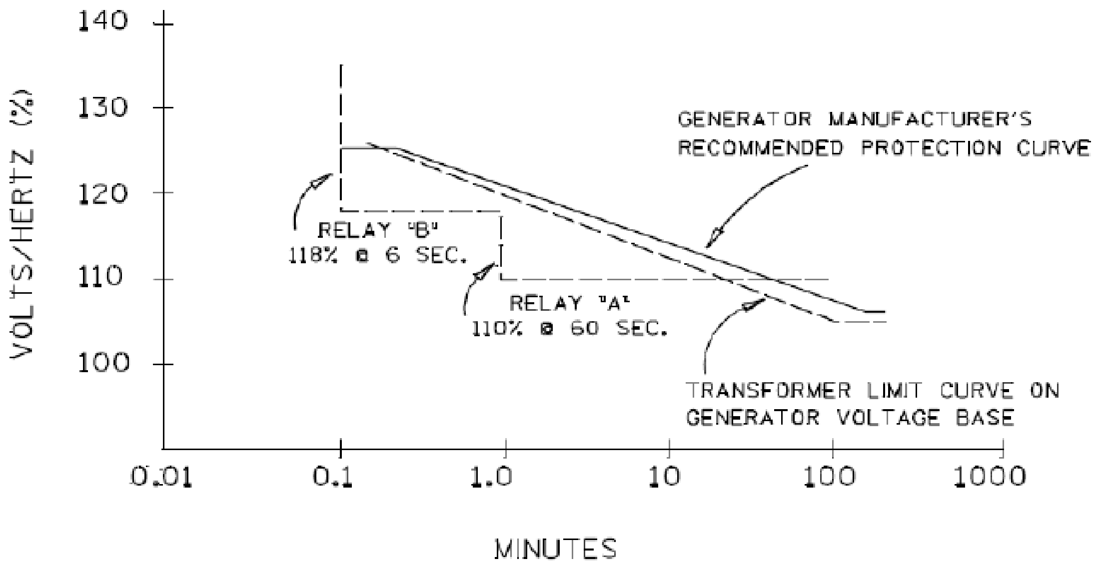

Figure 5:- Example of Setting for Dual Fixed-Time V/Hz Relay [6]

WECC assumes a 118% overvoltage limit after 1.2s as a typical synchronous generator setting to ensure that new VRT standards will not conflict with V/Hz relay curves defined in IEEE C37-102 [6] [7].

3 Literature Review - Existing Requirements

3.1 Electricity Governance Rules (2008)

3.1.1 Voltage Support

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

- having adjustable reactive power output (export reactive power at least equal to 50% of Maximum Continuous MW rating, import reactive power at least equal to 33% of Maximum Continuous MW rating) over the HV grid voltage range (e.g. 0.9 pu to 1.1 pu);

- continuously operating (when connected) in a manner that supports voltage and voltage stability on the grid; and

- having an excitation and voltage control system with a voltage set point that is adjustable over the grid voltage range and always operating in voltage control mode when connected.

3.1.2 Voltage Ride Through

The EGRs do not set out low voltage ride through capability requirements for wind or other types of generation. There is a requirement that protection systems must operate selectively and disconnect the minimum amount of plant required to remove the fault. Similarly, the EGRs do not set out the dynamic requirements for voltage support during and following faults.

3.2 Transmission 2040 Grid Planning Guidelines (2008)

Recently developed Grid Planning Guidelines drafted for the Transmission 2040 Grid Development Strategy state the following power system performance requirements:

Undervoltage Criteria: [4] [5]

Recovery criteria for undervoltage events are based on studies carried out by Transpower for transmission upgrades into the Upper North Island and Upper South Island [8].

- Voltage must be greater than 0.5 pu following a credible contingency which removes an item of equipment from service without a transmission system short circuit fault.

- All load is assumed to stay connected during the event and load is assumed to recover to its pre-disturbance level;

- Voltage on 33 kV and 66 kV buses must recover to above 0.8 pu in less than 4 seconds following a credible contingency; and

- Motor current must be maintained at a suitable level according to the typical setting of motor over-current protection, to avoid unnecessary loss of load and reduce risk of cascade tripping and voltage collapse.

Connected assets including generation must be capable of withstanding the low voltage (LV) criteria envelope shown in Figure 6.

Overvoltage Criteria for 220 kV and 110 kV Voltage Buses [4] [5]

Recovery criteria for Temporary Overvoltage (TOV) are adapted from the overvoltage criteria from the DC Hybrid Link Project [9]

- Voltage must not be greater than 1.43 pu, when the pre-fault voltage is 1.1 pu;
- Voltage must not be greater than 1. 3 pu, when the pre-fault voltage is 1.0 pu;
- Voltage must recover to below 1.2 pu in less than 0.5 seconds (25 cycles) for a pre-fault voltage of 1.1 pu;
- Voltage must recover to below 1.1 pu in less than 1 second (50 cycles) for pre-fault voltage of 1.1 pu; and
- Voltage must recover to below 1.1 pu in less than 0.5 seconds (25 cycles) following a credible contingency for pre-fault voltage of 1.0 pu;

Connected assets including generation must be capable of withstanding the high voltage (HV) criteria envelope shown in Figure 6.

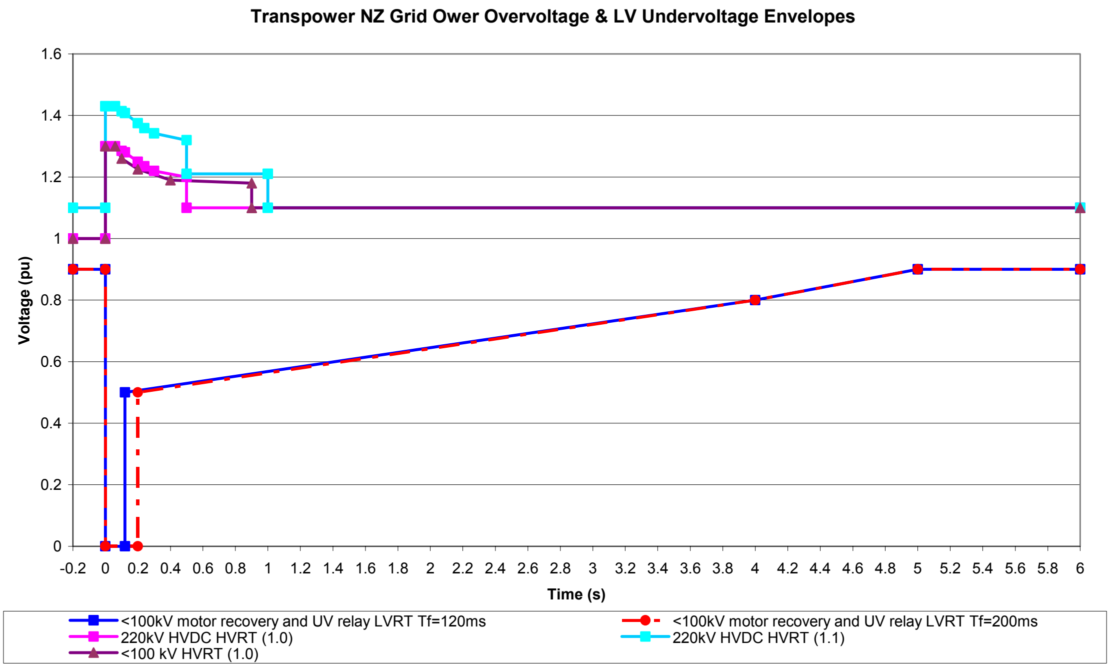

Figure 6:- Grid Owner Undervoltage and Overvoltage criteria for high voltage buses

Overvoltage Criteria for Low Voltage (<110 kV) Buses [4]

Low voltage buses where pre-event voltage is regulated to approximately nominal value shall be defined by the curve in Figure 7. The requirement is the same as that specified in the Australian National Electricity Rules [Australian National Electricity Rules 6th March 2008]. The defining features of the curve are:

- Voltage must not be greater than 1.3 pu; and
- Voltage must not be greater than 1.1 pu after 0.9 s

Please note that grid-planning criteria are currently under review. It is expected that the overvoltage criteria for low voltages will be changed to state that voltage should not be greater than 1.1 pu after 1.0 s to bring it in line with the requirements for the high voltage network.

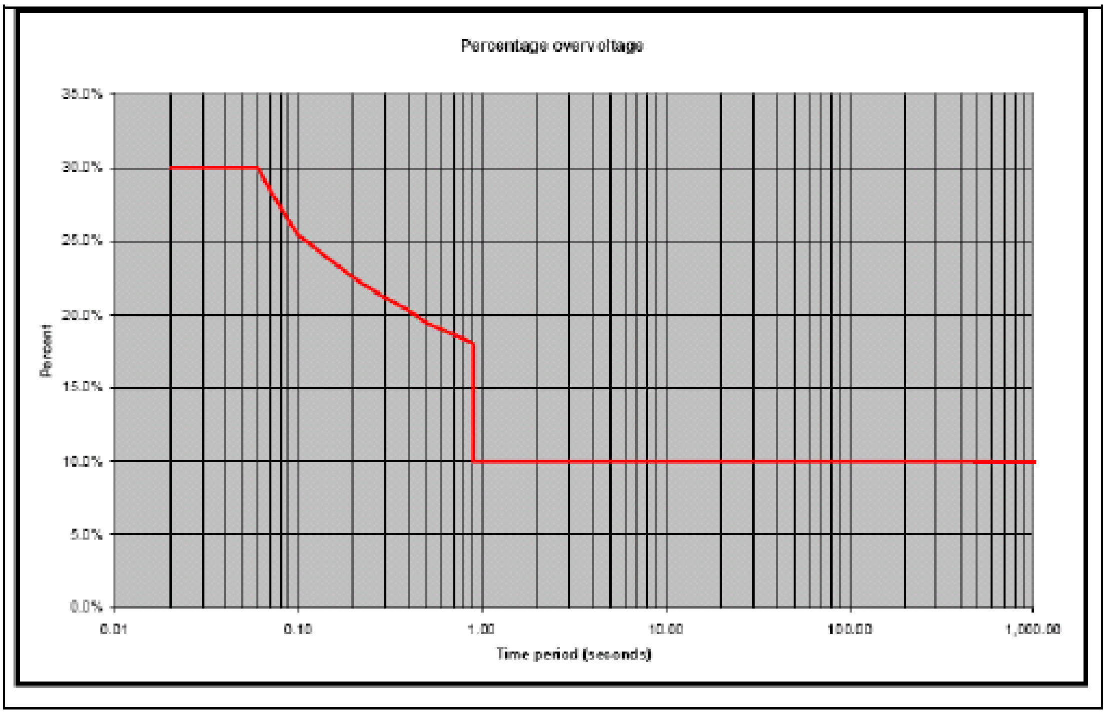

Figure 7:- Overvoltage criteria for low voltage buses [10]

3.3 MED Publication: Wind Integration in New Zealand (2005)

Reference 11 outlines minimum and maximum voltage design targets for the New Zealand power system. The design profile in reference 11 indicates that voltage may recover to above 60% following fault clearance and recover to 90% within 1 s to 2.1 s. It should be stressed that these requirements are not adopted by Transpower. Indication of how the design targets have been derived is not provided, supporting documentation is not referenced.

3.4 HVDC Fault study and VRT Requirements

For the HVDC specification, the undervoltage HVDC performance envelope was based on limitations associated with existing protection settings [5]. For faults in the region of the HVDC link the post fault undervoltage should not be prolonged so that Zone 3 and Zone 4 distance relays mistake the low voltage and high current for a fault and consequently cascade trip AC circuits. Transpower's Protection Group advised that typical distance protection will not trip if the post-fault inception voltage is above 0.8 pu in 0.5 s and above 0.9 pu in 3 s.

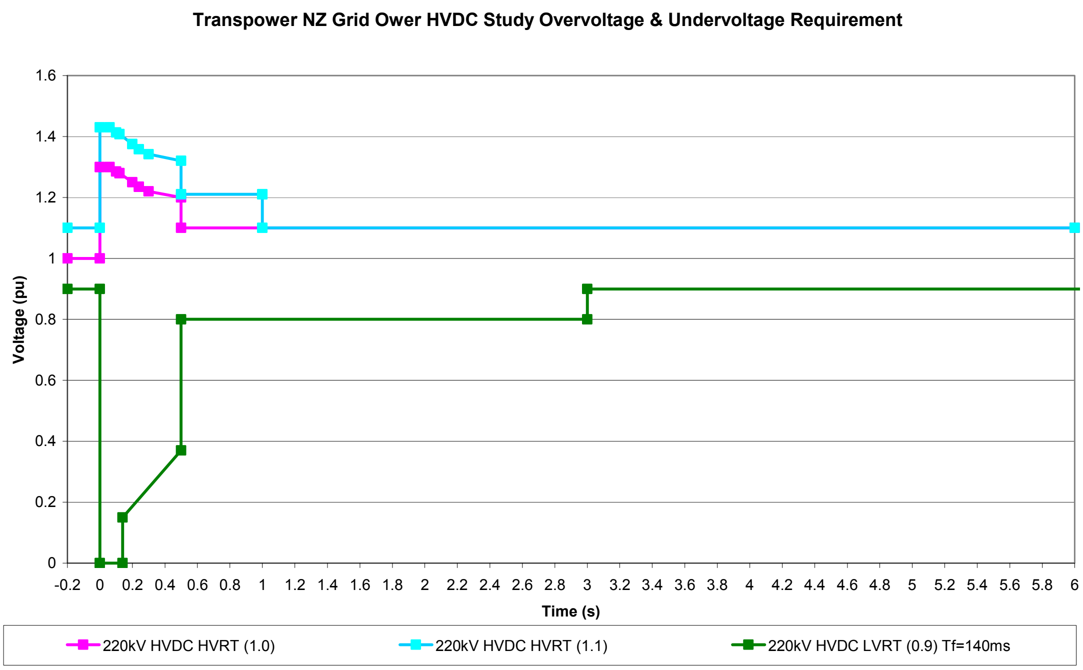

Figure 8:- Voltage-Duration Profile: Transpower HVDC Study

The overvoltage envelope is based on voltages observed following the loss of the link and is dependent upon the pre-fault voltage level. Following a 3 phase fault at Benmore, assuming a pre-fault voltage of 1.1 pu, the voltage at Haywards is likely to rise to approximately 1.43 pu.

The HVDC is designed to recover to 90% of pre-fault MW transfer within 200 ms following fault clearance.

3.5 Woodville 110 kV Fault study

Reference 12 provides voltage-duration locus observed at Woodville 110 kV bus following faults at various locations and different fault clearance scenarios. *Figure 9* shows that the Woodville 110 kV bus may be exposed to low voltages for up to 700 ms.

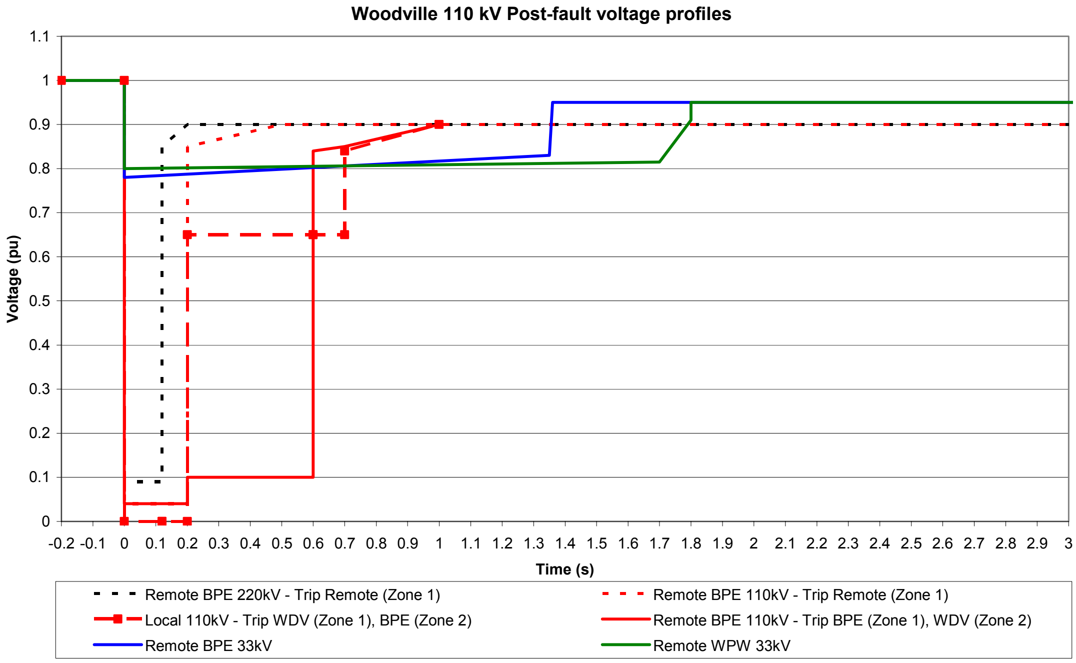

Figure 9:- Woodville post fault study: voltage profiles at neighbouring buses

From the figure it can be seen that the voltages on the 110 kV bus following a 220 kV fault recover to above 85% of nominal following fault clearance.

The voltage durations associated with the 110 kV faults are more severe. The time-voltage durations shown are determined by zone 2 protection settings.

The voltage dip observed at Woodville following a local Woodville 110 kV fault resulting in zone 1 (200 ms) tripping at Woodville and zone 2 tripping at Bunnythorpe is indicated by the dashed red line in *Figure 9*. Following zone 1 protection operation the voltage recovers to approximately 65%. Following zone 2 protection and complete fault clearance at approximately 0.7s voltage recovers to 85% and returns to 90% of nominal within 1 s.

The voltage dip observed at Woodville following a 110 kV fault at Bunnythorpe resulting in zone 1 (200 ms) protection operation at Bunnythorpe followed by zone 2 (600 ms) tripping at Woodville is indicated by the solid red line in *Figure 9*. Following zone 1 protection operation the voltage recovers to approximately 10%. The zone 2 clearance time of 600 ms is characteristic of a circuit with no protection signalling present. Following operation of zone 2 protection the voltage recovers to 85% and returns to 90% of nominal within 1 s. It is worth noting that Zone 2 fault clearance times on 110 kV circuits with no protection signalling can be up to 1s in duration.

4 International Connection Codes

4.1 Overview

For avoiding scenarios where generators are disconnected during grid faults, grid operators have developed voltage and time duration profiles that define requirements of a generator to "ride through" grid faults without disconnection.

In addition, some grid operators require contribution to voltage stabilisation and system recovery during and after grid failure [13].

The ride-through requirements from the following grid owners/country have been reviewed. Relevant extracts from the grid codes can be found in Appendix 3.

- Australian Energy Market Commission (AEMC) - Australia
- AESO Alberta -Canada
- EIRGRID - Ireland
- Eltra & Elkraft - Denmark
- Energinet.dk - Denmark
- E.ON - Germany
- Federal Energy Regulatory Commission (FERC) - USA
- Hydro Quebec - Canada
- National Grid (NGT) - England & Wales
- Nordel - Scandinavia (Denmark, Finland, Norway & Sweden)
- PSE - Poland
- Red Electrica de Espańa (REE) - Spain
- Scottish power/Scottish Hydro Electric - Scotland
- Affärsverket svenska kraftnäts (SvK) - Sweden
- WECC - USA

The following sections summarise and compare the requirements of the grid codes considered.

4.2 Low Voltage Ride Through (LVRT)

A summary of low voltage ride through (LVRT) capability specified in different grid codes is given in Table 6.

TSO/Country	Voltage Level (kV)	Threshold values	Fault Duration (s)	Min. Voltage Level	Recovery time	Voltage profile
AEMC	100<V<250	----	0.12	0% Ur	----	----
AESO	TS	> 5 MW	0.625	15% Ur	90% after 3s	Figure 22
EIRGRID	110, 220	----	0.625 *	15% Ur	90% after 3s	Figure 23
Elkraft & Eltra	132, 150	Wind >100 kV	0.1	25% Ur	75% after 0.75s 100% after 10s	Figure 24
Energinet.dk (West Denmark/UCTE)	132, 150, 400	>1.5MW >100 kV	0.15	0% Ur	60% after 0.7s U_{LF} after 1.5s	Figure 26
Energinet.dk (East Denmark)	132, 150, 400	>1.5MW >100 kV	0.25	0% Ur	60% after 0.7s U_{LF} after 1.5s	Figure 26
E.ON	110, 220	Type 1	0.15	0% Ur	U_{LF} after 1.5s	Figure 29
E.ON	110, 220	Type 2 Limit 1	0.15	45% Ur	70% after 0.15s U_{LF} after 1.5s	Figure 30
E.ON	110, 220	Type 2 Limit 2	0.15	0% Ur	U_{LF} after 1.5s	Figure 30
FERC	115, 230, 345	> 20 MW	0.625 or 0.15	15% or 0% Ur**	90% after 3s	Figure 32
Hydro-Quebec	TS	----	0.15	0% Ur	90% after 3s	Figure 33
NGT	275, 400	----	0.14	15% Ur	90% after 3s	Figure 34
Nordel	132, 150 220, 400	Various ***	0.25 or 0.15	0% Ur	90% after 0.75s 25% after 0.25s	Figure 35
PSE	TS	----	0.625	15% Ur	80% after 3s	Figure 36
REE	TS	----	0.5	20% Ur	95% after 15s 80% after 1s	Figure 37
Scottish Power	132, 275	≥5MW	0.14 or 0.1	0% Ur	90% after 3mins 80% after 1.2s	Figure 38
Svk Sweden	220, 400	>100MW	0.25	0% Ur	90% after 0.75s 25% after 0.25s	Figure 39
Svk Sweden	220, 400	>1.5MW <100MW	0.25	25% Ur	90% after 0.25s	Figure 40
Transpower	110, 220	----	0.2 or 0.12	----	----	----
WECC	115, 230, 345	>10MVA >60 kV	0.15	0% Ur	90% after 1.75s	Figure 41

Table 6: Summary of Low Voltage Ride Through Requirements

Notes:
* EIRGrid Fault clearance times of 0.1s for 220 kV and 0.12ms for 110 kV
**FERC "Transitional period" minimum voltage of 15%Ur during 0.15s fault clearance time. "Post-Transitional period" (from 1st Jan 2008) minimum voltage of 15%Ur during 0.15s fault clearance time.
*** Nordel Thresholds: All Wind; Thermal: >50 MW or >100MW; Hydro: >10MW or 50MW

4.3 High Voltage Ride Through (HVRT)

A summary of high voltage ride through (HVRT) capability specified in different grid codes is given in Table 7.

TSO	**Voltage Level (kV)**	**Overvoltage Profile**
AEMC	100 – 250	0s < t ≤ 0.7s 130% 0.7s < t ≤ 0.9s non-linear decrease 0.9s < t 110% Refer to Figure 21
AESO	TS	0s < t 110%
EIRGRID	110, 220	0s < t 113%
ELTRA & ELKRAFT (TOV Requirement)	132, 150	0s < t < 0.1s 130% 0.1s < t 120%
Energinet.dk	132, 150	0s < t < 0.2s 120% 0.2s < t 110%
E.ON	110, 220, 380	Not specified
FERC	115, 230, 345	Not specified
Hydro-Quebec	TS	Not specified
NGT	275, 400	Not specified
Nordel	132,150, 220, 400	Not specified
PSE	TS	Not specified
REE	TS	Not specified
Scottish Power	132, 275	T>0s 120% (132kV) T>0s 115% (275kV) T>15mins 110%
SvK	220, 400	Not specified
Transpower	110, 220	Not specified
WECC	115, 230, 345	T>0s 120% T>1s 117.5% T>2s 115% T>3s 110%

Table 7: Summary of HVRT Requirements

Low Voltage Ride Through (LVRT) and High Voltage Ride Through (HVRT) voltage-duration profiles for the TSOs listed are shown in Figure 10 to Figure 13 on the following pages.

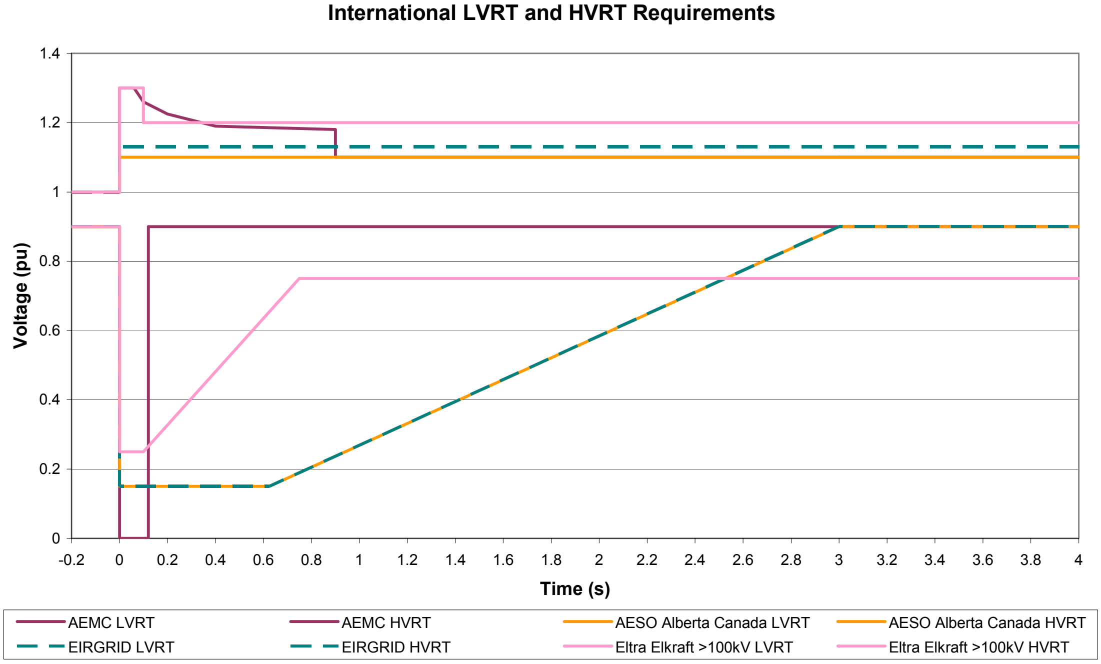

Figure 10:- Graph 1 - Under & Overvoltage Grid Code Requirements

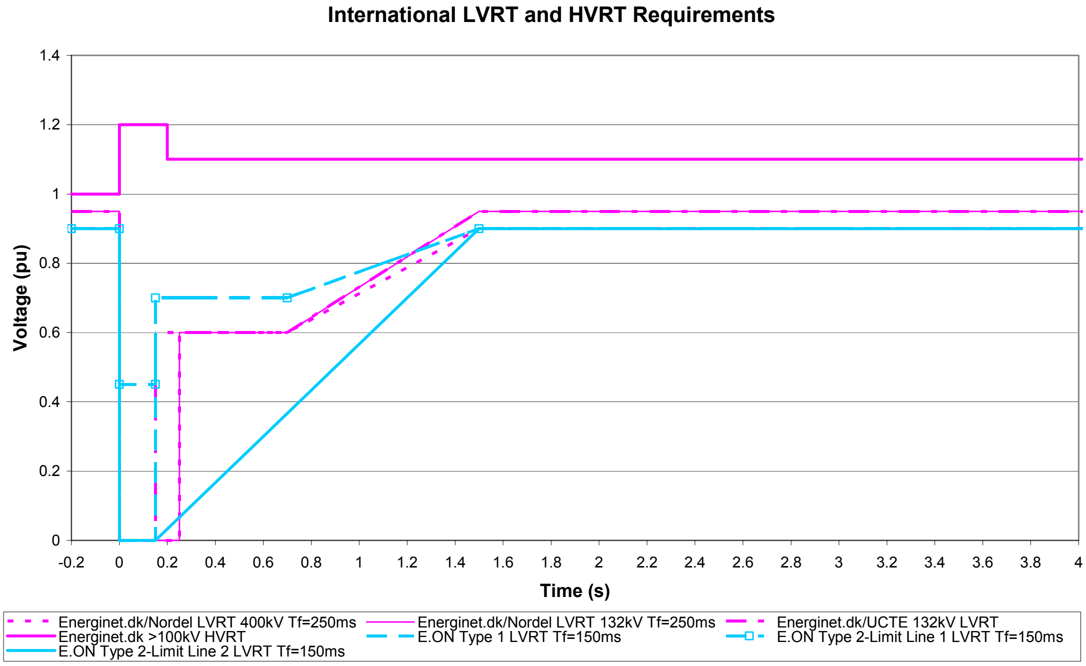

Figure 11:- Graph 2 -Under & Overvoltage Grid Code Requirements

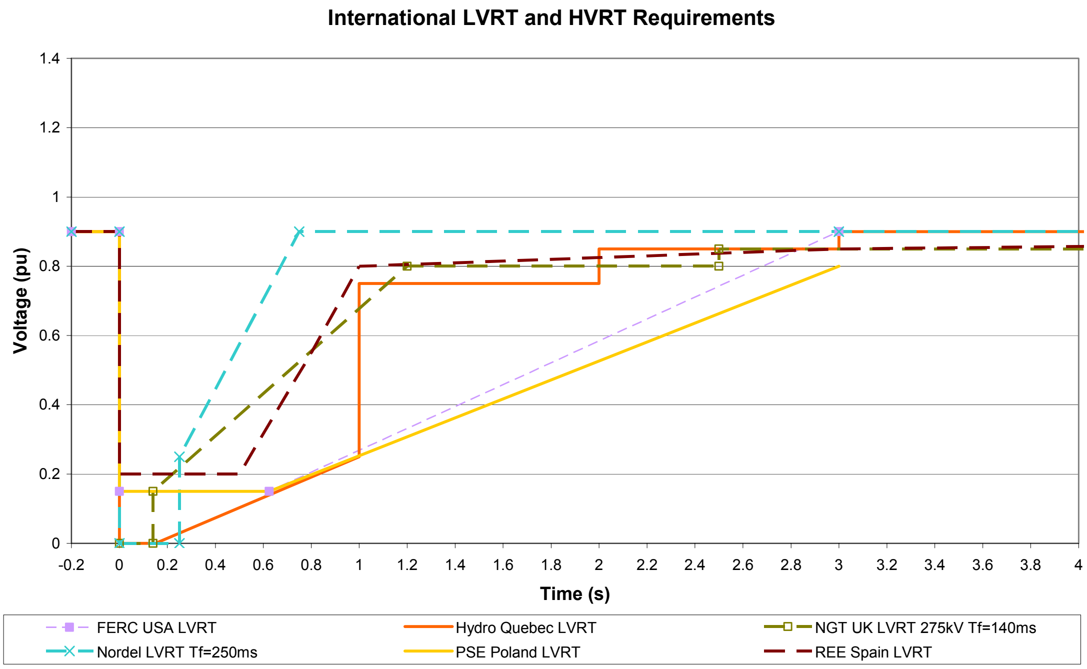

Figure 12:- Graph 3 - Under & Overvoltage Grid Code Requirements

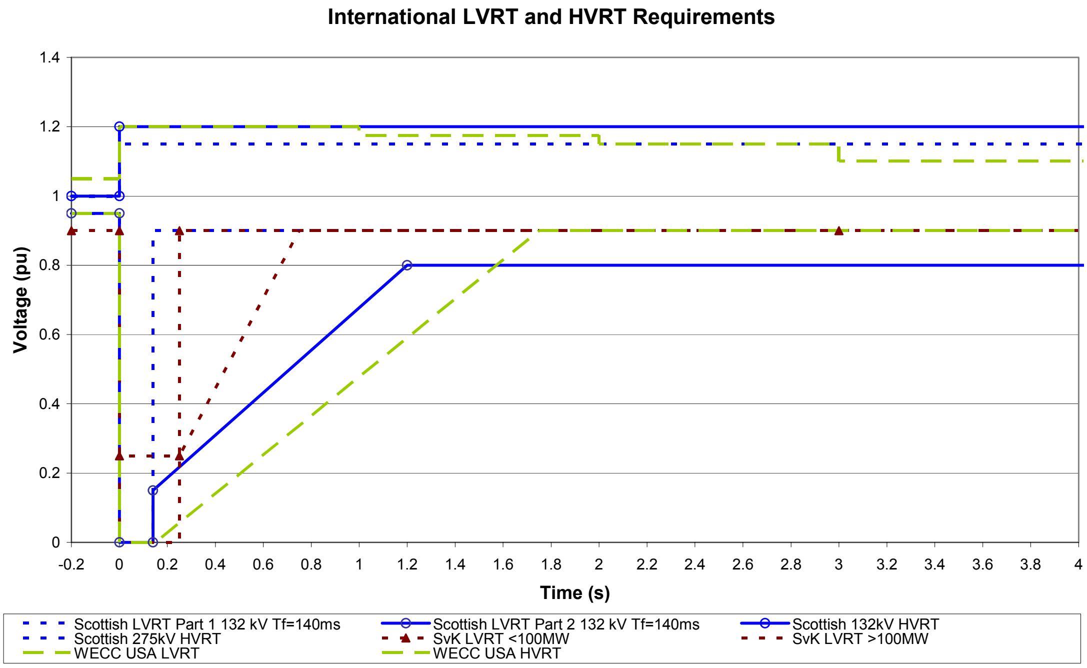

Figure 13:- Graph 4 -Under & Overvoltage Grid Code Requirements

Figure 14 shows LVRT and HVRT voltage duration profiles for all grid codes reviewed.

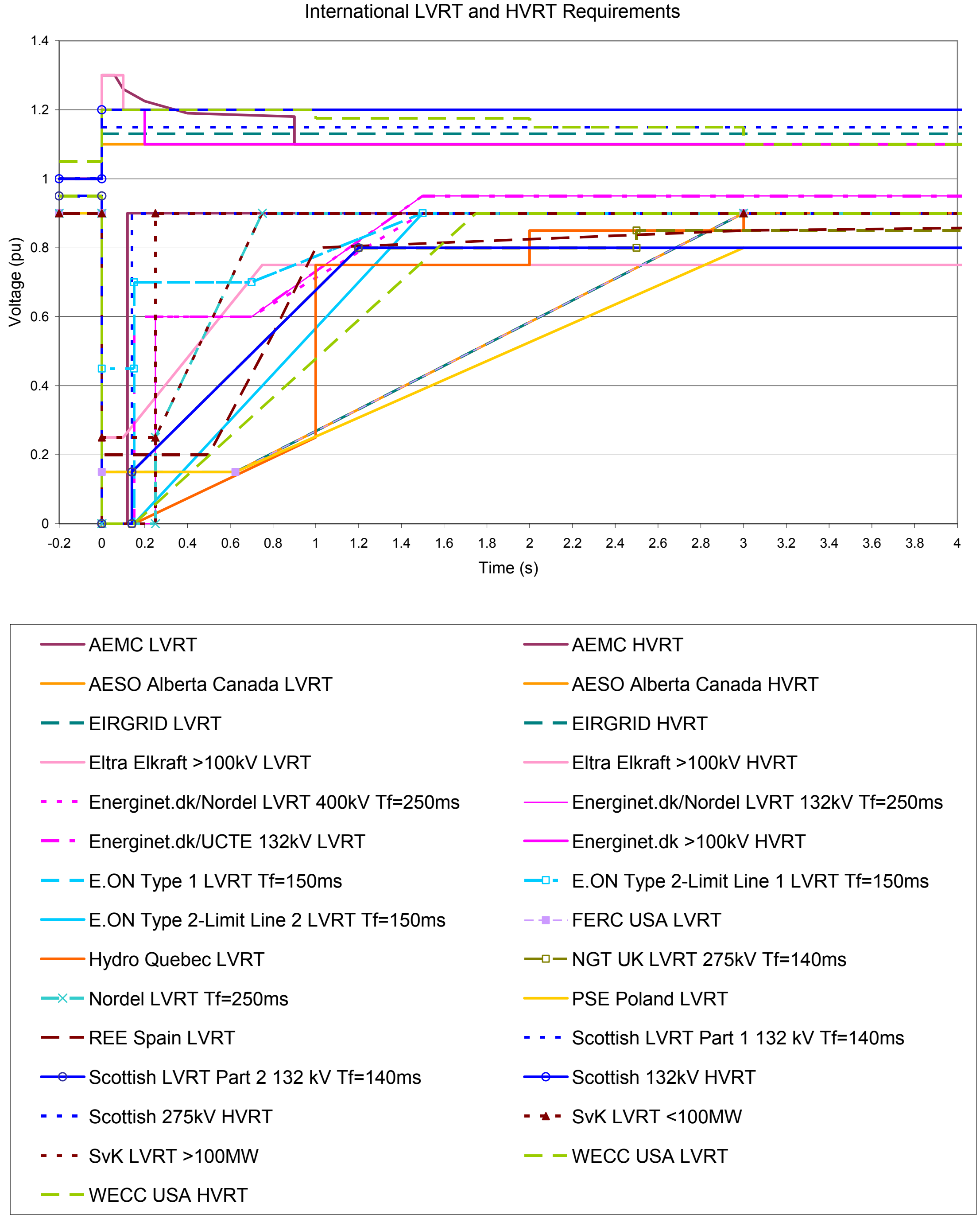

Figure 14:- Under & Overvoltage requirements for all Grid Codes Considered

4.4 Generator Active Output Following Fault Clearance

Some of the codes considered specify that active power has to be restored with a minimum gradient and/or to a defined output level within a specified time. Requirements in the grid codes considered are summarised in Table 8 below.

TSO	Requirement
AEMC	Restoration of active power output to 95% of $P_{Pre\text{-}disturbance}$ within 100 ms after fault clearance (Automatic access standard)
AESO	----
EIRGRID	During voltage dip generation should provide active power in proportion to retained voltage. Restoration of active power output to 90% of $P_{Max.\ available}$ within 1s after the voltage returns to U = 90% of rated system voltage
Eltra & Elkraft	Restoration of active power rated power within 10s after the voltage returns to U = 90% of rated system voltage. During the voltage dip the active power in the connection point shall meet the following condition: $P_{current} \geq K_p \times P_{t=0} \times (U_{current} / U_{t=0})$ ^2 For further details see Appendix 3, Section 7.4
Energinet.dk	----
E.ON	Restoration of active power output immediately after fault clearance to $P_{Pre\text{-}disturbance}$ with a gradient (G) of at least 20% of rated power (Pr) per second, G≥0.2Pr/s.
FERC	----
Hydro-Quebec	----
NGT	Dip duration up to 140 ms: Restoration of active power output to 90% of $P_{Pre\text{-}disturbance}$ within 500 ms after the voltage returns to U = 90% of rated system voltage Dip duration above 140 ms: Restoration of active power output to 90% of $P_{Pre\text{-}disturbance}$ within 1.0s after the voltage returns to U=90% of rated system voltage.
Nordel	----
PSE	----
REE	----
Scottish	----
Transpower	----
WECC	----

Table 8: Summary of Generator Active Output requirements during fault and following fault clearance

4.5 Multiple Faults / Auto-reclose

A few codes state requirements for generators to ride-through multiple faults or failed auto-reclose events. Details of such requirements (if any), fault clearance times and auto-reclose dead times are summarised in Table 9.

TSO	**Voltage Level (kV)**	**Fault clearance & auto-reclose times**	**Grid Requirement**
AEMC	110-250	Fault clearance 0.12s	Not specified
AESO	TS	----	Not specified
EIRGrid	110, 220	220 kV Fault clearance 0.1s 110 kV Fault clearance 0.12s Auto-reclose delay: 0.4s	Not specified
Eltra & Elkraft	132, 150	Fault clearance: 0.1s Auto-reclose delay: 0.3-0.5s	Apply ph-g, ph-ph or ph-ph-g fault Clear fault after 0.1s Re-apply fault within 0.3-0.5s Clear fault after 0.1s
			Apply two 1-ph, 2-ph or 3-ph faults within 2 minutes
			Apply six 1-ph, 2-ph or 3-ph faults with 5 minute interval in between
Energinet.dk [14]	132, 150	Fault clearance: 0.15s Auto-reclose delay: 0.3-0.8s	Apply ph-g, ph-ph or ph-ph-g fault Clear fault after 0.15s Re-apply fault within 0.3-0.8s Clear fault after 0.15s
E.ON	110, 220, 380	Fault clearance: 0.15s HV 3-ph auto-reclose delay: 0.4-0.8s, EHV 1-ph auto-reclose delay: 1.0-1.2s	Not specified
FERC	115, 230, 345	Fault clearance: 0.15s	Not specified
Hydro-Quebec	TS	Fault clearance: 0.15s	Not specified
NGT	275, 400	Fault clearance: 0.14s	Not specified
Nordel	132, 150, 220, 400	Fault clearance: 0.15s or 0.25s	Not specified
PSE	----	----	Not specified
REE	----	----	Not specified
Scottish	275, 400	Fault clearance: 0.14s	Not specified
SvK	220, 400	Fault clearance: 0.25s	Not specified
Transpower	110, 220	110 kV Fault clearance 0.20s 220 kV Fault clearance: 0.12s 220 kV Auto-reclose delay: 1.5s	Not specified
WECC	115, 230, 345	Fault clearance: 0.15s	Not specified

Table 9: Summary of fault clearance times, auto-reclose times and multiple fault ride through requirements

4.6 Generator Dynamic Voltage Support

Additional reactive support during voltage recovery is required by a number of TSOs including Australia, Germany (E.ON) and the UK. Wind farms have to maximise their reactive current generation for system voltage stabilization.

In Germany this has to be done with a defined reactive current injection of minimum 2% $I_{Nominal}$ per %ΔU at the low voltage side of each wind turbine transformer. In Australia with the greater of $I_{b\ Pre\text{-}disturbance}$ and 4% $I_{Nominal}$ per % U (automatic access standard) at the Point of Common Coupling (PCC) [13] [15] [16].

The review of dynamic voltage support requirements of different countries is outside the scope of this project.

4.7 Short Term Interruption (STI)

E.ON requires a Fault Ride Through (FRT) capability as specified in Figure 15. Wind Turbines must stay connected even when the voltage at the Point of Common Coupling (PCC) with the grid drops to zero. The 150 ms delay shown in the figure accounts for the normal operating time of protection relays. The red solid line in Figure 15 marks the lower voltage boundary rather than any characteristic voltage behaviour [17].

Short term interruption (STI) is allowed under specific circumstances. STI in area 3 requires resynchronization within 2 s and a power increase rate of at least 10% of the nominal power per second. In area 2 the interruption time allowed is much less, just a few hundred milliseconds. During fault ride through, reactive power supply by wind turbines is a requirement. Wind turbines have to supply at least 1.0 pu reactive current when the voltage falls below 50% [17].

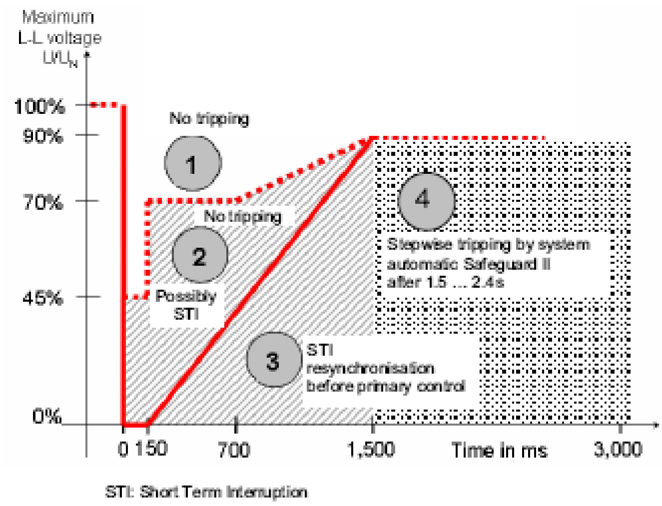

Figure 15:- Voltage-Duration Profile E.ON Type 2 LVRT Requirement

4.8 Wind Generation Performance

An overview of wind turbine technology is provided in Appendix 5.

4.8.1 Double Fed Induction Generator (DFIG)

Typical DFIG wind turbines will ride through 3 phase faults defined by a “DFIG low tolerance voltage curve” of 0.05 pu up to 0.2s, 0.2 pu up to 0.63s, ramping to 0.8 pu at 2.5 s, then 0.8 pu to 10.2 s, then 0.9 pu [5]. The voltage duration characteristic of DFIG generator is shown in Figure 17.

DFIG wind turbines may be capable of operating to a more onerous curve defined by “DFIG protection settings” of 0.0 pu up to 0.2 s, ramping to 0.7 pu at 2.5 s, then 0.7 to 11s, then 0.8 pu for 60 s. Below this curve the wind turbine will disconnect from the grid. The area between the two curves is expressing the voltage level during which the turbine might disconnect or stay connected

These wind generators have overvoltage protection settings on the machine terminals that allow 1.2 pu for 0.2 s and 1.135 pu for 60 s, after this time the voltage must return to 1.1 pu.

LVRT test envelopes for Vestas wind turbines equipped with Advanced Grid Options (AGO) [18] are shown in Figure 16 below:

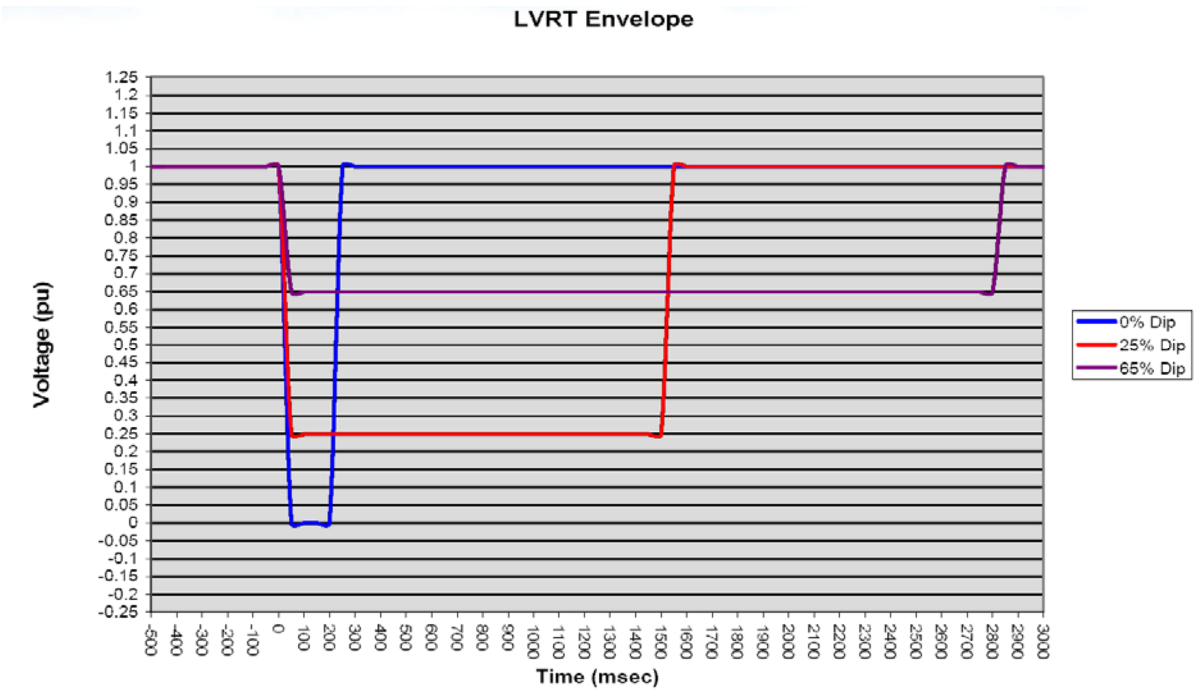

Figure 16:- Vestas Test Envelopes [18]

4.8.2 Full Scale Frequency Converter (FSFC) Connected Wind Turbine

This type of wind generator will ride through 3 phase faults of 0.0 pu for 0.85s, 0.15 pu for 1.6s, 0.4 pu for 2.6s, 0.7 pu for 10.5s and 0.85 pu for 181s at which time the voltage must return to 0.9 pu [5].

The full converter wind generators typically have overvoltage protection settings on the machine terminals (690V) of 1.2 pu for 0.15s and 1.1 pu for 1s. The Voltage duration characteristic of Full Scale Frequency Converter (FSFC) connected wind generator is shown in Figure 17.

These generators would not ride through the Temporary Overvoltage (TOV) envelope shown in *Figure 8* (section 3.4) applied directly to the machine terminals. However studies [19] have suggested that if the TOV criteria envelope is applied to the 220 kV or 110 kV bus then the TOV at the machine terminals will be sufficiently attenuated to avoid tripping the wind generators.

4.8.3 Summary of Wind Turbine Performance

The voltage-duration ride-through capabilities of DFIG and FSFC connected wind turbines is summarised in Figure 17.

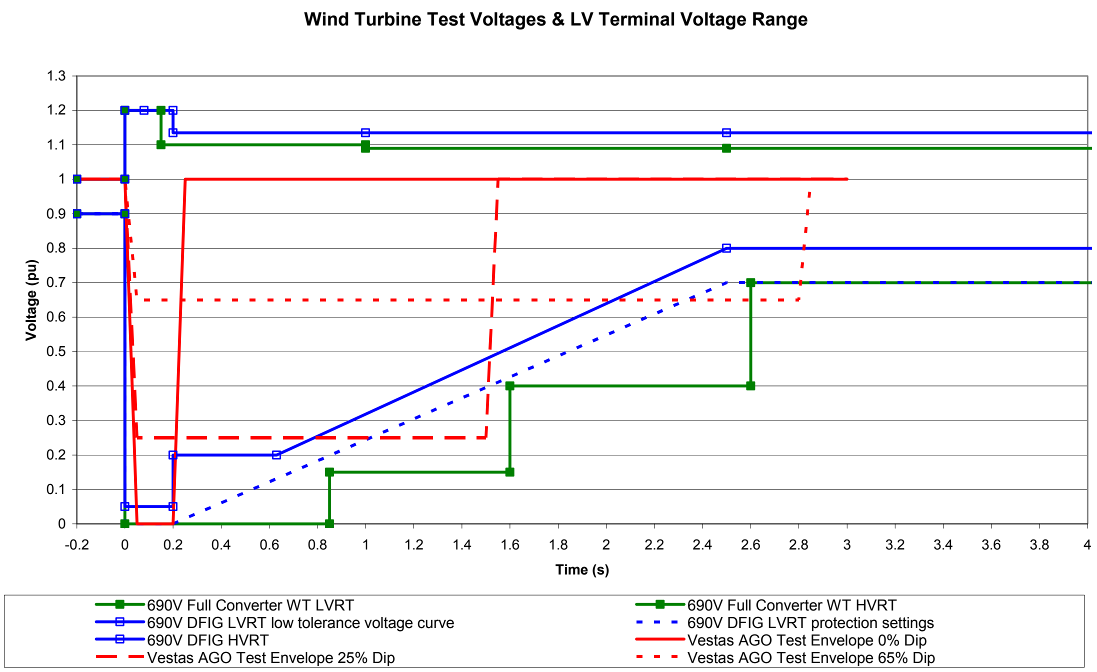

Figure 17:- Voltage-Duration Profile: Wind turbine fault ride-through performance

4.9 Transient Performance of Network

4.9.1 Regional generation

For a region with a significant amount of other generation such as Auckland, the displacement of thermal generation at Huntly by generation elsewhere reduces local short-circuit levels considerably. Voltage performance during short circuit faults is affected as a direct result of this reduction in short-circuit level. As for regions with little or no generation locally, new generation installed locally can improve the voltage performance.

4.9.2 Load

Some load within the distribution network is almost always lost during the low voltage period of a fault due to, for example, motor contactors opening.

4.10 Reactive Support Devices

WGIP investigation 9 [2] analysis has shown that FSIG technology reduces voltage sag performance. This arises from the need for the FSIG to draw large amounts of reactive power from the grid post fault to magnetise the rotor circuit and return the generating unit to stable operation. Voltage sag performance can be improved by installing reactive power support devices such as static compensators (STATCOMs) at the wind farm to reduce the amount of reactive power needed to be drawn from the grid post fault.

Without the STATCOM faults may result in voltage collapse. The STATCOM significantly reduces both the minimum voltage experienced during the sag and the time for voltage to recover.

5 Comparing Voltage-Duration Profiles

This section compares the following sets of voltage-duration profiles

- International LVRT and HVRT grid code requirements
- Woodville 110 kV post-fault voltages
- Transpower 220 kV HVDC equipment requirements
- Wind turbine performance profiles

5.1.1 *Comparison of Woodville 110 kV fault study and grid code requirements*

Figure 18 compares the post-fault voltage levels at Woodville 110 kV against international grid code requirements.

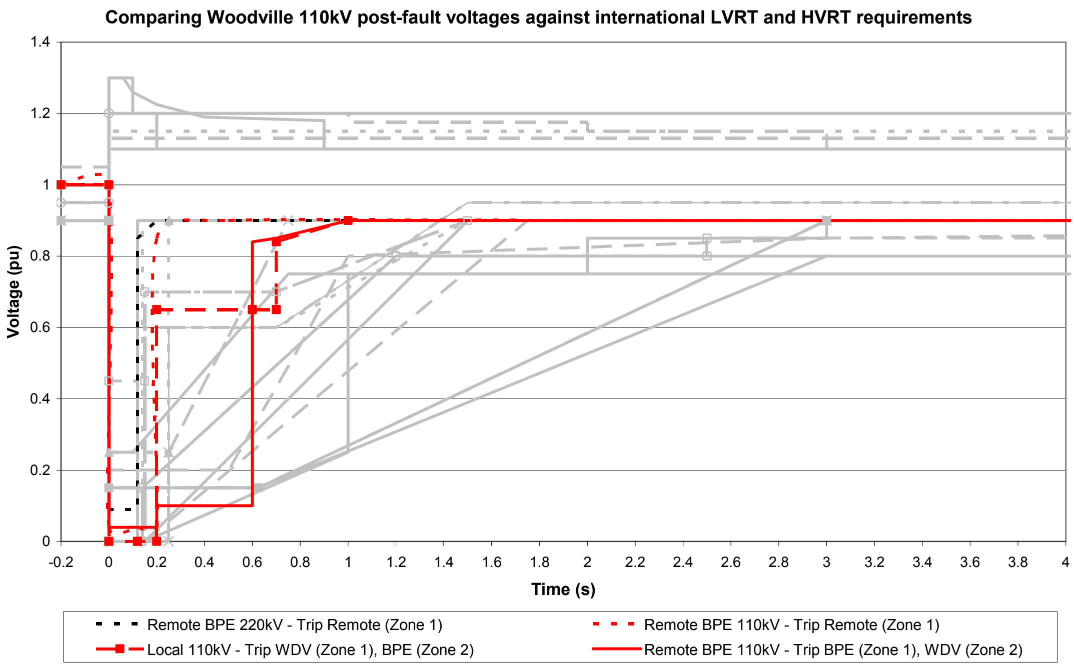

Figure 18:- Voltage-Duration Profile: Comparing post-fault voltage levels at Woodville 110 kV against international grid code requirements

From the figure it can be seen that the voltage on the 110 kV bus following a 220 kV fault recovers quickly and falls within many international voltage-duration requirements. However voltage-durations associated with 110 kV faults are more severe, particularly those associated with remote 110 kV faults on circuits with no protection signalling, requiring the operation of zone 2 protection.
The voltage duration profile associated with a local Woodville 110 kV fault resulting in zone 1 tripping at Woodville and zone 2 tripping at Bunnythorpe (shown as a dashed

red line in Figure 18) falls within a number international VRT standards thus indicating that this fault would not be considered onerous by international standards.

However, the voltage dip resulting from a 110 kV fault at Bunnythorpe (the solid red line in Figure 18) resulting in zone 2 tripping at Woodville in 600 ms, falls outside of all international grid codes considered during the time period of 0.5 to 0.6 seconds.

5.1.2 Comparison of Woodville 110 kV fault study, requirements for HVDC equipment and international grid code requirements

Figure 19 compares the post-fault voltage levels at Woodville 110 kV and the requirements specified for HVDC equipment against international grid code requirements.

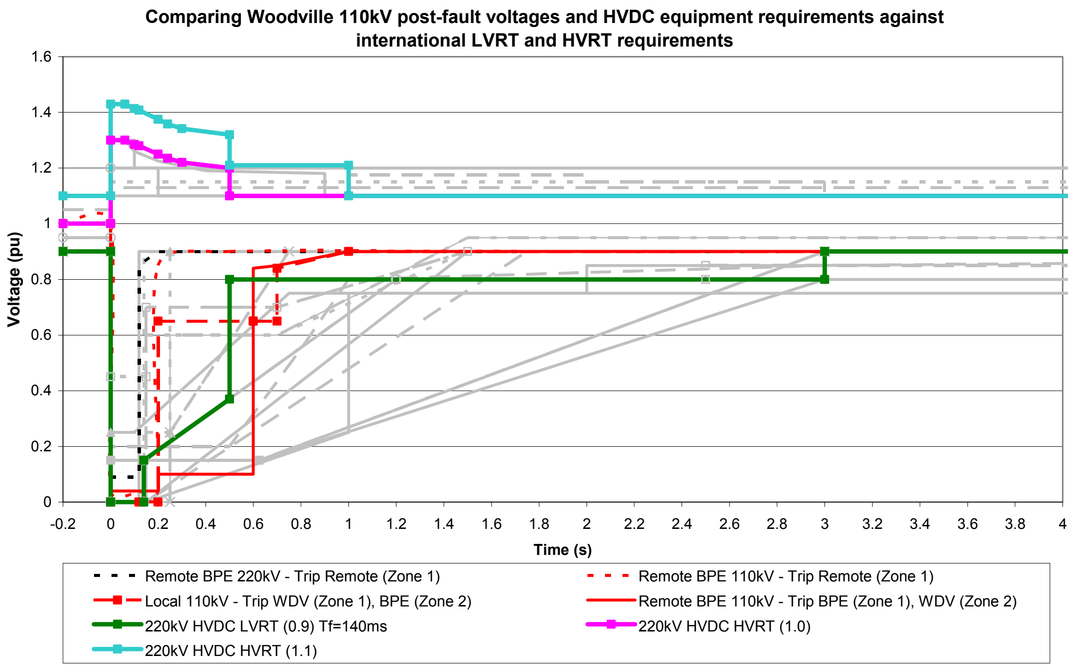

Figure 19:- Voltage-Duration Profile: Comparing post-fault voltage levels at Woodville 110 kV and requirements for HVDC equipment against international grid code requirements

The LVRT voltage-duration requirements for HVDC equipment is a suitable envelope to encompass the expected voltage at Woodville 110 kV following 220 kV faults. However this envelope does not capture the expected low voltage-durations resulting from 110 kV faults.

Further studies will have to be performed to ascertain if the HVDC LVRT voltage-duration profile is a suitable requirement for all generation wishing to connect to the 220 kV power system.

The HVDC LVRT profile would not be suitable for the 110 kV network, a different profile would need to be formulated based on the possible voltage drops that could be seen on the 110 kV network following local and remote faults.

5.1.3 Comparison of wind turbine performance and grid code requirements

Figure 20 compares wind turbine fault ride-through performance against international grid code requirements.

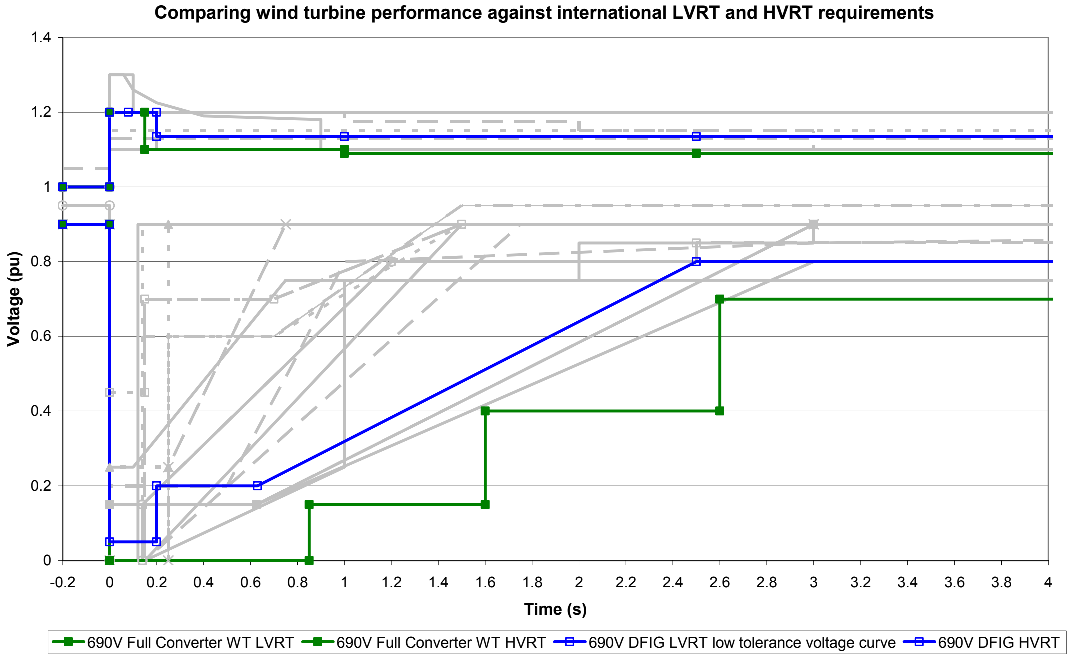

Figure 20:- Voltage-Duration Profile: Comparing wind turbine fault ride-through performance against international grid code requirements

Wind generators connected via a full scale frequency converter (FSFC) have voltage ride through capabilities that comply with all international grid codes reviewed. DFIG generators have a lesser fault ride through capability that may not comply with some grid codes.

Considering Figure 18 in conjunction with Figure 20 indicates that DFIG generators may not be able to ride through the low voltages experienced at Woodville 110 kV following a remote 110 kV fault, during the time period 0.2s - 0.6s. Wind generators with full scale frequency converters (FSFC) are capable of maintaining a connection to the network.

6 Considerations for Stage 2

6.1 Study Methodology

The basic methodology is as follows:

- Gather relevant fault recorder data
    - 3 phase fault event data
    - extended 110 kV fault event data
- Formulate a complete list of study cases, generation scenarios and fault events
- Generate simulated fault data
- Compare fault recorder data and generated fault data against:
    - International LVRT and HVRT requirements
    - Wind Turbine voltage tolerances/ride-through capabilities
- Recommend LVRT and HVRT voltage-duration curve for the New Zealand power system.

6.1.1 Static and Dynamic Studies

Both static (steady state) and dynamic analysis methods can be employed to assess the impact of generation on the network.

Static methods are generally used to analyse power flow and short-circuit power contribution under steady state conditions.

Dynamic studies are performed to analyse voltage response during and following a power system event. Dynamic studies allow the study of the voltage recovery following a fault. Such studies involve using power system dynamic models and applying a fault to determine how the power system reacts during and following the removal of the faulted asset.

6.1.2 Static Study

Static studies are undertaken to assess the impact of different network conditions and generation /load scenarios. Short circuit levels at a number of buses around the power system can be calculated for different system conditions and generation dispatch scenarios.

- Network Conditions:
    - The intact network
    - The network with a single network element out of service**

- Generation Scenarios:
    - All existing and committed generation in service
    - High wind generation scenario
        - displacing synchronous generating plant
        - types of wind generation technology
    - HVDC Transfer
        - North/South/Slack
- Load Scenarios:
    - Winter Peak
    - Summer Peak

** If the network element removed from service is a bus section then reconfiguration of the network to re-connect as much of the system as possible is assumed. Any generation disconnection associated with the bus section outage is applied.

A list of cases, scenarios and fault events will be developed and agreed with the electricity commission before commencing static studies.

6.1.3 Dynamic Study

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

Studies should consider:

- 3 phase faults on the 220 kV and 110 kV system;
- 3 phase faults on the 66kV and 33 kV system, with fault clearance times of up to 1.5 seconds;
- a range of fault locations;
    - Faults located at the ends of feeders close to the bus (rather than applied directly to the bus);
- Studies should involve two-stage fault clearance action(s), to simulate zone 1 and zone 2 clearing of line faults on the 110 kV network;
- multiple faults / auto-re-close events.

The overall approach is:

- A bolted three phase short circuit fault is applied to the power system (HV or LV network) and is cleared by main protection.
- Voltage waveforms at buses of interest are obtained.
- The minimum voltage is recorded.
- The time required for the voltage to recover to 0.9 pu is recorded.

A list of cases, scenarios and fault events will be developed and agreed with the electricity commission before commencing dynamic studies.

6.1.4 Study Assumptions

General Assumptions:

- Any reactive power compensation devices associated with particular generation technology will be modelled to produce a more accurate dynamic voltage response from the model.
- New wind farms connected to the system are modelled with a generic medium voltage and low voltage distribution system.
- In addition to the unit capacitors a small fixed capacitor is added to the 33 kV bus to offset reactive losses in the distribution system – in accordance with the typical practice for modern wind-farms.

Tap Changers

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

Shunt Capacitors

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

Planned Outages

- Planned transmission outages are not considered.

A complete list of assumptions will be developed and agreed with the electricity commission before commencing studies.

7 Conclusion

Background documentation associated with the Transpower network including protection operation and clearance times, indicative voltage-time durations and existing planning requirements has been documented. In addition international grid code requirements and the ability of wind generators to ride through faults has been documented and reviewed.

Woodville 110 kV post-fault voltage studies indicate that although the VRT profile specified for HVDC equipment may be suitable to capture voltage drops following 220 kV faults, it will not be suitable to describe the requirements following 110 kV faults.

From 220 kV HVDC protection settings and the indicative Woodville 110 kV post-fault voltage studies, it is clear that the voltage observed on the 220 kV network and the 110 kV network could be significantly different due to the different protection philosophies employed. Key voltage-time markers for the 220 kV network can be extracted from main (1^{st} and 2^{nd} main) and circuit breaker fail (CBFail) protection operation times. For the 110 kV network voltage-time markers include main (zone 1 and 2) and back up protection. The data points upon which an initial voltage-duration profile can be based are given below.

Undervoltage Criteria

220 kV voltage-duration profile to capture the following points:

- 220 kV voltage is likely to drop to 0% for 0.12 s following a 220 kV fault
- 220 kV total fault clearance time 0.35 s following a 220 kV fault
- 220 kV voltage to recover to 40%-80% following 220 kV fault clearance
- 220 kV voltage to recover to 80% within 0.5 s
- 220 kV voltage to recover to 90% within 1-3 s

110 kV voltage-duration profile to capture the following points:

- 110 kV voltage is likely to drop to 0% for 0.2 s following a 110 kV fault
- 110 kV voltage may recover to 10%-60% following a 110 kV fault and an initial zone 1 (0.2 s) clearance
- 110 kV voltage may recover to 40%-80% following final 110 kV fault clearance by zone 2 or back up protection
- Zone 2 & back up protection clearance times vary
  - 0.35 s for circuits with protection signalling
  - 0.60 to 1.0 s for circuits without protection signalling

- 110 kV voltage may recover to 90% within 4-6 s.
    - 110 kV back up protection operation up to 4-6 s

Overvoltage Criteria

Initial recovery overvoltage criteria can be based on the grid planning guidelines [4] and international standards.

- 220 kV and 110 kV voltage may rise to 1.3 pu following a fault until special Protection Schemes operate to reduce voltage within a time period of 0-200 ms

- Voltage may recover to 1.2 pu in less than 0.5 s following action of Special Protection Schemes

- Voltage will recover to below 1.1 pu in less than 1 s

The DC Hybrid Link Project [9] indicates that voltage may rise to 1.43 pu, when the pre-fault voltage is 1.1 pu in the region of the HVDC link. High overvoltages (above 1.3 pu) may also be observed in Southland following the loss of a pot-line at Tiwai, or in areas with large capacitor bank installations such as Islington and Kaitaia following a network fault. Generation wishing to connect in regions where pre-fault voltage is high, close to HVDC terminations (Haywards and Benmore), Southland (Tiwai) or Islington/Kaitaia, may need to be able to comply with the more onerous overvoltage criteria given below.

- 220 kV and 110 kV voltage may rise to 1.43 pu following a fault until Special Protection Schemes operate to reduce voltage within a time period of 0-200 ms.

- Voltage may recover to 1.32 pu - 1.2 pu in less than 0.5 s following action of Special Protection Schemes.

- Voltage will recover to below 1.1 pu in less than 1 s.

Following a review of fault ride-through requirements of other countries and indicative voltage-durations at the Woodville 110 kV bus following network faults, it is expected that a Low Voltage Ride Through (LVRT) profile for 220 kV busbars will compare well with voltage-time profiles specified by other TSOs. However voltages expected at 110 kV busbars may remain low for extended periods of time particularly following faults on circuits that do not have protection signalling and are reliant upon extended zone 2 fault clearance times.

This review indicates potential issues for:

- DFIG wind generators with regard to compliance with some international grid codes.

- DFIG wind generators connected to the 110 kV network riding through remote faults with zone 2 fault clearance times > 0.2 s.

- Wind generators with Full Scale Frequency Converter (FSFC) connected to the 110 kV network riding through remote faults with zone 2 fault clearance times > 0.8 s.

- Capability of wind generators to ride through overvoltages experienced on the New Zealand power system.

System Operator wishes to avoid developing a profile based solely on protection settings that may be present on certain circuits that would lead to over-demanding voltage duration profiles. Similarly the development of a ride through requirement that does not reflect the connection voltage to which a generator is connected or may wish to connect to may also seem over-demanding.

Stage 1 Recommendations

This report recommends the development and introduction of a VRT requirement in the EGRs. A requirement should specify a voltage-duration profile as a means to measure and compare power system performance and plant (load and generator) fault ride through capability. The development and validation of a voltage-duration profile for the New Zealand power system should be based on dynamic studies. Generator active power should be restored with a minimum gradient and/or to a defined output level within a specified time. It is recommended that stage 2 of the project should develop the requirement for generator active power recovery.

It has been found necessary for studies to be undertaken to determine a suitable voltage-duration profile for the New Zealand power system simulating response following 220 kV, 110 kV and 33 kV fault studies. Consideration should be given to defining a range of VRT profile(s) for generators wishing to connect to the 220 kV network and another for those wishing to connect to voltage levels of 110 kV and below with differing levels of protection.

With limited VRT capability it may be necessary to improve the fault clearance times on sections of the transmission network. Although the System Operator is aware that technical issues associated with main and backup protection coordination, plus the potential cost of upgrades to the transmission system protection and protection signalling systems may make extensive improvements impractical. The flexibility of protection settings in the region before requiring generators to comply with a more onerous VRT requirement.

The following clarifying statements as to the application and purpose of the voltage duration profile should accompany the voltage-duration profile.

- The System Operator would be responsible for maintaining power system voltage within a specified post-fault voltage-duration profile.

- Generation and other system plant would be expected to remain connected for voltages within the voltage-duration profile

- Generation should not have a detrimental effect on the ability of the System Operator to maintain system voltage within this profile.

- The VRT standard applies to the voltage at the high voltage side of the generating plant step-up transformer, not at the generator terminals.

- The standard can be met by the performance of the generators or by installing additional equipment (e.g. SVC, etc) within the generating facility.

- The standard does not apply to faults that would occur between the generator terminals and the high voltage side of the generator step-up transformer.

- Generators may be tripped after fault initiation if this action is intended as part of a Special Protection Scheme.

- In the event that existing and new generators do not meet the voltage ride through requirements the generator may be required to apply for a dispensation under this rule.

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Appendix 1 – Scope of Work

The scope of work has been divided into two stages, as described below:

Stage 1: Literature Review & Data Collection

- Review of international standard and generator unit requirement with regards to fault ride through and voltage recovery
- Review of documentation related to the voltage response of generator units following a fault on the New Zealand power system.
- Review of voltage performance requirements specified by the Grid Owner.
- Review of protection settings, fault clearance times and auto-re-close strategy.
- Review voltage support projects proposed by the Grid Owner that may influence power system dynamic behaviour.
- Check availability of fault disturbance data from on-line recorders.

Stage 2: Dynamic Simulations

Undertake dynamic studies to investigate the dynamic response of the New Zealand network following a fault. Studies should consider:

- North Island and South Island power system
    - regional/zone issues
- Type of fault
    - line fault
    - loss of generator unit
    - size of lost unit
    - fault duration / fault clearance time
- Location of fault relative to connection point of generation units
- Impact on and response of various types/sizes of generating units at various distances from the fault
- Pre-fault power transfer, generation and load conditions
    - motor load
    - light/peak load conditions

- local generation dispatch
- HVDC power transfer

- The effect of existing /planned voltage support/control devices
- Consecutive faults

Studies should identify potential risks (if any) and issues associated the New Zealand power system.

Derive a voltage envelope for generators wishing to connect to the Transpower network.

Assess the impact of a voltage requirement for generators, identify potential issues and propose solutions.

Studies undertaken in Stage 2 will be reviewed following the completion of Stage 1.

Appendix 2 – List of Transmission System Operators

Europe

Austria	Verbund Austrian Power Grid AG	www.verbund.at
	TIWAG-Netz AG	http://www.tiwag-netz.at
	VKW- Übertragungsnetz AG – VKW-UNG	www.vkw-grid.at
Belgium	Elia System Operator S.A.	www.elia.be
Czech Republic	CEPS, a.s.	www.ceps.cz
Denmark	ELTRA	www.eltra.dk
	Elkraft System	www.elkraft-system.dk
Finland	Fingrid Oyj	www.fingrid.fi
France	Reseau de Transport D'electricite – RTE	www.rte-france.com
Greece	Hellenic Transmission System Operator S.A. – HTSO	www.desmie.gr
Spain	Red Electrica de España SA	www.ree.es
Holland	TenneT, Transmission System Operator B.V.	www.tennet.org
Ireland	ESB National	www.esb.ie
	EirGrid	www.eirgrid.com
Luxemburg	CEGEDEL SA	www.cegedel.lu
Germany	EnBW Transportnetze AG	www.enbw.com
	E.ON Netz GmbH – E.ON Netz	www.eon-netz.com
	RWE Transportnetz Strom GmbH	www.rwetransportnetzstrom.com
	Vattenfall Europe Transmission GmbH	http://transmission.vattenfall.de
Norway	Statnett	www.statnett.no
Portugal	REN – Rede Eléctrica Nacional, S.A.	www.ren.pt
Slovakia	SEPS, a.s.	www.sepsas.sk
Slovenia	ELES	www.tso.eles.si
Switzerland	Aare-Tessin Ltd. for Electricity – ATEL	www.atel.ch
	BKW Übertragungsnetz AG	www.bkw.ch
	EGL Grid AG	www.egl.ch
	Energie Ouest Suisse SA – EOS	www.eos-gd.ch
	Nordostschweizerische Kraftwerke AG – NOK	www.nok.ch
Sweden	Affärsverket Svenska Kraftnät	www.svk.se
Hungary	MAVIR Rt.	www.mavir.hu
Great Britain	Scottish Power	www.scottishpower.com
	Scottish and Southern Energy Plc	www.scottish-southern.co.uk
	SONI (System Operator for Northern Ireland)	www.soni.ltd.uk
	National Grid UK	www.nationalgrid.com/uk
Italy	Terna S.p.A. - Rete Elettrica Nazionale	www.terna.it

Organisations of TSOs

ETSO	http://www.etso-net.org
UCTE	http://www.ucte.org
NORDEL	http://www.nordel.org
SUDEL	http://www.sudel.org
BALTREL	http://www.baltrel.com
EURELECTRIC	http://www.eurelectric.org
DG TREN energy in the EU Commission	http://europa.eu.int/comm/energy/index_en.html

Appendix 3 – International Grid Codes

8.1 AEMC - Australia

The Australian Grid Code defines requirements for the connection to the distribution system and the transmission system. Prior to 2007 wind farms and wind turbines had been classified as unscheduled units due to their intermittent power source and were exempted from most requirements. Since March 2007 new amendments for wind turbines have been published by the Australian Energy Market Commission (AEMC) and have been assimilated in the Grid Code. These connection conditions are also applicable to wind turbines and are similar to those from other Grid Operators. Requirements have been subdivided into an automatic access standard, a minimum access standard and a negotiated access standard. For wind farms complying with the automatic access standard grid access won't be denied. [13]

Chapter 5 of the AEMC Grid Code states that the network service provider should provide the connection applicant with the following technical requirements/standards relevant to the proposed plant: [16]

(a) the automatic access standards;

(b) the minimum access standards;

(c) the applicable plant standards;

(d) the negotiated access standards that will require NEMMCO's involvement; and

(e) the normal voltage level, if that is to change from the nominal voltage level.

Notes: [16]

- If the application to connect involves the connection of generating units having a nameplate rating of 10MW or greater to a distribution network, the distribution network service provider must consult the relevant transmission network service provider regarding the impact of the connection contemplated by the application to connect on fault levels, line reclose protocols, and stability aspects.

- NEMMCO require a registered participant to meet or exceed the minimum access standard but do not require the registered participant to exceed the relevant automatic access standard for the requirement.

- A negotiated access standard must be no less onerous than the corresponding minimum access standard provided by the network service provider.

AEMC grid code requirements for fault ride through are summarised below, for a complete and detailed specification please refer to chapter 5 of AEMC "National Electricity Rules Version 23", AEMC, Sydney, November 2008 [16].

Link: http://www.aemc.gov.au/rules.php

8.1.1 *Power Frequency Voltage*

Schedule 5.1a.4 of the AEMC grid code establishes the following maximum and minimum power frequency voltage limits:

Except as a consequence of a contingency event, the voltage of supply at a connection point should not vary by more than 10% above or below its normal voltage, provided that the reactive power flow and the power factor at the connection point is within the corresponding limits set out in the connection agreement.

As a consequence of a credible contingency event, the voltage of supply at a connection point should not rise above its normal voltage by more than a given percentage of normal voltage for longer than the corresponding period shown in Figure 21 (Figure S5.1a.1) for that percentage.

As a consequence of a contingency event, the voltage of supply at a connection point could fall to zero for any period.

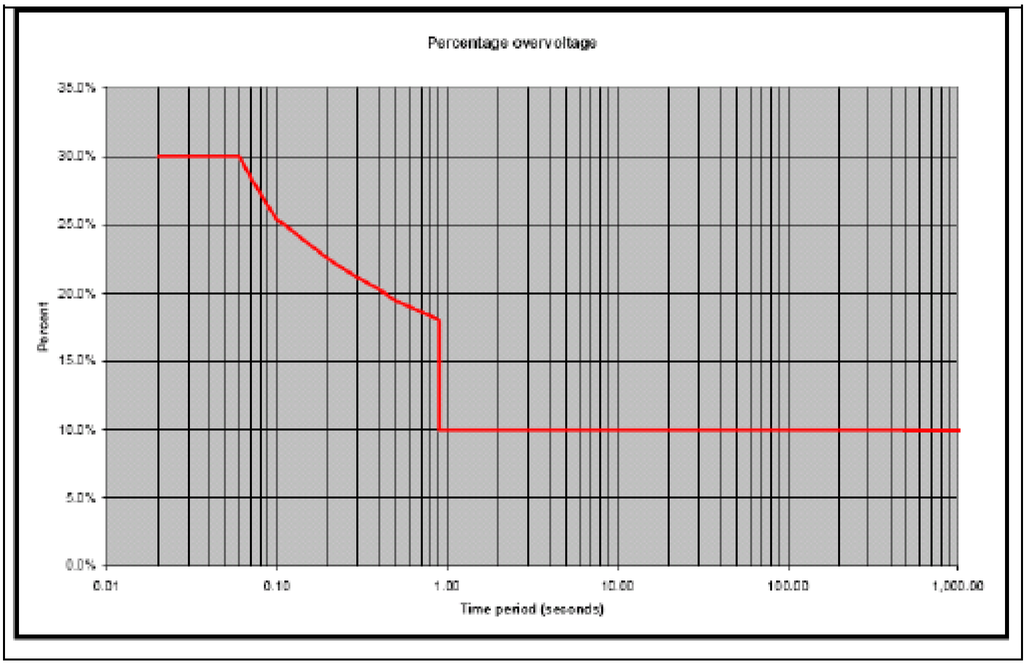

Figure 21:- Voltage-Duration Profile AEMC Overvoltage Requirement

8.1.2 *Fault Clearance Times*

Schedule 5.1a.8 of the AEMC grid code establishes maximum fault clearance times shown in Table 10. Registered participants may negotiate relevant terms of a connection agreement to improve the standard of supply to the level of the system standard.

Nominal Voltage at fault location (kV)	Time (ms)		
	Primary protection (Zone 1)	Primary protection remote fault (Zone 2)	Breaker Fail / Back-up
Voltage ≥ 400 kV	80	100	175
250 kV ≤ Voltage < 400 kV	100	120	250
100 kV < Voltage < 250 kV	120	220	430
Voltage ≤ 100 kV	As necessary to prevent plant damage and meet stability requirements		

Table 10: Maximum Fault Clearance Times (Schedule 5.1a table S5.1a.2 [16])

8.1.3 Generator response to voltage disturbances

Schedule 5.2 of the AEMC grid code provides additional requirements that generators must satisfy to connect to the power system. Generator response to voltage disturbances is specified in Schedule 5.2.5.4.

The ***automatic access standard*** requires continuous uninterrupted operation of generators for the following connection point voltage levels and time durations:

1) voltages over 110% for the durations permitted under clause S5.1a.4 (refer to Figure 21);

2) 90% to 110% of normal voltage continuously;

3) 80% to 90% of normal voltage for a period of at least 10 seconds; and

4) 70% to 80% of normal voltage for a period of at least 2 seconds.

The ***minimum access standard*** requires continuous uninterrupted operation over the voltage range of 90% to 110% of normal voltage, provided that the ratio of voltage to frequency (as measured at the connection point and expressed as percentage of normal voltage and percentage of 50Hz) does not exceed:

1) a value of 1.15 for more than 2 minutes; or

2) a value of 1.10 for more than 10 minutes.

8.1.4 Generator response to disturbances following contingency events

Schedule 5.2 of the AEMC grid code provides additional requirements that generators must satisfy to connect to the power system. Generator response to disturbances following contingency events is specified in Schedule 5.2.5.5.

The ***automatic access standard*** requires:

Continuous uninterrupted operation of generator units following a fault or credible contingent event. The fault should be cleared in the longest time expected to be taken for a breaker fail protection system to clear the fault or a relevant primary protection systems to clear the fault. (Refer to Table 10).

A generating system and each of its generating units must supply or absorb from the network:

1) capacitive reactive current of at least the greater of its pre-disturbance reactive current and 4% of the maximum continuous current of the generating system including all generating units for each 1% reduction (from its pre-fault level) of connection point voltage during the fault;

2) reactive power after disconnection of the faulted element, to ensure that the connection point voltage is within the range for continuous uninterrupted operation (see clause S5.2.5.4); and

3) active power 100 milliseconds after disconnection of the faulted element, to at least 95% of the level existing just prior to the fault.

The ***minimum access standard*** requires:

Continuous uninterrupted operation of generator units following a fault or credible contingent event. The fault should be cleared in the longest time expected to be taken for a breaker fail protection system to clear the fault or a relevant primary protection systems to clear the fault. (Refer to Table 10).unless NEMMCO and the network service provider agree that:

1) A total reduction of generation in the power system due to the fault would not exceed 100MW;

2) There is unlikely to be an adverse impact on quality of supply to other network users; and

3) There is unlikely to be a material adverse impact on power system security.

Provided that the event is not one what would disconnect the generating unit from the power system by removing network elements from service.

Subject to any changed power system conditions beyond the generators reasonable control after disconnection of the faulted element, each generating system must deliver to the network active power and supply or absorb leading or lagging reactive power sufficient to ensure that the connection point voltage is within the range for continuous uninterrupted operation agreed under clause S5.2.5.4.

8.1.5 Partial Load Rejection

Generator response to partial load rejection is specified in Schedule 5.2.5.5. This clause does not apply to asynchronous generating units. Minimum load means minimum sent out generation for continuous stable operation.

The ***automatic access standard*** requires:

A generating unit must be capable of continuous uninterrupted operation during and following a power system load reduction of 30% from its predisturbance level or equivalent impact from separation of part of the power system in less than 10 seconds provided that the loading level remains above minimum load.

The ***minimum access standard*** requires:

A generating unit must be capable of continuous uninterrupted operation during and following a power system load reduction of 5% or equivalent impact from separation of part of the power system in less than 10 seconds provided that the loading level remains above minimum load.

8.1.6 AEMC Wind

Wind farms shall stay connected during 3 phase faults in the transmission system until the primary protection system clears the fault. For all other types of fault the wind farm shall operate for the longest time expected for the respective breaker fail protection to clear the fault or the highest of 430 ms and the time needed by the relevant primary protection system to separate the faulty grid element [13][16].

8.2 AESO Alberta - Canada

The LVRT requirement for Alberta applied to voltage at the PCC and all transmission connected wind farms above 5 MW capacity, as shown in Figure 22 [20].

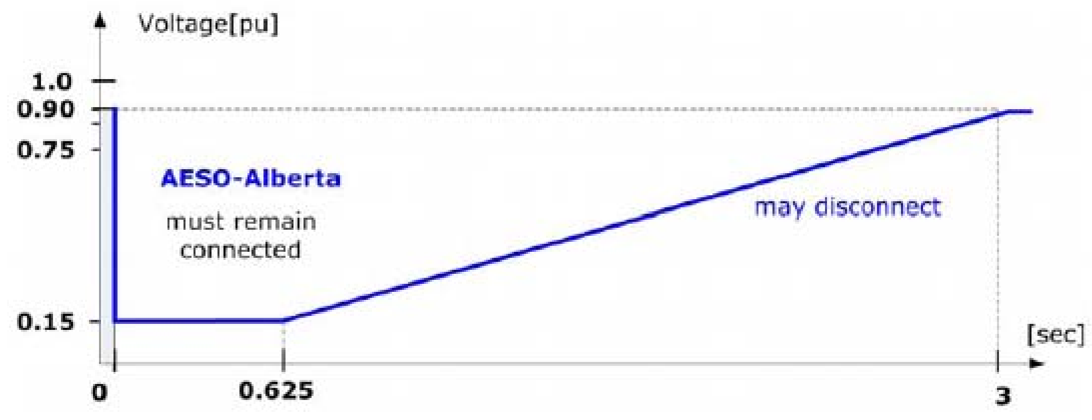

Figure 22:- Voltage-Duration Profile AESO-Alberta Canada Requirement [20]

A wind farm shall not trip any loaded wind turbine generators for voltage dips resulting from normally cleared transmission faults on any phase or combination of phases at or beyond the point of connection.

The following exceptions are given for wind farms:

- Are not required to ride-through transmission system faults that cause a forced outage of a radial line to the farm;
- Are not expected to ride-through faults that occur on the low voltage networks of the farm.

8.3 EIRGRID - Ireland

EIRGrid ROI grid code requirements for fault ride through are summarised below, for a complete and detailed specification please refer to the EIRGrid Grid Code, version 3.2, December 2008.
Link:
http://www.eirgrid.com/EirGridPortal/DesktopDefault.aspx?tabid=Grid%20Code&TreeLinkModID=1451&TreeLinkItemID=18

8.3.1 Power Frequency Voltages

Table 11 shows transmission system voltage ranges during normal operating conditions and following a transmission fault.

Nominal voltage U_n [kV]	**Normal operating ranges**		**Operating range following transmission fault**	
	Lower voltage [kV]	**Upper voltage** [kV]	**Lower voltage** [kV]	**Upper voltage** [kV]
400	370	410	350	420
220	210	240	200	245
110	105	120	99	123

Table 11: Transmission system voltage ranges EIRGrid Requirements (CC8.3 [21])

Some transmission system disturbances (e.g. earth faults, lightning strikes will result in short-term voltage deviations outside the above ranges.

8.3.2 Fault Clearance Times

CC.10.1 of the EIRGrid grid code establishes maximum fault clearance times shown in Table 12. Registered participants may negotiate relevant terms of a connection agreement to improve the standard of supply to the level of the system standard.

Nominal voltage at fault location (kV)	Primary protection time (ms)
400 kV	80
220 kV	100
110 kV	120

Table 12: Maximum Primary Protection Fault Clearance Times, EIRGrid Requirements (CC.10.1 [21])

CC.10.4 of the EIRGrid grid code indicates that high speed automatic reclosing (HSAR) is a feature of transmission system operation, characterised by the sudden re-energisation of the power supply after a dead time of approximately 400 ms. All tripping and high speed reclosing on the 110 kV and 220 kV systems is three pole.

CC.10.8 of the EIRGrid grid code indicates that where feasible the TSO will provide circuit breaker fail protection on grid connection point circuit breakers installed in new transmission stations.

8.3.3 Fault Ride Through Requirement for Wind Generators

WFPS1.4 EIRGrid grid code indicates that wind farms should remain connected to the transmission system for voltage dips where the voltage measured at the HV terminals of the grid connected transformer remains above the heavy black line in Figure 23.

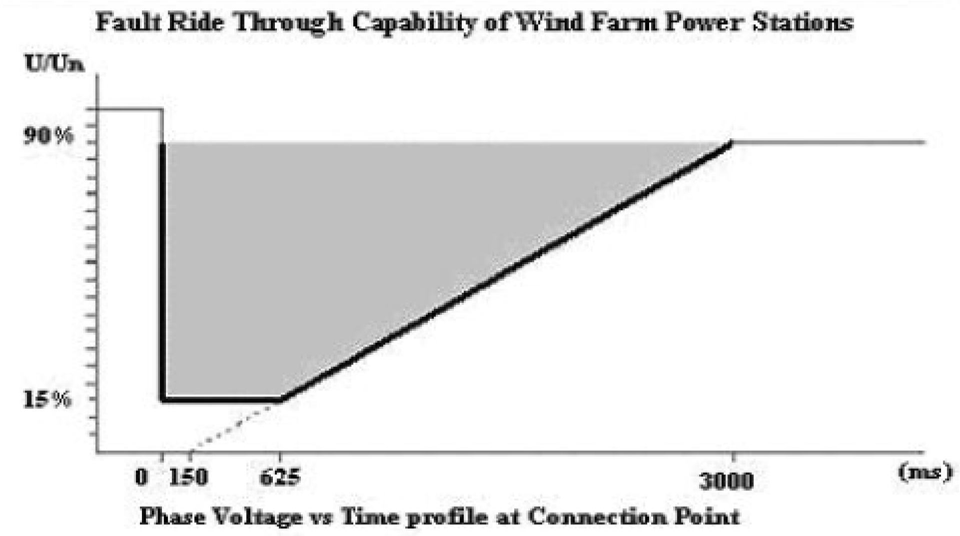

Figure 23:- Voltage-Duration Profile, EIRGrid Requirement for wind farms [21]

In addition to remaining connected to the Transmission system the wind farm should have the technical capability to provide the following functions:

1) During the transmission system voltage dip the wind farm should provide active power in proportion to retained voltage and maximise reactive current to the transmission system without exceeding wind turbine generator limits. The maximisation of reactive current should continue for at least 600 ms or until the transmission system voltage recovers to within the normal operational range of the transmission system, whichever is the sooner.
2) The wind farm should provide at least 90% of its maximum available active power as quickly as the technology allows and in any event within 1 second of the transmission system voltage recovering to the normal operating range.

8.4 Eltra & Elkraft - Denmark

8.4.1 Fault Ride Through Requirement for Wind Generators

The technical requirements for wind generators connected to the Eltra and Elkraft grids above 100 kV in Denmark, after December 2004 are given in this section [22].

Temporary Overvoltages

If the wind Farm is isolated with part of the power system, the wind farm shall not give rise to overvoltage which may damage the equipment in the power system.

The temporary overvoltages, which are defined in IEC-60071-1, shall be limited to 1.3 pu of the output voltage and be reduced to 1.20 pu of the output voltage after 100 ms.

Situations in which a wind turbine must not trip

The wind farm shall remain connected after the below faults in the transmission grid. Likewise, compensation plants shall remain connected.

Three-phase short circuit	Short circuit in 100 ms
Two-phase short circuit with/without earth contact	Short circuit in 100 ms followed by a new short circuit 300…500 ms later, also with a duration of 100 ms
Single-phase short circuit to earth	Single-phase earth fault 300…500 ms later, also with a duration of 100 ms

Table 13: Situations in which a wind turbine must not trip, Eltra & Elkraft Requirements (Section 8.2 [22])

A wind farm should have sufficient capacity to meet the above mentioned requirements in case of the following three independent sequences:

- At least two single-phase earth faults within two minutes
- At least two two-phase short circuits within two minutes
- At least two three-phase short circuits within two minutes

Additionally, there should be sufficient energy reserves (emergency power, hydraulics and pneumatics) for the following three independent sequences:

- At least six single-phase earth faults with five minute intervals
- At least six two-phase short circuits with five minute intervals
- At least six three-phase short circuits with five minute intervals.

Furthermore, the wind farm shall be able to withstand the impacts from asymmetrical faults in the grid where unsuccessful automatic reclosure takes place without necessitating disconnection of wind turbines in the wind farm from the grid.

Stability following symmetric three-phase grid fault

Eltra and Elkraft require that a turbine test is undertaken with the voltage profile shown in Figure 24 to show the behaviour of the wind farm in the case of a three-phase fault with a slowly recovering voltage.

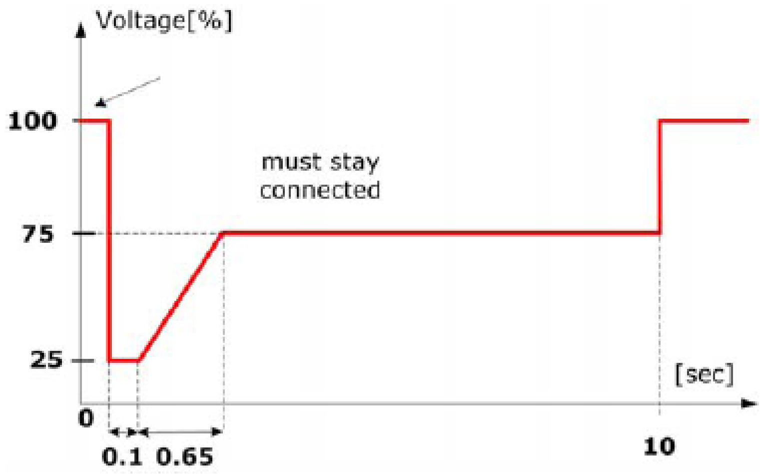

Figure 24:- Voltage-Duration Profile Eltra & Elkraft Requirement for Wind Generators [20][22]

The power system is represented by a Thevenin equivalent. The power value of the voltage at the clamps of the Thevenin generator varies as shown in Figure 24 based on the rated voltage in the connection point.
The short-circuit power (S_K) in the connection point is assumed to be 10 times the rated power (P_n) of the wind farm and the phase angle 84.3deg (R/X = 0.1).

In addition to riding through the fault the wind farm is expected to produce the rated power no later than 10 seconds after the voltage is above 0.9pu again. During the voltage dip the active power in the connection point shall meet the following condition:

$P_{current} \geq K_p \times P_{t=0} \times (U_{current} / U_{t=0})$ ^2

Where:

$P_{current}$ Current active power measured at the connection point

$P_{t=0}$ Power measured at the connection point immediately before the voltage dip

$U_{t=0}$ The voltage at the connection point immediately before the voltage dip

$U_{current}$ Current voltage measured at the connection point

K_p = 0.4: Reduction factor considering any voltage dips to the generator terminals

Stability following asymmetric grid faults and unsuccessful reclosure

The wind turbine should be able to withstand the impacts from the following asymmetric faults in the grid without requiring disconnection of wind turbines in the wind farm:

- Two phase fault on a line in the transmission grid with unsuccessful reclosure, as shown in Figure 25.
- Single-phase fault on a line in the transmission grid with unsuccessful reclosure.

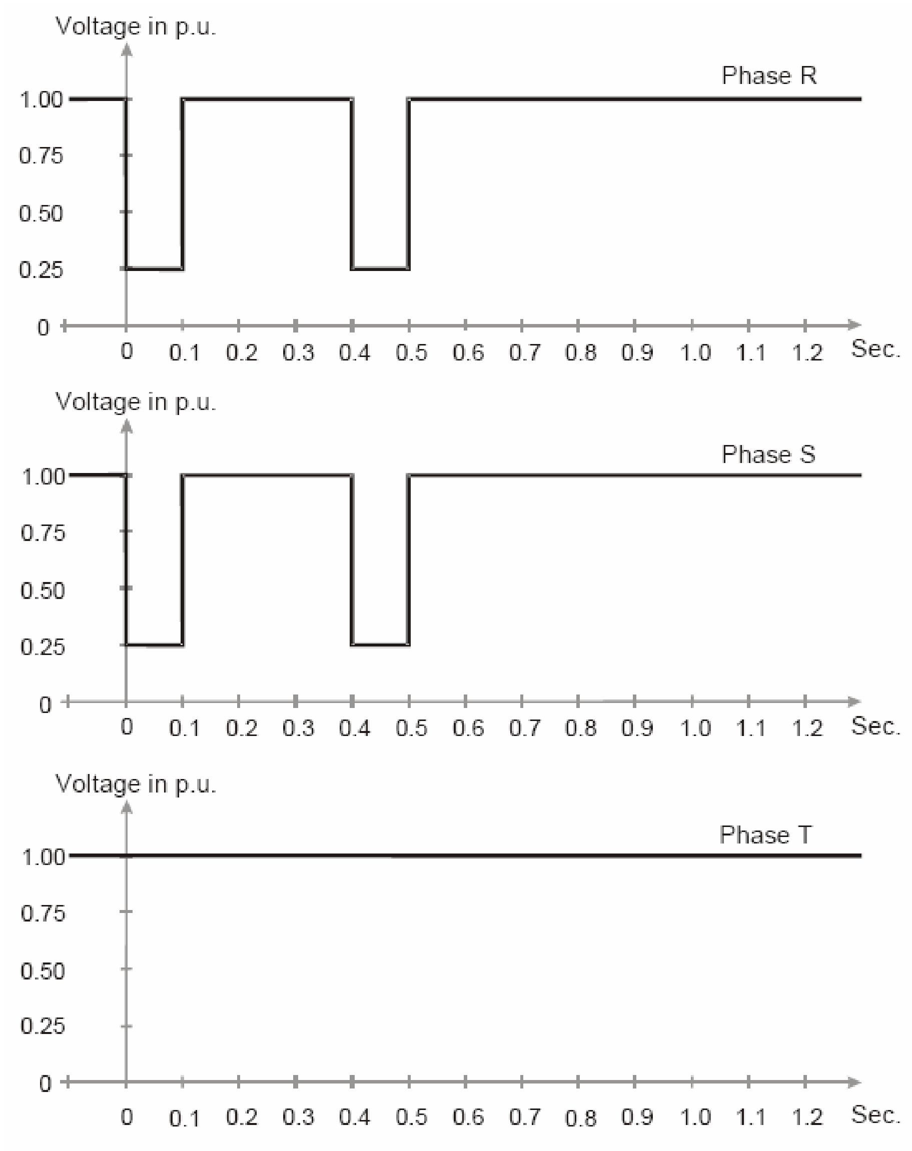

Figure 25:- Voltage-Duration Profile for Two-phase fault Eltra & Elkraft Requirement for Wind Generators [22]

In addition the plant owner should confirm that:

- The wind turbines can withstand the thermal impacts at repetition the turbine test after 2 minutes.

- The wind turbines in the wind farm can withstand the thermal impacts at repetitions of the asymmetric faults described above after two minutes.

- There are sufficient energy reserves for six repetitions of the turbine test at five minute intervals.

- There are sufficient energy reserves for six repetitions of asymmetric faults described above at five-minute intervals.

8.5 Energinet.dk - Denmark

Energinet.dk grid code requirements for fault ride through are summarised below, for a complete and detailed specification please refer to Energinet.dk Regulations for Grid Connection [14] [22], Link:

http://www.energinet.dk/en/menu/System+operation/Technical+Regulations+for+electricity/Regulations+for+grid+connection/Regulations+for+grid+connection.htm

[14] Technical Regulations 3.2.3 for Thermal Power Station Units 1.5 MW or above Version 5.1, November, 2008, Energinet.dk Regulations for Grid Connection.

[22] Technical Regulations 3.2.5 Wind Turbines connected to Grids with Voltages above 100 kV, published by Elkraft System and Eltra December 3, 2004, Energinet.dk Regulations for Grid Connection.

Energinet.dk specify requirements for:

- Thermal power plants [14]
- Wind Generators [22] (refer to previous section)

8.5.1 Power Frequency Voltage

Table 14 shows fixed voltage values indicating full-load voltage range at the point of common coupling. For voltages of 132 kV and higher the upper voltage limit is higher than recommended in EN 60038 due to brief high voltages in the event of re-reestablishment of the grid after blackout.

Nominal voltage U_n [kV]	**Lower voltage U_L** [kV]	**Lower full-load voltage U_{LF}** [kV]	**Upper full-load voltage U_{HF}** [kV]	**Upper voltage U_H** [kV]
400	320	360	420	440
150	135	146	170	180
132	119	125	145	155
60	54	57	66	72.5
50	45	47.5	55	60

Table 14: Full-load voltage range in relation to upper and lower voltage limit [14]

8.5.2 Fault Ride Through Requirement for Thermal plant

A power station unit, including auxiliary supply system and auxiliary facilities, must stay connected to the grid during and after a voltage disturbance at the connection point as described below with a subsequent load reduction of maximum 10%.

Connecting points above 100 kV

A power station unit must be able to withstand a voltage disturbance nearby on the high voltage side of the generator transformer and in the connecting point as stated in Figure 26 and Figure 27.

Faults near a power station – short line faults

A voltage disturbance near a power station means a voltage disturbance occurring in such a distance from a power station unit that, in the event of a three-phase short-circuit, the share of AC in the initial short-circuit current (IK") from the power station unit's generator(s) is minimum 1.8 times the nominal current of the generators(s).

In the event of three phase voltage disturbances, the power station unit must be capable of withstanding a voltage curve in the three phases as stated in Figure 26.

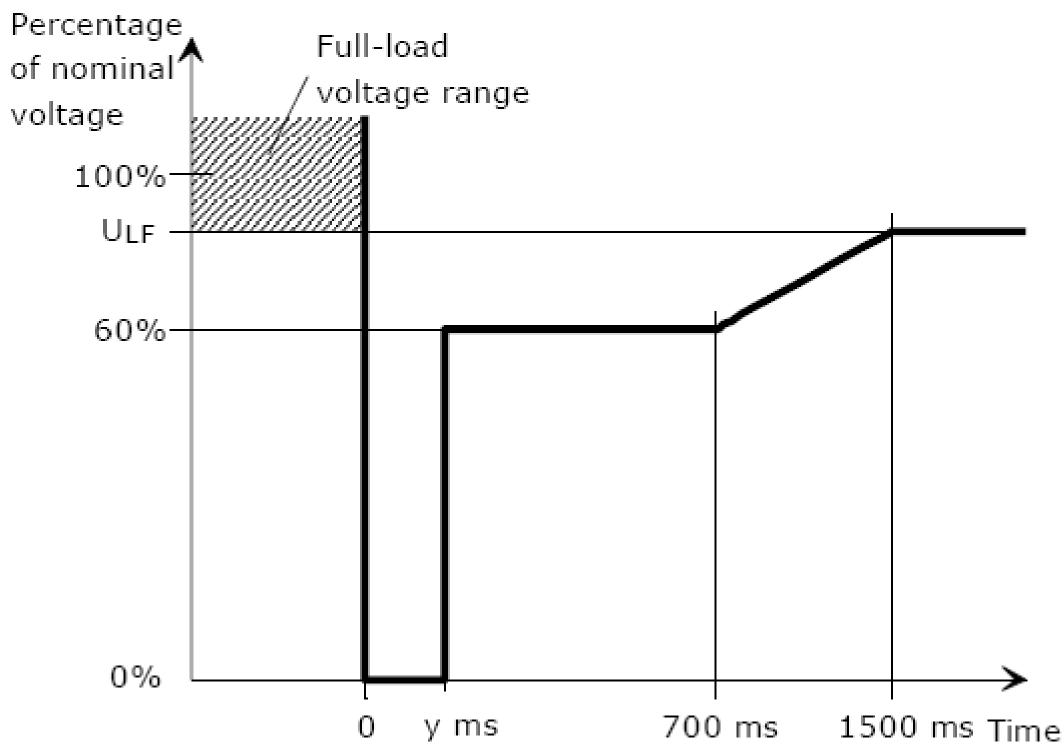

Figure 26:- 3-Phase Voltage-Duration Profile Energinet.dk Requirement for thermal plant > 1.5MW [14]

Figure 26 shows the 3-phase voltage disturbance which must not lead to the disconnection of the power station unit. U_{LF} designates the lower limit of the full-load voltage range according to Table 14.

In Easter Denmark, y is required to be 250 ms (in accordance with Nordel), and in Western Denmark, y is required to be 150 ms (in accordance with the UCTE).

In the event of one-phase or two-phase voltage disturbances, the power station unit must be capable of withstanding a voltage curve in the faulty phases as stated in

Figure 27 at the same time as the voltage in the non-faulty phases is between the lower limit for the full-load voltage range (U_{LF}) and 1.4 times the upper limit for the full-load voltage range (1.4 x U_{HF}) according to Table 14. The time interval, x, in Figure 27 may vary between 300 ms and 800 ms.

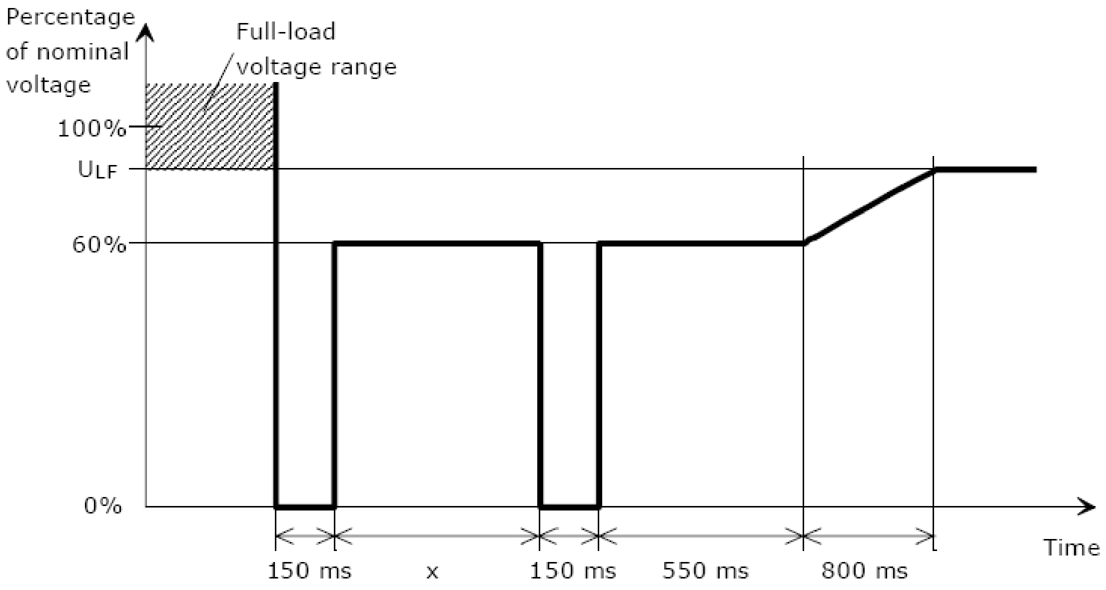

Figure 27:- Phase Voltage-Duration Profile Energinet.dk Requirement for thermal plant >1.5MW [14]

Figure 27 shows the phase voltage during faulty phases in the event of one-phase or two-phase voltage disturbances which must not lead to the disconnection of the power station unit. U_{LF} designates the lower limit of the full-load voltage range according to Table 14.

Faults far from a power station

A voltage disturbance far from a power station means a voltage disturbance occurring in such a distance from the power station unit that, in the event of a three-phase short circuit, the share of AC in the initial short-circuit current (IK") from the power station unit's generator(s) is less than 1.8 times the nominal current of the generators(s).

A power station unit must be capable of tolerating any one-, two- or three-phase voltage disturbance far from the power station of up to five seconds in connecting points with nominal voltage above 100 kV.

Connection points up to 100 kV

A power station unit must be designed in such a way that the connecting points with nominal voltage up to 100 kV are able to withstand voltage sags up to 50% of the nominal voltage in one second in all three phases and voltage sags to 0% voltage during one second in one phase.

A power station unit must be designed in such a way that the connecting points with nominal voltage up to 100 kV are able to withstand voltage sags up to $U_{3\varphi}$ in between one and five seconds in one phase. The size of $U_{3\varphi}$ and $U_{1\varphi}$ in pu is given at $U_{3\varphi}$ = 1-(0.5 seconds)/t and $U_{1\varphi}$ = 1-(1 second)/t where t is the duration of the voltage sag (nominal voltage equal to 1 pu) as illustrated in Figure 28.

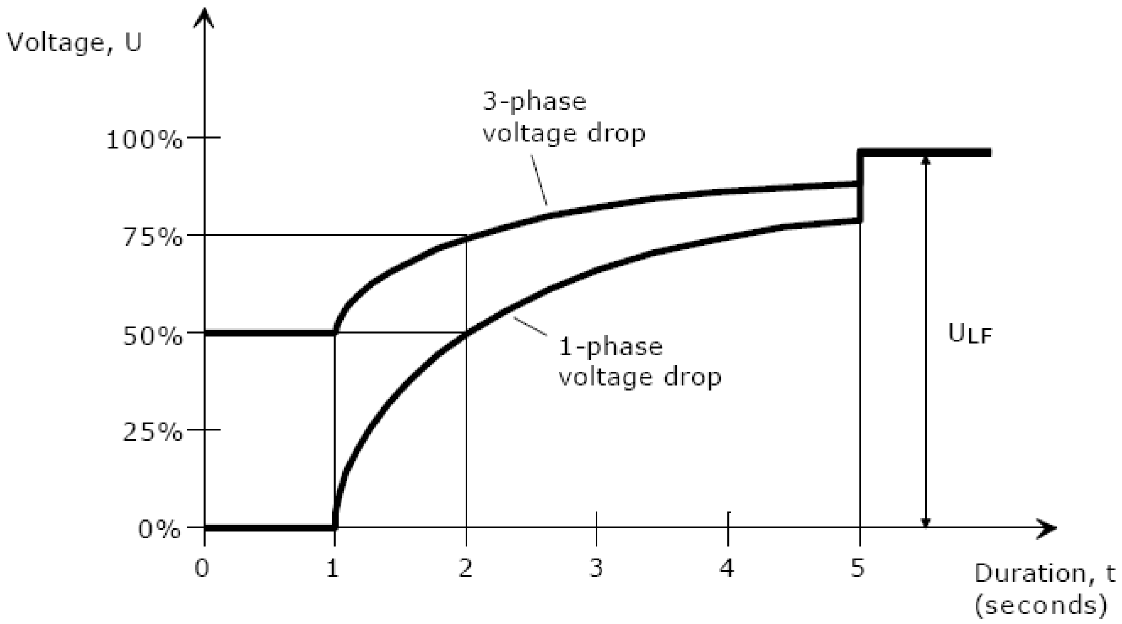

Figure 28:- Relationship between duration and range of one-phase and 3-ph voltage sags which power station units connected up to 100 kV must be able to withstand, Energinet.dk Requirement for thermal plant >1.5MW [14]

8.6 E.ON - Germany

Germany is divided into 4 control areas managed by the TSOs EnBW, E.ON, Vattenfall Europe Transmission and RWE. Smaller wind farms or single wind turbines being connected to the Distribution system are currently not covered by the connection conditions of the German TSOs [13].

With respect to the older Grid Code E.ON has dramatically changed the LVRT requirements in the Code of 2006 [13] [15]. The voltage-time-diagram is now divided into more areas defining behaviours during grid failure. Below 1500 ms and depending on the respective area brief disconnection by the wind turbine generator might be allowed, if defined re-synchronisation times are kept. This requires agreement with the System Operator. If system voltage does not recover to 80% of the highest phase-to-phase value measured at the low voltage side of each turbine transformer a quarter of all turbine in the wind farm shall be disconnected by automatic protection device after 1.5s, 1.8s, 2.1s and 2.4s [13].

8.6.1 Fault Ride Through Requirements

EON grid code requirements for fault ride through are summarised below, for a complete and detailed specification please refer to section 3.2., E.ON "Grid Code High and Extra High Voltage", E.ON Netz GmbH, Bayreuth, April 2006 [15].

Link: http://www.pvupscale.org/IMG/pdf/D4_2_DE_annex_A-3_EON_HV_grid__connection_requirements_ENENARHS2006de.pdf

The EON Grid Code defines requirements for

(a) Type 1 generating plants, described as synchronous generator connected directly to the grid; and

(b) Type 2 generating plants, described as all generators that do not meet the performance requirements/conditions of type 1 generating plant.

Type 1 generator plant requirements

A Type 1 generating plant refers to a synchronous generator connected directly to the grid.

Three-phase short circuits must not cause instability or a disconnection from the grid for fault-clearing times of up to 150 ms in the entire operating range of the generating plant.

Figure 29 shows the limit curve for the voltage pattern at the grid connection in the case of a three-phase short circuit, above which Type 1 generating plants may not be disconnected from the mains and may not become unstable. This requirement applies to the entire operating range of the generating plant.

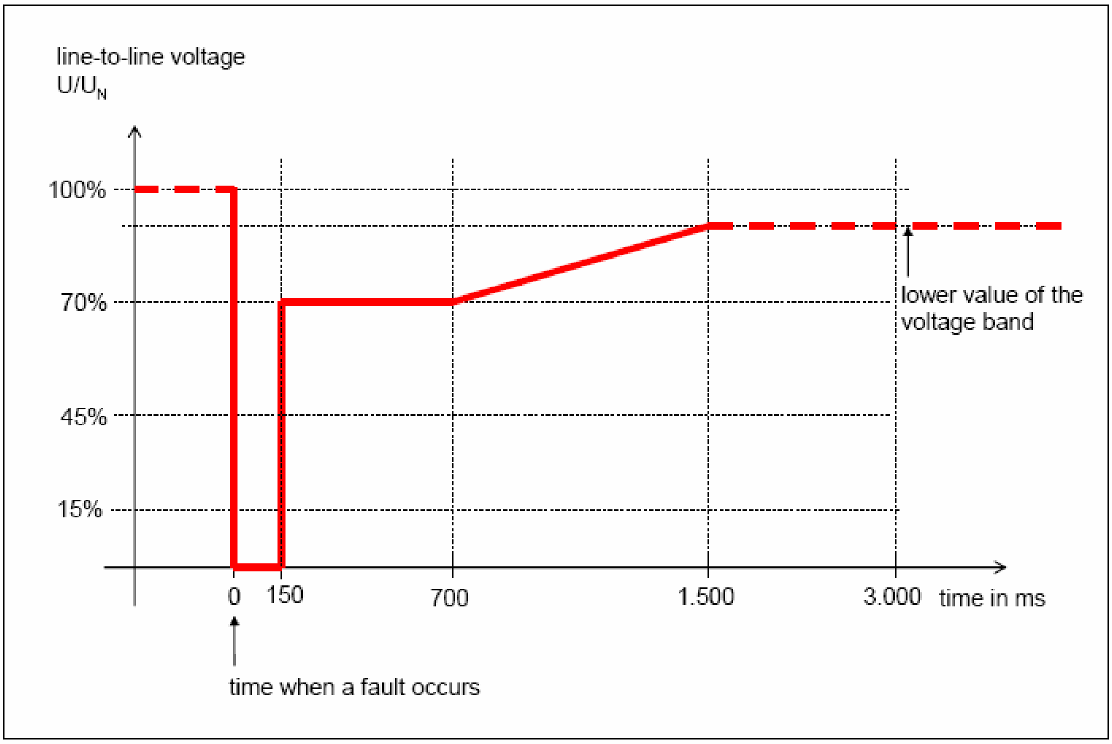

Figure 29:- Voltage-Duration Profile E.ON LVRT Requirement for Type 1 plant

Type 2 generator plant requirements

When the conditions for Type 1 are not fulfilled the generating plant is of Type 2.

In the event of faults in the grid outside the protection range for the generating plant, there must be no disconnection from the grid. A short circuit current must be fed into the grid during the period of a fault.

Due to the system technology used; e.g. asynchronous generators or frequency converters, the short circuit current contribution must be agreed with E.ON in each individual case.

If the voltage at the grid connection point falls and remains at a value of and below 85% of the reference voltage (380/220/110 kV e.g. 110 kV x 0.85 = 93.5kV) and with a simultaneous reactive power direction to the connectee (under-excited operation), the generating plant must be disconnected from the grid after a time delay of 0.5 seconds. The voltage value refers to the highest value of the three line-to-line grid voltages. The disconnection must be made at the generator circuit breaker. This function performs the voltage support monitoring.

If the voltage on the low voltage side of each individual generator transformer falls and remains at and below 80% of the lower value of the voltage band (e.g. 690 V x 0.95 x 0.8 = 525 V) based on a resetting ratio of 0.98, one quarter of the generators must disconnect themselves from the grid after 1.5s, after 1.8s, after 2.1 s and after 2.4 s respectively. The voltage value refers to the highest value of the three line-to-line grid voltages. Different time stages can be agreed in individual cases.

If the voltage on the low voltage side of each individual transformer rises and remains at over 120% of the upper value of the voltage band (e.g. 690 V x 1.05 x1.2 = 870 V) based on a resetting ratio of 1.02, the generator affected must disconnect itself from the grid with a time delay of 100 ms. The voltage value refers to the lowest value of the three line-to-line grid voltages. Different time stages can be agreed in individual cases.

In addition, it is recommended to switch off the affected generators without a time delay on the low voltage side of each generator transformer in the event of frequency deviation below 47.5Hz or above 51.5 Hz.

It is recommended to perform the over-frequency and under-frequency, overvoltage and undervoltage functions on the generators in one unit in each case. In general these functions, including the undervoltage function at the grid connection point, can be referred to as automatic system.

Following disconnection of a generating plant from the grid due to an over frequency, underfrequency, undervoltage, overvoltage or after the end of isolated operation, automatic synchronisation of the individual generators with the grid is only allowed if there is a voltage at the grid connection point greater than 105 kV in the 110 kV grid, greater than 210 kV in the 220 kV grid and greater than 370 kV in the 380 kV grid. The voltage value refers to the lowest value of the three line-t-line grid voltages. After this deactivation, the increase in the active power output to the E.ON grid must not exceed a maximum gradient 10% of the grid connection capacity per minute.

Figure 30 shows the limit curves for the voltage pattern at the grid connection for Type 2 generating plants.

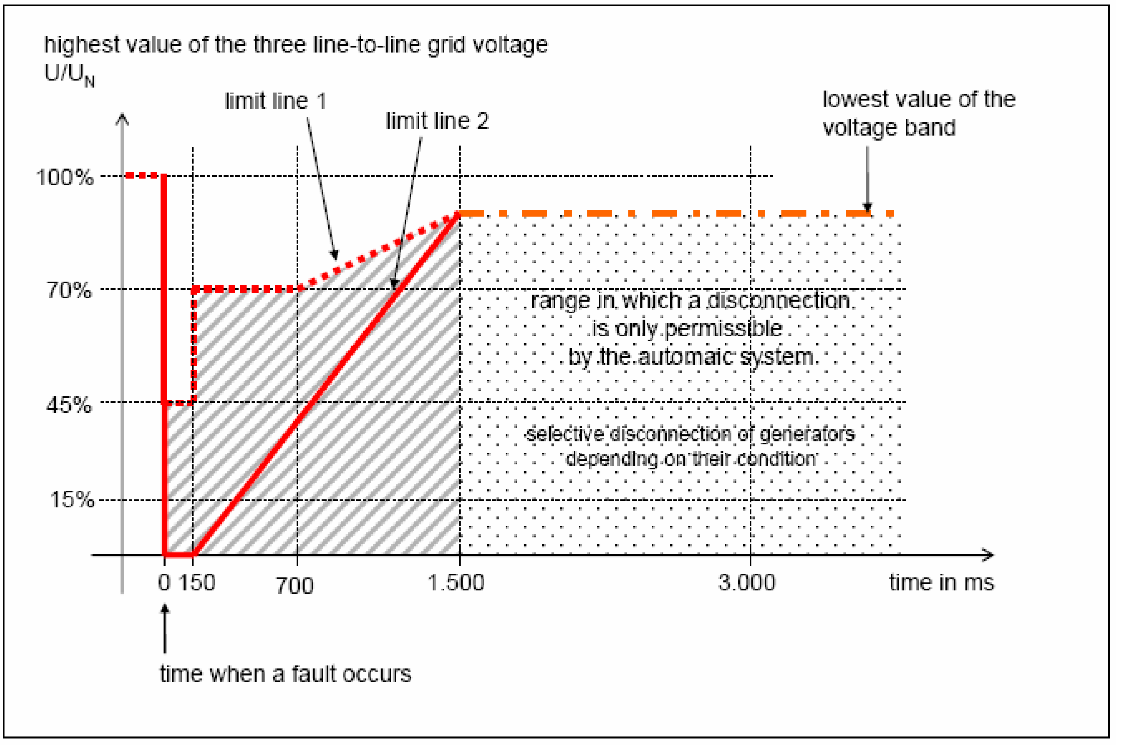

Figure 30:- Voltage-Duration Profile E.ON LVRT Requirement for Type 2 plant

Three-phase short circuits or fault related symmetrical voltage dips must not lead to instability above the Limit line 1 in Figure 30 or to disconnection of the generating plant from the grid.

The following applies within the shaded area and above the Limit Line 2 in Figure 30.

All generating plants should experience the fault without disconnection from the grid. If due to the grid connection concept (plant concept including generators), a generating plant cannot fulfil this requirement, it is permitted with agreement from E.ON to shift the limit line while at the same time reducing the resynchronisation time and ensuring a minimum reactive power infeed during the fault. The reactive power infeed and resynchronisation must take place so that the generating plant meets, in a suitable way, the respective requirements of the grid at the grid connection point.

If when experiencing the fault, the individual generator becomes unstable or the generator protection responds a brief disconnection of the generating plant (KTE) from the grid is allowed by agreement with ENE. At the start of a KTE, resynchronisation of the generating plant must take place within 2 seconds at the latest. The active power infeed must be increased to the original value with a gradient of a least 10% of the rated generator power per second.

A KTE from the grid is always allowed below Limit line 2 in Figure 30. Here, resynchronisation times of more than 2 seconds and an active power increase following fault clearance of less than 10% of the rated power per second are also possible in exceptional cases by agreement with E.ON.

For all generating plants that do not disconnect from the grid during the fault the active power output must be continued immediately after fault clearance and increased to the original value with a gradient of at least 20% of the rated power per second.

The generating plants must support the grid voltage with additional reactive current during a voltage dip. To do this, the voltage control must be activated as shown in Figure 31 in the event of a voltage dip of more than 10% of the effective value of the generator voltage. The voltage control must take place within 20 ms after fault recognition by providing a reactive current on the low voltage side of the generator transformer amounting to at least 2% of the rated current for each percent of the voltage dip. A reactive power output of at least 100% of the rating current must be possible if necessary.

After the voltage returns to the dead band, the voltage support must be maintained for a further 500 ms in accordance with the specified characteristic. The transient balancing procedures following the voltage return must be completed after 300 ms. If the generating plants generators are too far away from the grid connection point, resulting in the voltage support being ineffective, E.ON requires measurement of the voltage dip at the grid connection point and the voltage support there as a function of the measured value.

Particularly in the extra high voltage grid, the voltage control can be required as continuous control also with out a dead band in normal operation.

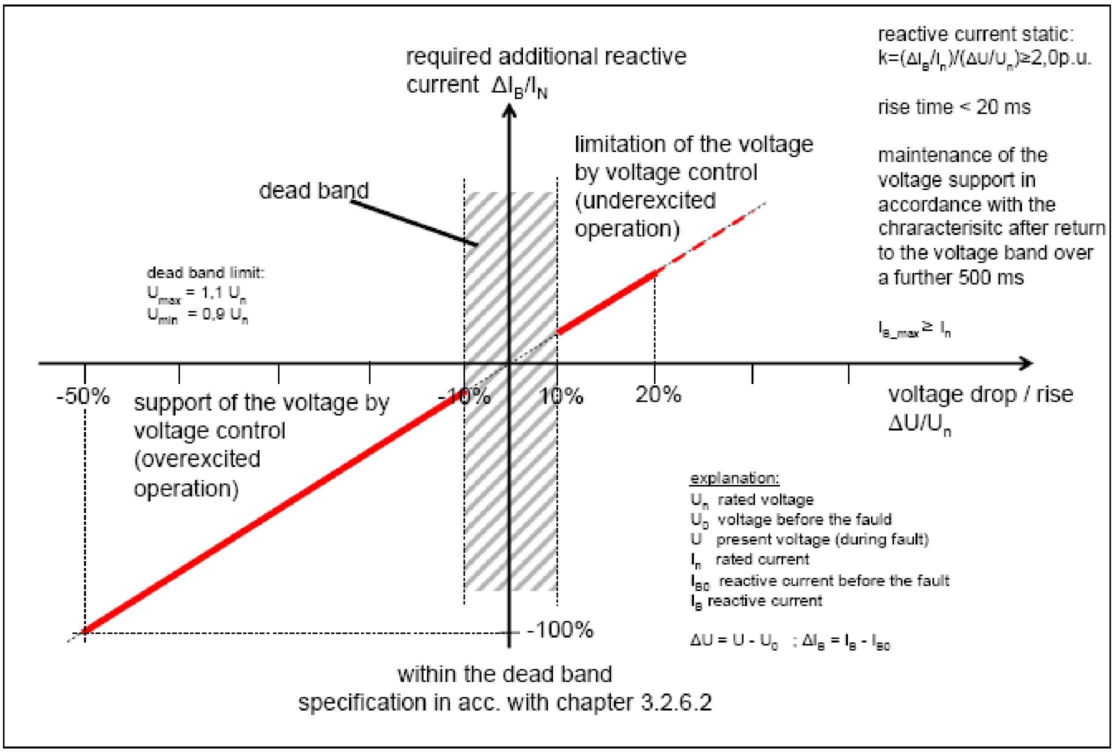

Figure 31:- The principle of voltage support in the event of grid faults

8.7 Federal Energy Regulatory Commission (FERC) - USA

FERC grid code requirements for fault ride through are summarised below [7] [18] [20] [23].

The Federal Energy Regulatory Commission (FERC) in the US has issued LVRT requirements for wind energy facilities larger than 20 MW connected to the transmission network.

The requirement states that wind power plants "shall be able to remain online during voltage disturbances up to the time periods and associated voltage levels" shown in Figure 32. Also the wind generating plant must be able to operate continuously at 90% of the rated line voltage, measured at the high voltage side of the wind plant substation transformer".

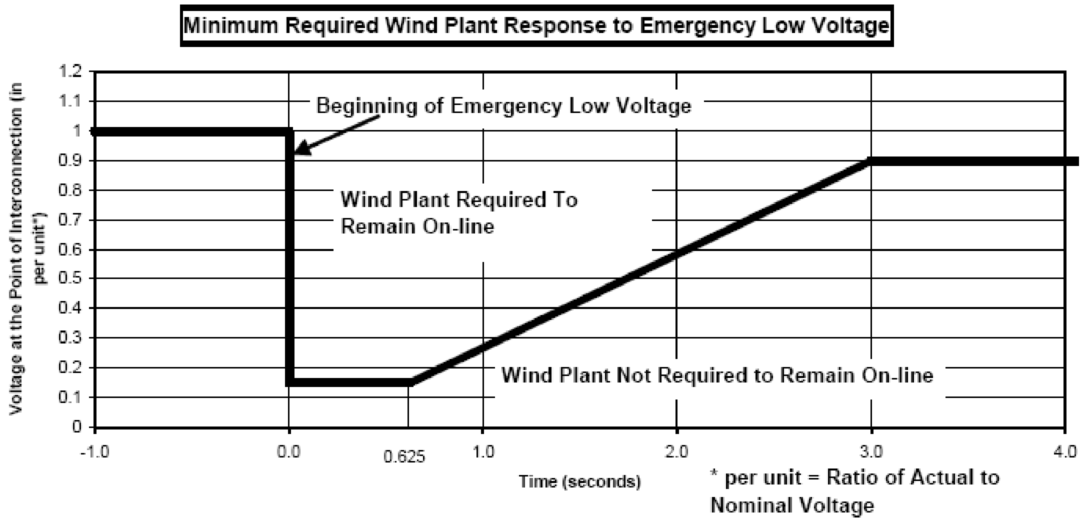

Figure 32:- Voltage-Duration Profile FERC - USA Requirement [23]

Recent requirements [7] [23] indicate different requirements for the "Transition Period", up to 31^{st} Dec 2007 and the "Post-Transition period" generation from 1^{st} January 2008.

8.7.1 Transition Period LVRT Standard

The transition period standard applies to wind generating plants subject to FERC Order 661 that have either: (i) interconnection agreements signed and filed with the Commission, filed with the Commission in unexecuted form, or filed with the commission as non-conforming agreements between January 1, 2006 and December 31, 2006, with a scheduled in-service date no later than December 31, 2007, or (ii) wind generating turbines subject to a wind turbine procurement contract executed prior to December 31, 2005, for delivery through 2007.

1) Wind generating plants are required to remain in-service during three-phase faults with normal clearing (which is a time period of approximately 4 – 9 cycles) and single line to ground faults with delayed clearing, and subsequent post-fault voltage recovery to prefault voltage unless clearing the fault effectively disconnects the generator from the system. The clearing time

requirement for a three-phase fault will be specific to the wind generating plant substation location, as determined by and documented by the transmission provider. The maximum clearing time the wind generating plant shall be required to withstand for a three-phase fault shall be 9 cycles at a voltage as low as 0.15 pu, as measured at the high side of the wind generating plant step-up transformer (i.e. the transformer that steps the voltage up to the transmission interconnection voltage or "GSU"), after which, if the fault remains following the location-specific normal clearing time for three-phase faults, the wind generating plant may disconnect from the transmission system.

2) This requirement does not apply to faults that would occur between the wind generator terminals and the high side of the GSU or to faults that would result in a voltage lower than 0.15 per unit on the high side of the GSU serving the facility.

3) Wind generating plants may be tripped after the fault period if this action is intended as part of a special protection system.

4) Wind generating plants may meet the LVRT requirements of this standard by the performance of the generators or by installing additional equipment (e.g., Static Var Compensator, etc.) within the wind generating plant or by a combination of generator performance and additional equipment.

5) Existing individual generator units that are, or have been, interconnected to the network at the same location at the effective date of the Appendix G LVRT Standard are exempt from meeting the Appendix G LVRT Standard for the remaining life of the existing generation equipment. Existing individual generator units that are replaced are required to meet the Appendix G LVRT Standard.

8.7.2 Post-transition Period LVRT Standard

All wind generating plants subject to FERC Order No. 661 and not covered by the transition period described above must meet the following requirements:

1) Wind generating plants are required to remain in-service during three-phase faults with normal clearing (which is a time period of approximately 4 – 9 cycles) and single line to ground faults with delayed clearing, and subsequent post-fault voltage recovery to prefault voltage unless clearing the fault effectively disconnects the generator from the system. The clearing time requirement for a three-phase fault will be specific to the wind generating plant substation location, as determined by and documented by the transmission provider. The maximum clearing time the wind generating plant shall be required to withstand for a three-phase fault shall be 9 cycles after which, if the fault remains following the location-specific normal clearing time for three-phase faults, the wind generating plant may disconnect from the transmission system. A wind generating plant shall remain interconnected during such a fault on the transmission system for a voltage level as low as zero volts, as measured at the high voltage side of the wind GSU.

2) This requirement does not apply to faults that would occur between the wind generator terminals and the high side of the GSU.

3) Wind generating plants may be tripped after the fault period if this action is intended as part of a special protection system.

4) Wind generating plants may meet the LVRT requirements of this standard by the performance of the generators or by installing additional equipment (e.g., Static Var Compensator) within the wind generating plant or by a combination of generator performance and additional equipment.

5) Existing individual generator units that are, or have been, interconnected to the network at the same location at the effective date of the Appendix G LVRT Standard are exempt from meeting the Appendix G LVRT Standard for the remaining life of the existing generation equipment. Existing individual generator units that are replaced are required to meet the Appendix G LVRT Standard.

8.8 Hydro Quebec - Canada

Hydro-Quebec grid code requirements for fault ride through are summarised below. [20]

Hydro-Quebec's LVRT requirement is defined for "the positive sequence voltage on the high-voltage side of the switchyard" as given in Figure 33. The wind generators must remain connected to the transmission system without tripping during:

- A three-phase fault cleared in 9 cycles including a fault on the high voltage side of the switchyard and for the time required to restore voltage after the fault is cleared as specified in Figure 33 for the positive-sequence voltage;
- A two-phase-to-ground fault ora phase-to-phase fault cleared in 9 cycles including a fault on the high voltage side of the switchyard and for the time required to restore voltage after the fault is cleared;
- A single-phase to ground fault cleared in 15 cycles including a fault on the high-voltage side of the switchyard and for the time required to restore voltage after the fault is cleared.

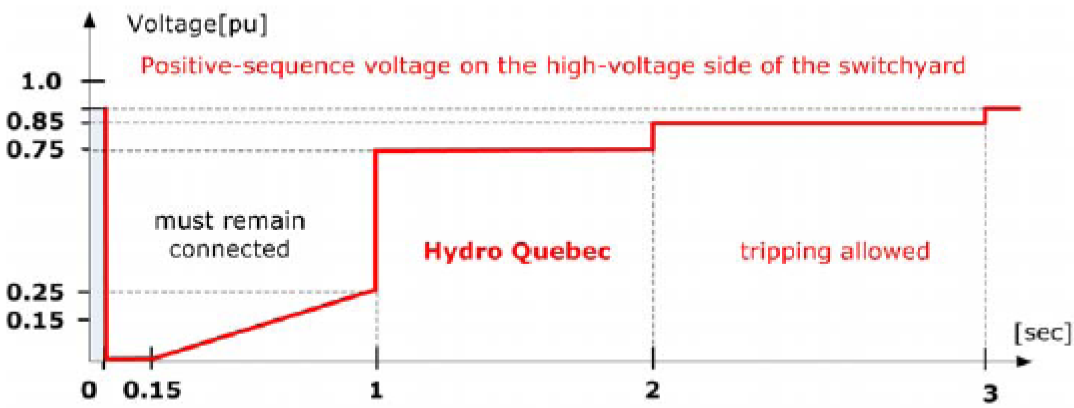

Figure 33:- Voltage-Duration Profile Hydro Quebec Canada Requirement [20]

Also, the wind generators must remain in service without tripping during a remote fault cleared by slow protective device (up to 45 cycles) and for the time required to restore voltage after the fault is cleared, whether the remote fault is:

- A three-phase fault, if the positive sequence voltage on the high-voltage side of the switchyard does not fall below 0.25pu;
- A two-phase-to ground fault, if the positive-sequence voltage on the high-voltage side of the switchyard does not fall below 0.5pu;
- A phase-to-phase fault if the positive-sequence voltage on the high-voltage side of the switchyard does not fall below 0.6 pu.

8.9 National Grid (NGT) - United Kingdom

Wind Farms are divided into embedded and non-embedded systems in the UK [1] [13]. Non-embedded generating units are directly connected to the transmission system whereas embedded units only have an indirect connection to the transmission system by another user (e.g. a wind farm or Distribution system). Embedded and non-embedded units need to fulfil different requirements. Furthermore different requirements have been defined for the two transmission areas Scotland and England/Wales, which are also dependent upon the rated power output of the wind farm. The PCC of a wind farm might also be defined on a remote transmission system busbar in the UK [13].

NGT grid code requirements for fault ride through are summarised below, for a complete and detailed specification please refer to pages 159-161 & 194-196 National Grid "Grid Code", Issue 3 Rev 31, National Grid Electricity Transmission, Warwick 2008. [1]

Link: http://www.nationalgrid.com/NR/rdonlyres/1403354E-36F2-4010-A72C-F36862E1FF3E/28912/zFullGBGridCodeI3R31.pdf

8.9.1 Fault Ride Through Requirements

The NGT Grid Code defines requirements for

(a) short circuit faults at a supergrid voltage up to 140 ms; and

(b) supergrid voltage dips greater than 140 ms in duration

NGT supergrid voltage is defined as the 400 and 275 kV transmission system.

For short circuit faults at supergrid voltage up to 140 ms:

- For short circuit faults at supergrid voltage up to 140 ms each generator unit should remain transiently stable and connect to the system without tripping for a close up solid 3 phase short circuit fault or any unbalanced short circuit fault for a total fault clearance time of up to 140 ms.
- Following fault clearance recovery of the supergrid voltage to 90% may take longer than 140 ms as illustrated in Figure 34.
- Active power output should be restored to at least 90% of the level available immediately before the fault:
  - following clearance of the fault and within 0.5s of the restoration of the voltage to minimum nominal voltage level at the grid entry point; or
  - within 0.5s of restoration of the voltage at the User system entry point to 90% of nominal or greater if embedded.
- During the period of the fault each generating unit shall generate maximum reactive current without exceeding the transient rating limit of the unit.
- Once the Active power output has been restored to the required level, active power oscillation should be acceptable provided that:
  - The total active energy delivered during the period of the oscillations is at least that which would have been delivered if the active power was constant
  - The oscillations are adequately damped.

For supergrid voltage dips greater than 140 ms in duration:

In addition to the above requirements the following applies:

- For balanced supergrid voltage dips having durations greater than 140 ms and up to 3 minutes the fault ride through requirement is defined by the voltage-duration profile illustrated in the Figure 34.
- During supergrid voltage dips the unit should provide active power output at least in proportion to the retained balanced voltage at the grid entry point (or the voltage at the user system entry point if embedded). The exception being a non-synchronous generating unit or power park module if there has been a reduction in the intermittent power source in the time range what restricts the active power output.
- Generator units should provide maximum reactive current with out exceeding transient rating limits of the unit.
- Active power output following supergrid voltage dips should be restored to at least 90% of the pre-fault output:
  - within 1s of restoration of the voltage at the grid entry point to minimum levels; or
  - within 1s of restoration of the voltage at the user system entry point to 90% of nominal or greater if embedded.

  Except in the case of a Non-synchronous generating unit where there has been a reduction in the intermittent power source during the time range that restricts the active power output.

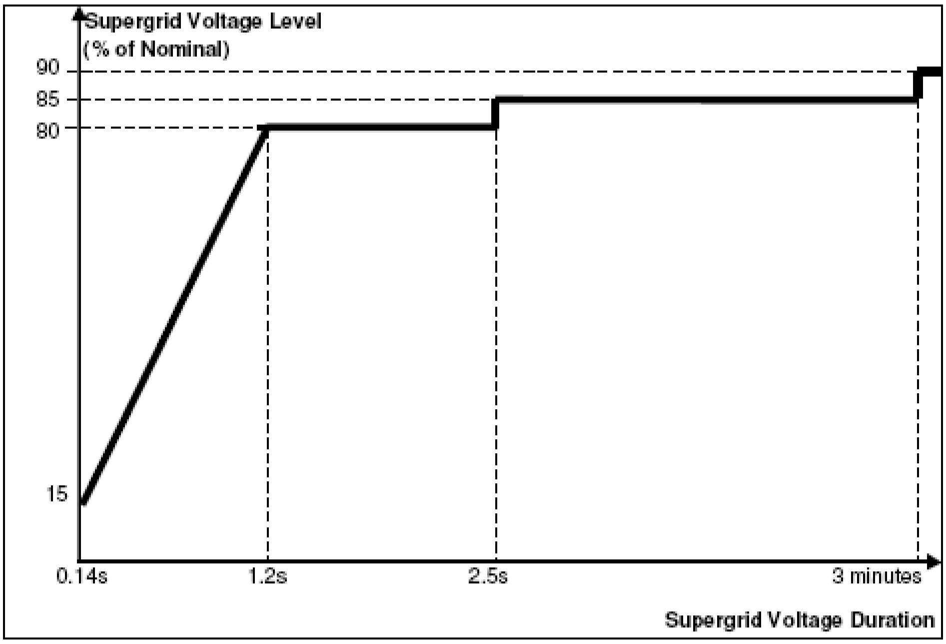

Figure 34:- Voltage-Duration Profile NGT LVRT Requirement

Other Requirements:

- In the case of a power park module (comprising of wind-turbine generator units), the above requirements do not apply then the power park module is operating at less than 5% of its Rated MW or during very high wind speed conditions when more than 50% of the wind turbine generator units in a power park have been shut down or disconnected under an emergency shutdown sequence to protect users plant and apparatus.

- Non-synchronous generating unit or power park module is required to withstand without tripping, the negative phase sequence loading incurred by clearance of a close-up phase-to-phase fault by system back up protection on the GB transmission system operating at supergrid voltage.
- Power park modules in Scotland with a completion date prior to 2005 may be exempt from certain ride through requirements. See detailed grid code.
- To avoid unwanted island operation, Non-synchronous generating units in Scotland or power park modules in Scotland should be tripped for the following conditions:
  - Frequency above 52Hz for more than 2 seconds
  - Frequency below 47Hz for more than 2 seconds
  - Voltage at the connection Point or user system entry point below 80% for more than 2 seconds
  - Voltage at the connection point or user system entry point above 120% for more than 1 second.

8.10 Nordel - Scandinavia (Denmark, Finland, Norway & Sweden)

Nordic grid code requirements for fault ride through are summarised below, for a complete and detailed specification please refer to "Nordic Grid Code", Nordel, January 2007 [24].

Link: http://www.nordel.org/content/default.asp?pagename=openfile&DocID=4948

In Denmark, Finland, Norway and Sweden, Transmission System Operators (TSOs) have been appointed with overall responsibility for ensuring that every subsystem works properly. These TSOs are Energinet.dk for the Danish subsystem, Fingrid Oyj for the Finnish subsystem, Statnett SF for the Norwegian subsystem and Affarsverket Svenska Krafnat for the Swedish subsystem.

The following AC voltage levels are used in the Nordic grid (there are also interconnections at lower voltage across national borders):

Denmark: 132/150/220/400 kV

Finland: 110/220/400 kV

Norway: 300/420 kV (and 132 kV in the North of Norway)

Sweden: 220/400 kV

8.10.1 Fault Ride Through Requirements

Nordel specify requirements for:

- Thermal power plants (Norway, Sweden and Denmark > 100MW, Finland > 50MW)
- Hydro power plants (Norway >10MW, Sweden and Finland > 50MW)
- All wind plant connected to the Nordic Power system

National requirements may be stricter than the requirements stated.

Line Side Faults of Clearing Time up to 0.25 Seconds

The unit shall be designed so that it remains connected to the grid and continues its operation after isolation of line side fault within 0.25 seconds.

Thermal power plants > 100MW in Denmark East (synchronous to the Nordel grid) shall fulfil the above demands. Thermal power plants > 100MW in Denmark West (synchronous to the UCTE grid) shall fulfil UCTE demands. (Clearing time 0.15s and the demands are to the line side of the generator transformer.) For smaller thermal power plants and wind power plants the demands are weaker see detailed specifications.

Deep Voltage Transient

The units shall be designed so that they can withstand the following line side voltage variation resulting from faults in the grid, without disconnection from the grid:

- Step reduction to 0% of the line side voltage lasting for 0.25s,
- Followed by linear increase from 25% to 90% in 0.5s,
- Followed by constant line side voltage 90%.

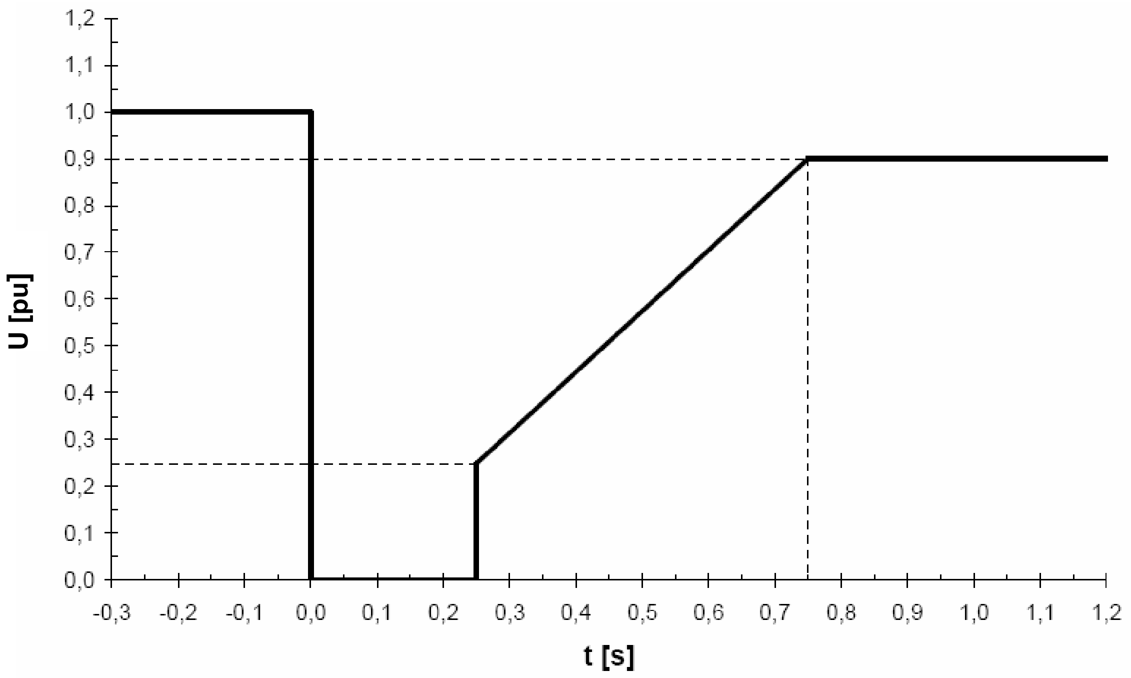

Figure 35:- Voltage-Duration Profile Nordic Requirement

It should be noted that the design criteria for the voltage protection may deviate, as the unit must manage several kinds of other faults that may occur in the generators/power grid. The rise-time of the voltage is highly dependent on the local system characteristics i.e. short circuit capacity. The TSO may decide to use a different curve in his own area to ensure adequate system security.

Large Voltage Disturbances

The unit may be disconnected from the power system, if larger voltage variations or longer durations than those for which the unit has been designed occur, and shall, in each case, be disconnected if the unit falls out of step.

The unit and its auxiliary power system shall be designed for such voltage variation that a safe changeover to house load operation can take place after disconnection from the network.

8.11 PSE - Poland

The Polish (PSE) transmission owner specifies the following voltage-duration profile for generators wishing to connect to the Polish network: [13].

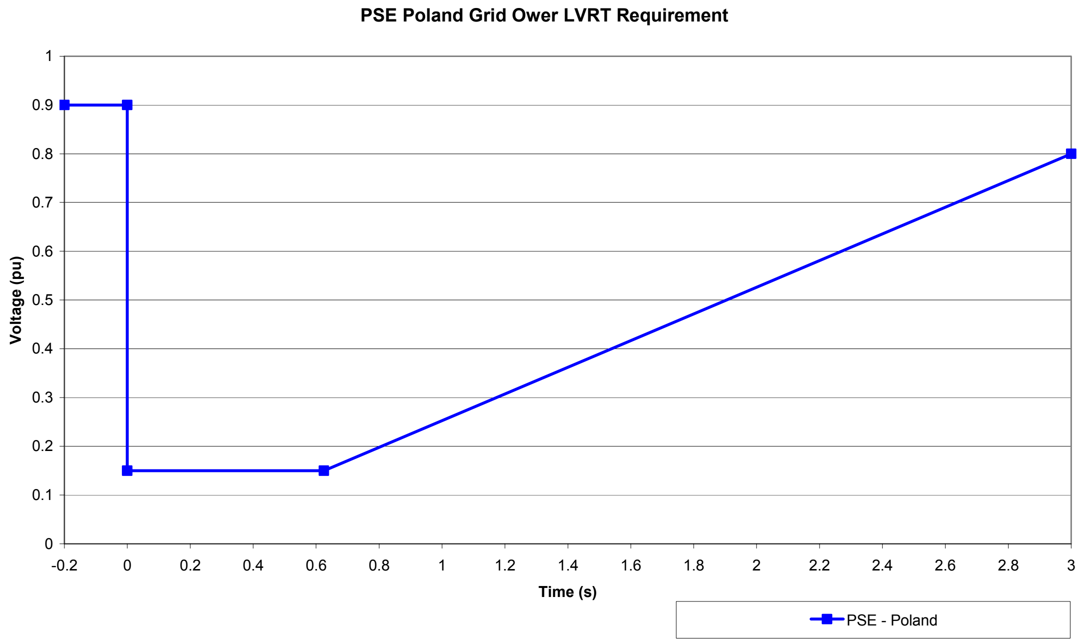

Figure 36:- Voltage-Duration Profile Polish Requirement

8.12 Red Electrica de Espańa (REE) Spain

Red Electrica de Espańa (REE) the Spanish transmission owner specifies the following voltage-duration profile for generators wishing to connect to the Spanish network: [20] [25].

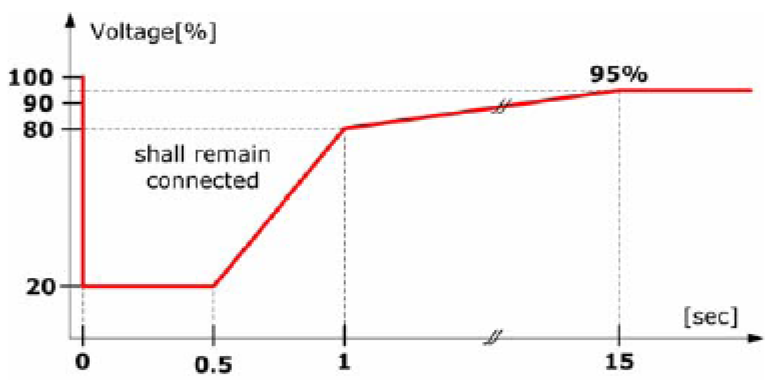

Figure 37:- Voltage-Duration Profile Spanish Requirement

8.13 Scottish Power/ Scottish Hydro - Scotland

Scottish grid code requirements for fault ride through are summarised below, for a complete and detailed specification please refer to Connection Conditions within the "Scottish Grid Code", Scottish Power, November 2002 [26].

Link: http://www.scottishpower.com/uploads/ScottishGridCode8a.pdf

8.13.1 Fault Clearance Times

Clause 4.2.2 of the Scottish grid code establishes the following maximum fault clearance times:

- Main protection for 400 kV circuits: 80 ms;
- Main protection for 275 kV circuits: 100 ms;
- Main protection for 132 kV circuits: 140 ms;
- Main protection for LV Network owners and directly connected customers (<132 kV circuits): 250 ms

The probability that these times will be exceeded for any given fault must be less than 2%.

- CB failure time: 300 ms;

In the case of the failure to trip of a users circuit-breaker provided to interrupt fault current interchange with the Transmission system, circuit breaker fail protection should be provided to trip all necessary electrically adjacent circuit breakers within 300 ms

- Back-up protection for 220 kV circuits: approx. 300 ms;

Back up protection should be provided with a target maximum fault clearance time of 300 ms to cover for the failure of the main protection.

8.13.2 Fault Ride Through Requirements

The voltage at any point on the transmission network will normally remain within the following nominal values unless abnormal conditions prevail.

Following major system faults, the maximum overvoltage values given may occur but the duration will not exceed 15 minutes unless exceptional circumstances prevail.

Nominal Voltage (kV)	Normal Range	15 Minutes Overvoltage
400	±5%	+10%
275	±10%	+15%
132	±10%	+20%

Table 15: Voltage Variations on the Scottish Grid

Under fault and circuit switching conditions the rated frequency component of voltage could fall to zero on one or more phases or rise to 150% of nominal phase-to-earth voltage on the 275 kV network.

The Scottish low voltage fault ride through profile for generation connected to the 132 kV transmission system is shown in Figure 38 [27].

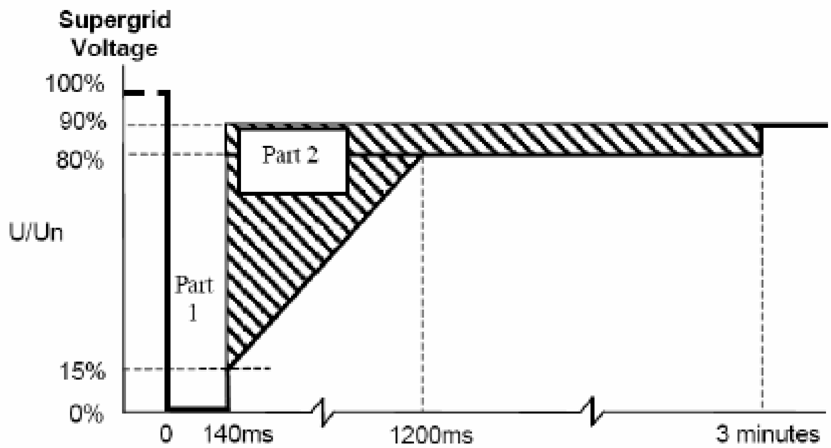

Figure 38:- Voltage-Duration Profile Scottish Requirement

8.14 Affärsverket svenska kraftnäts (SvK) - Sweden

SvK Sweden grid code requirements for fault ride through are summarised below, for a complete and detailed specification please refer to the Affärsverket svenska kraftnäts (SvK) Grid Code, December 2005. "Affärsverket svenska kraftnäts föreskrifter och allmänna råd om driftsäkerhetsteknisk utformning av produktionsanläggningar". Link: http://www.svk.se/Tekniska-krav/Foreskrifter/

All thermal and wind generation above 100 MW should remain connected for the voltage profile indicated in Figure 39.

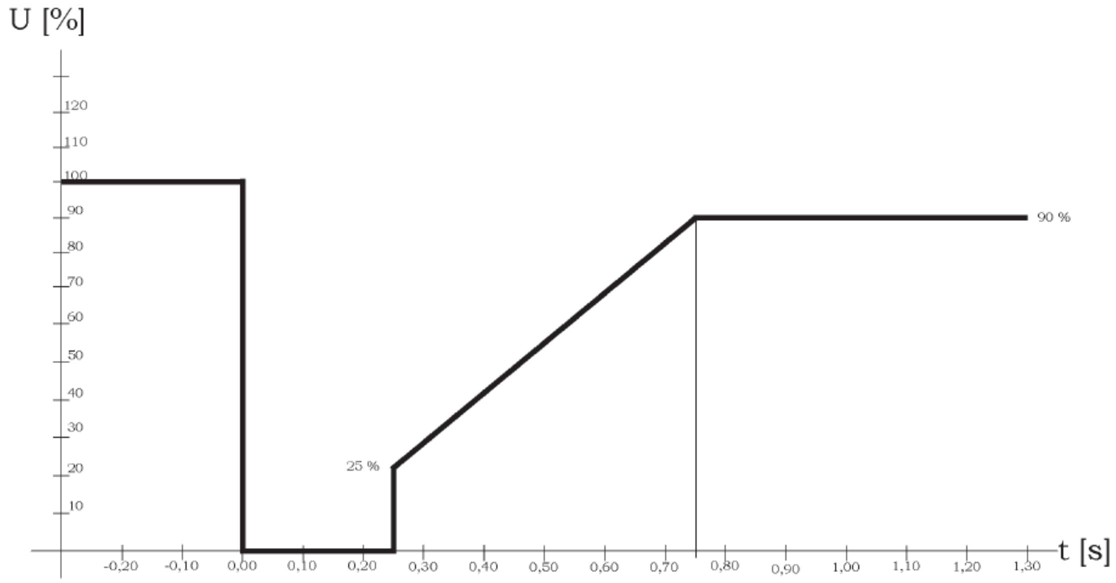

Figure 39:- Voltage-Duration Profile, SvK Requirement for Generators > 100 MW [28]

All thermal and wind generation above 1.5 MW and below 100 MW should remain connected for the voltage profile indicated in Figure 40.

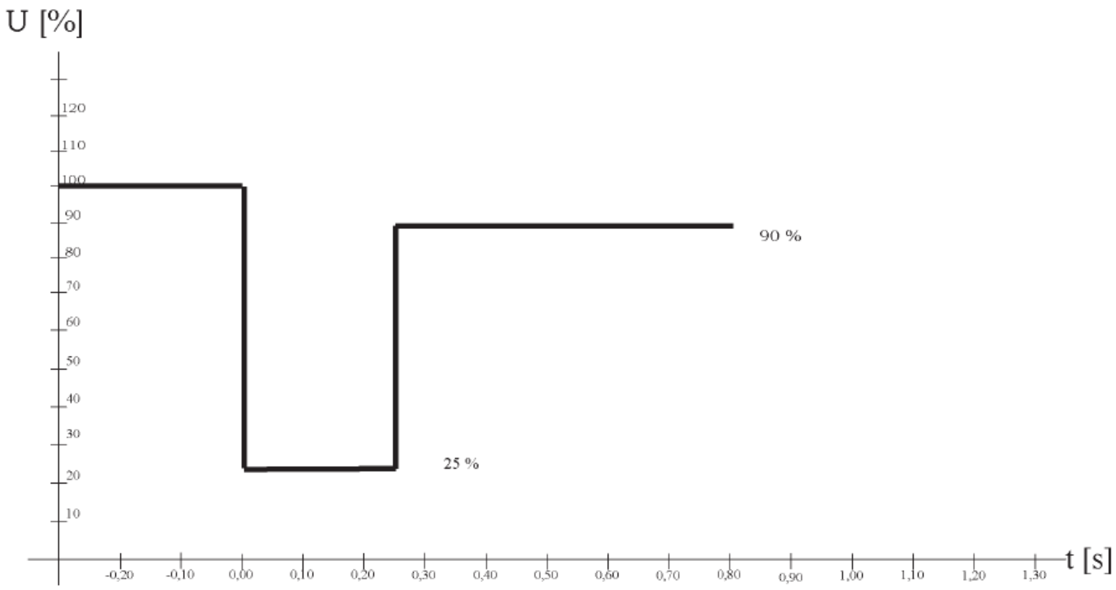

Figure 40:- Voltage-Duration Profile, SvK Requirement for Generators < 100 MW [28]

8.15 WECC - USA

WECC grid code requirements for fault ride through are summarised below.

8.15.1 Fault Ride Through Requirements

In April 2005, the WECC board approved the WECC Low Voltage Ride Through Standard. [29]

1) Generators are required to remain in-service during system faults (three phase faults with normal clearing and single line to ground faults with delayed clearing) unless clearing the fault effectively disconnects the generator from the system. This requirement does not apply to faults that would occur between the generator terminals and the high side of the generator step up transformer or to faults that would result in a voltage lower than 0.15 per unit on the high side of the generator step-up transformer.

2) In the post-fault transient period, generators are required to remain in-service for the low voltage excursions specified in WECC Table W-1 as applied to a load bus. These performance criteria are applied to the generator interconnection point, not the generator terminals.

3) Generators may be tripped after the fault period if this action is intended as part of a special protection system.

4) This Standard does not apply to a site where the sum of the installed capabilities of all machines is less than 10 MVA, unless it can be proven that reliability concerns exist.

5) This Standard applies to any generation independent of the interconnected voltage level.

6) This Standard can be met by the performance of the generators or by installing additional equipment (e.g., SVC, etc).

7) Existing individual generator units that are interconnected to the network at the time of the adoption of the Standard are exempt from meeting this Standard for the remaining life of the existing generation equipment. Existing individual generator units that are replaced are required to meet this standard.

NERC and WECC Categories	Outage Frequency Associated with the Performance Category (outage/year)	Transient Voltage Dip Standard	Minimum Transient frequency Standard	Post Transient Voltage Deviation Standard
A	N/A	Nothing in addition to NERC		
B	≥0.33	Not to exceed 25% at load buses or 30% at non-load buses. Not to exceed 20% for more than 20 cycles at load buses.	Not below 59.6 Hz for 6 cycles or more at a load bus.	Not to exceed 5% at any bus
C	0.033-0.33	Not to exceed 30% at any bus. Not to exceed 20% for more than 40 cycles at load buses.	Not below 59.0 Hz for 6 cycles or more at a load bus.	Not to exceed 10% at any bus
D	<0.033	Nothing in addition to NERC		

Table 16: WECC disturbance-performance table of allowable effects on other systems times (Table W-1[29])

Notes:

The WECC disturbance-performance table applies equally to either a system with all elements in service, or a system with one element removed and the system adjusted.

As an example in applying the WECC disturbance performance table, a Category B disturbance in one system shall not cause a transient voltage dip in another system this is greater than 20% for more than 20 cycles at load buses, or exceed 25% at load buses or 30% at non-load buses at any time other than during the fault

Recently WECC published “The Technical Basis for the New WECC VRT Standard“ this document was prepared by the Wind Generation Task Force (WGFT) for WECC and proposes new voltage duration curves for high voltage and low voltage ride through, shown in Figure 41 below.

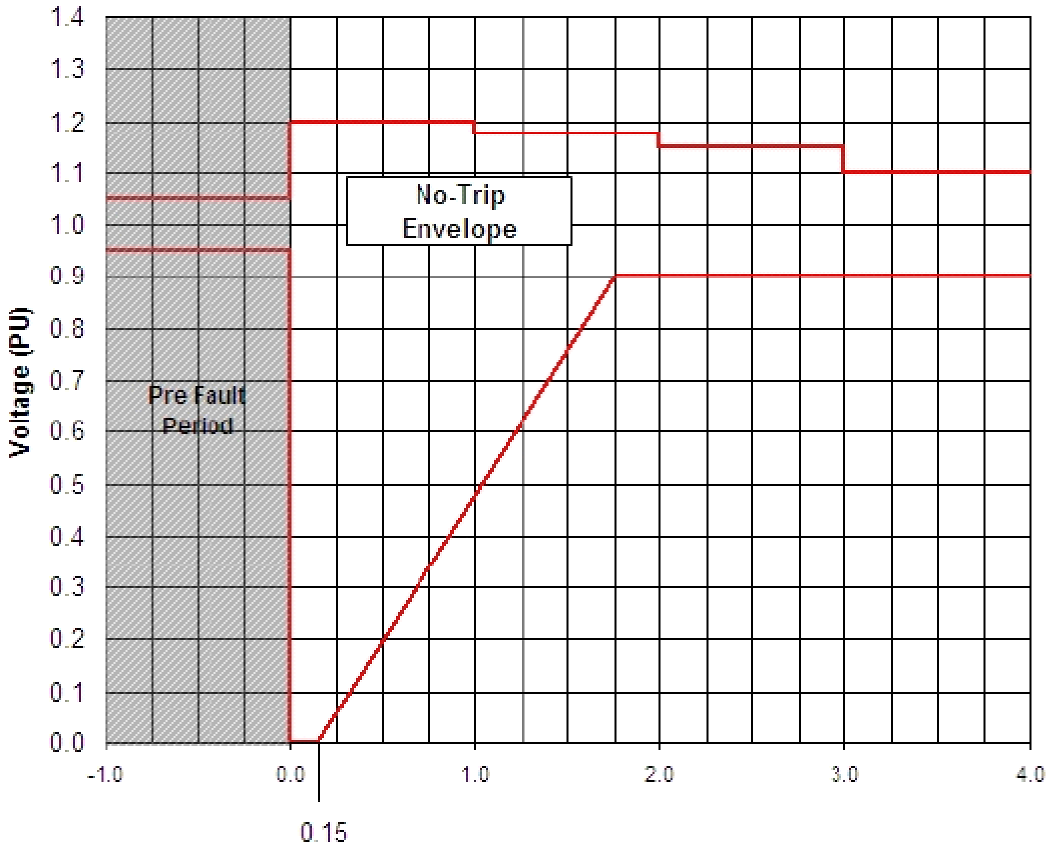

Figure 41:- Voltage-Duration Profile WECC- USA Requirement

Appendix 4 – WGIP Investigation 9

Discussion

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

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

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

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

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

Conclusions

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

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

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

Appendix 5 – Wind Turbine Technology

A summary of Wind Turbine Technology types is provided in the following sections.

8.15.2 Fixed Speed Induction Generator (FSIG)

The most basic form of wind generation technology is a conventional squirrel-cage induction (asynchronous) generating unit directly connected to the grid through a transformer deriving its mechanical power from stall-regulated (fixed pitch) blades connected to a hub via gear and soft-start mechanism. Figure 42 shows an FSIG topology. Induction generating units are basically an induction motor operating at a speed slightly higher than the synchronous speed and are mainly used in the wind generation technology as an energy conversion medium due to its robustness in construction and low investment cost.

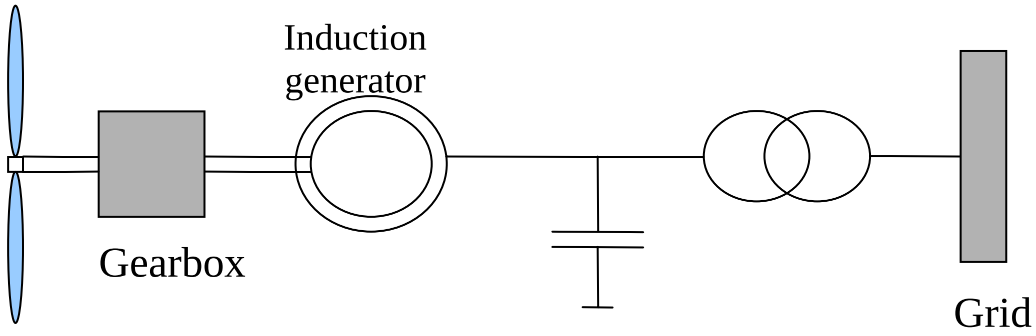

Figure 42:- Fixed Speed Induction Generation (FSIG) Wind Generation Technology Topology

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

8.15.3 Doubly-Fed Induction Generator (DFIG)

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

The DFIG topology is shown in Figure 43.

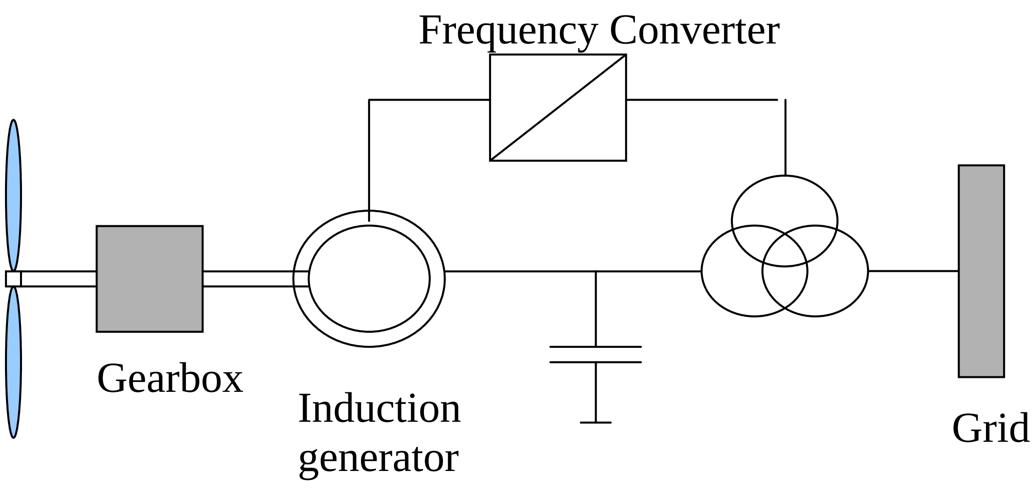

Figure 43:- Doubly-Fed Induction Generation (DFIG) Wind Generation Technology Topology

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

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

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

8.15.4 Full Scale Frequency Converter (FSFC)

The Full Scale Frequency Converter (FSFC) wind generation technology has a power converter connected between the grid and the wind turbine. All the power generated by the wind turbine is processed by the converter before being transmitted to the grid system. This effectively isolates the wind dynamic and generator characteristics from the grid system. Any forms of energy conversion medium (induction, synchronous, permanent magnet etc) can be adapted to convert wind energy to electrical power. An example of FSFC configuration can be shown in Figure 44.

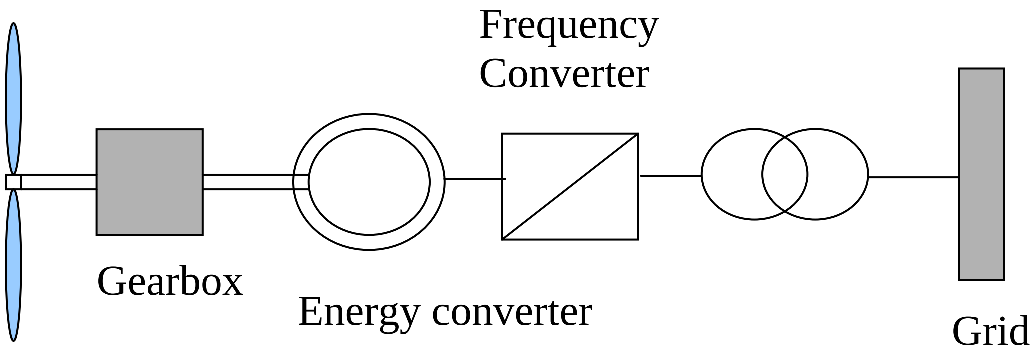

Figure 44:- Full Scale Frequency Converter Wind Generation Technology Topology

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

Dynamic Response

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

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

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