WIND TURBINE PLANT CAPABILITIES REPORT

2013 Wind Integration Studies

Published by

AEMO

Australian Energy Market Operator

ABN 94 072 010 327

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Acknowledgement

AEMO acknowledges the support, cooperation and contribution of the wind farm developers and turbine manufacturers who provided data and information used in this publication.

EXECUTIVE SUMMARY

As the National Electricity Market (NEM) operator, AEMO manages the operation and security of Australia's interconnected south-eastern power system. This includes overseeing the performance of all generation connected to the NEM, including wind generation. A primary concern of AEMO is to facilitate the entry of new generation into the NEM while ensuring the ongoing reliable and secure operation of the power system.

AEMO's 2012 National Transmission Network Development Plan (NTNDP) forecasts 8.88 GW of additional wind generation in the NEM by 2020. This substantial growth results primarily from the Federal Government's Large-scale Renewable Energy Target (LRET), which creates financial incentives to support investment in and deployment of large-scale renewable energy projects.

Integrating this level of additional wind generation into the NEM introduces potential challenges for existing systems and processes for NEM operations and new connections.

AEMO is now undertaking a range of wind integration studies to investigate the potential network and operational impacts resulting from the projected increase in NEM-connected wind generation. This work seeks to gain a clear understanding of the key issues that may arise, and to help identify what may be required to maintain power system security into the future.

This paper, the first of three planned reports, is a technical information paper on wind turbine plant capabilities. The key purpose of this paper is to provide modelling assumptions and methodologies for use in AEMO's wind integration studies, and identify any wind turbine performance issues that should be considered in the studies.

Key assumptions arising from this work to be used in subsequent studies are:

- All new wind turbines in the NEM will be either type 3 or type 4 turbines. Typical models for both existing and future wind turbines have been developed.
- Performance of new wind turbines will be improved from today's levels. This improvement may be marginal in some cases.
- The response speed of wind turbine controls will increase.
- Larger turbine sizes will be installed compared to those used historically.
- Turbine static and dynamic reactive capability will improve compared to that seen today. However, additional reactive support plant will continue to be required in many wind farms in order to meet required performance standards.
- New wind turbines will continue to offer no inertia or frequency control services to the power system

This report summarises the technical capabilities of existing wind turbines in the NEM and describes current developments in wind turbine capability, which underpin AEMO's assumptions about how this technology may evolve in future. It also identifies some areas where further work is required by AEMO to understand turbine capabilities and their potential effect on power system performance.

Subsequent reports in this series of wind integration studies will focus on the impact of high levels of wind generation on NEM power system limits, and will use market modelling to quantify some of these impacts. These reports aim to inform market participants and other interested parties about the issues relating to wind turbine technology, and how they might affect operation of the NEM out to 2020.

CONTENTS

TABLES

FIGURES

CHAPTER 1 - INTRODUCTION

AEMO's 2012 National Transmission Network Development Plan[1] (NTNDP) forecasts substantial new wind generation (8.88 GW) for the NEM by 2020, in addition to the approximately 2.6 GW installed as at May 2013.

AEMO is undertaking a range of wind integration studies to explore how well existing NEM systems, processes and arrangements are placed to integrate this generation, and what changes may be required. This work is divided into two phases.

Phase 1 (Undertaken in 2011)

The first phase of this work was undertaken as part of the 2011 NTNDP[2]. AEMO conducted a review of world best practice for wind integration, and undertook an initial investigation of network impacts in the NEM.

As part of this work AEMO commissioned three international studies, covering:

- International practice and wind integration experience.
- A review of international grid codes.
- Lessons learned from international studies.

AEMO also undertook a series of market simulations which modelled thermal limits arising from the forecast new wind generation. The details of these studies are published on AEMO's website.[3]

Phase 2 (Current phase)

In the current phase of wind integration studies, AEMO is investigating how the forecast increase in wind generation may affect the NEM network and operational limits. The purpose of this phase is for AEMO to understand the possible consequences of a 'business as usual' approach to connecting this new generation.

This phase consists of three parts:

- A study of current and projected wind generation grid performance (this report).
- A study of the impact of wind generation on power system limits (to be published by the end of July 2013).
- Market modelling (to be published by the end of August 2013).

The expected outcomes from this phase are as follows:

- To assist AEMO anticipate and plan for operational impacts of large scale wind generation.
- To enable better modelling of wind generation in future planning work.
- To identify possible need for changes to existing ancillary service arrangements.
- To inform AEMO's response to the AEMC's proposed technical standards review.

1.1 Context for this report

Projected additional wind generation capacity in the NEM could significantly affect network and operational limits. That said, wind technology is developing quickly, and technological advances are may affect the level of impact. Understanding the capabilities of existing and future wind turbines is very important when determining network and operational limits.

1 AEMO. Available at: http://www.aemo.com.au/Electricity/Planning/National-Transmission-Network-Development-Plan/Overview

2 AEMO. Available at: http://www.aemo.com.au/Electricity/Planning/Archive-of-previous-Planning-reports/2011-National-Transmission-Network-Development-Plan.

3 AEMO. Available at: http://www.aemo.com.au/Electricity/Planning/Archive-of-previous-Planning-reports/2011-National-Transmission-Network-Development-Plan/Wind-Integration-Studies.

This report provides the following:

- A summary of the technical capabilities of existing wind turbines in the NEM.
- Assumptions about the likely future performance of new wind turbines out to 2020.

The assumptions will inform the next reports to be published as part of this study phase, which assess the possible impacts of projected additional wind generation on power system limits.

1.2 Content and structure of this report

This report provides a survey of existing and likely future wind turbine technology in the NEM, focusing particularly on wind turbine plant capabilities affecting grid performance. A summary of AEMO's key modelling assumptions is contained in Chapter 2, based on the key findings and observations from AEMO's survey, which are summarised in Chapter 3.

The report also includes:

- A technical and historical overview of wind turbine technology development, particularly with relevance to plant capabilities affecting grid performance (Chapter 4).
- A summary of the turbine technology of the existing and likely future wind farms in the NEM (Chapter 5).
- A discussion and projection of trends in wind turbine plant capabilities to 2020 (Chapter 6).
- A more detailed description of the development scenarios and assumptions for subsequent wind integration studies on modelling wind turbine plant capabilities for turbines installed in the NEM to 2020 (Chapter 7).
- The report also identifies areas where future studies may be required to better understand turbine capabilities, and their potential effect on power system performance.

This report has been informed by:

- Discussions with several turbine manufacturers and wind farm developers, to help guide AEMO's understanding of likely developments in turbines that will be installed in Australia.
- AEMO's own information about turbine types and technologies being considered for pending wind farm connections in the NEM.
- Existing literature on wind turbine technology, and likely future directions in wind turbine technology capability.

A list of publicly available reference sources used in preparing this report can be found at the end of this report.

CHAPTER 2 - ASSUMPTIONS FOR AEMO'S WIND INTEGRATION STUDY

This chapter summarises AEMO's key assumptions about future wind turbine capability arising from this wind turbine capability report, and indicates where in the report further information regarding these capabilities can be found. These assumptions will be used in the two remaining reports that will complete these wind integration studies.

2.1 New turbines will be type 3 or type 4

In this report wind turbines have been classified as either type 1, type 2, type 3 or type 4, based on the technology they use. Older type 1 and 2 turbines are installed widely in the NEM, and are expected to continue to operate for the remainder of their economic life. However, these older technologies are considered to be near obsolete for new installations in the NEM. All new large wind farms developments that AEMO is aware of are proposing to use either type 3 or type 4 wind turbines.

The newer turbine technologies offer improved ability to meet NEM grid connection standards, and are available in a range of turbine sizes from several suppliers. A summary of the different turbine types is provided in Section 4.2, and a summary of turbine technology currently installed in the NEM is provided in Section 5.2.

2.2 Use of typical turbine models

To allow for assessments of power system performance with significantly increased levels of installed wind generation in the NEM, AEMO has developed typical models for existing and future wind turbines[4].

Two different models have been developed for each turbine technology type, to represent a more pessimistic and a more optimistic view of future performance capabilities. The characteristics and detailed design and setting of these typical models are presented in Chapter 7 and Appendix A.

While this report mainly focuses on wind generation, AEMO recognises that there is also significant potential for installation of utility scale photovoltaic (PV) solar systems in the NEM. Many of the key performance characteristics of utility scale solar PV systems are understood to be similar to full rated converter (type 4) wind turbines. AEMO also developed two different typical models to represent these PV solar systems.

2.3 Larger turbine sizes

Several recent wind farm developments in the NEM have been built using 3 MW wind turbines, compared to the 1.5 – 1.75 MW turbines typically used in earlier NEM projects.

Turbine manufacturers are continuing to offer larger turbine sizes, though it is understood that the largest wind turbine sizes are driven by offshore wind farm requirements, and are not currently expected in the NEM by 2020. It is expected that turbine sizes in the NEM will remain below 5 MW. Turbine size is discussed further in Section 6.2.

[4] The typical models developed are variations of existing generic models except for the type 4 wind turbine and solar PV models where a generic model does not exist in PSS®E v29.

2.4 Improved turbine performance and control response speed

Wind turbine performance covers several areas, including but not limited to: reactive power and voltage control, active power control, and response to system disturbances. This report provides a survey of these capabilities, which indicates there have been, and may continue to be, ongoing improvements in many of these areas. In particular, the potential speed of wind turbine response to disturbances is expected to improve; though in comparison to the best performance available today, such improvements may only be small or incremental. This is discussed further in Sections 5.3, 5.5 and 6.3.

It is expected that the inherent reactive capability of wind turbines will increase, allowing some improvements in the reactive capability at the point of grid connection. Depending on the static and dynamic reactive capability required for the wind farms, additional reactive plant such as static capacitors, and dynamic plant such as STATCOMS may still be required to provide the necessary overall wind farm capability. Wind turbine reactive capability is discussed further in Section 5.4.

2.5 Inertia and frequency control

Newer wind turbines based on type 3 and type 4 designs do not currently provide an inertial response to the power system, due to the design and arrangement of the power electronic controls used in these designs. There is currently no requirement for generation to provide an inertial response.

Participation in frequency control arrangements in the NEM is voluntary, and AEMO's experience is that wind generators choose not to participate. In the absence of any changes to existing arrangements, this situation is not expected to change, and all new wind generation is assumed to not participate in NEM frequency control arrangements.

The ability of wind generation to provide both 'synthetic' inertia and power system frequency control services has been discussed in academic literature and prototype models have been demonstrated successfully, however no wind generation currently installed in the NEM has elected to provide these services. This is discussed further in Section 5.6.

CHAPTER 3 - FINDINGS AND OBSERVATIONS

This chapter summarises the findings and observations described in this report. Two different sets of observations are provided:

- Issues that will be examined by AEMO in subsequent wind integration study reports.
- Observations for consideration outside of these subsequent wind integration study reports, which may for example occur during future wind generation connection studies. AEMO will continue to collaborate with our stakeholders to maintain the quality and value of our wind integration studies.

3.1 Wind turbine capability

3.1.1 Fault ride-through capability

The fault ride-through requirements set out in the NER consider a double-phase to ground fault as the critical contingency. The type 3 and 4 wind turbines reviewed are capable of meeting low voltage ride-through (LVRT) requirements for deep voltage dips down to zero residual voltage for a few hundred milliseconds. Additional dynamic reactive support plant may be installed to augment the turbines' LVRT capability. Compliance with LVRT requirements for long duration shallow dips (such as voltage drops in the range of 10–20% for 10–12 seconds) can be challenging for some wind turbines, and most are unable to withstand high voltages (of up 1.3 p.u.). LVRT issues are further discussed in Section 5.3.1.

Modern type 3 and 4 wind turbines can provide fast reactive current injection up to 1 p.u. in response to voltage dips. Compared to synchronous generators, wind turbines can provide a similar or faster response time, but the current injection magnitude can be significantly less, due to wind turbine power electronics ratings. Type 4 wind turbines can exhibit very fast active power recovery upon fault clearance, compliant with the relevant automatic access standards. Type 3 wind turbines—especially those connected to weak networks—may not be able to achieve such a fast power recovery. Issues around recovery after faults are further discussed in Sections 5.3.3 and 5.3.4.

Increasing wind generation may result in increased Rate of Change of Frequency (RoCoF) in some regions of the NEM following disturbances. It is expected that most wind farms installed in the NEM by 2020 will meet or exceed the automatic access requirement to tolerate a RoCoF of 4 Hz/s. RoCoF issues are further discussed in Section 5.3.5.

To be included in AEMO's subsequent wind integration study reports:

- Determine the maximum RoCoF which can be experienced in the mainland and Tasmanian power systems.

Observations for consideration outside of these wind integration study reports:

- Study the implications of using type 3 and 4 wind turbines in weaker parts of the network, in terms of active power recovery and energy deficit upon fault clearance.
- Investigate scenarios resulting in high temporary over-voltages (TOV) in the power system. Should the results identify high TOVs (in the range of 1.3 p.u.), identify whether system-wide controls might be required.
- Investigate the effects of reactive current injection limits of around 1 p.u. in weak and isolated parts of the power system.

3.1.2 Voltage and reactive power control

Wind turbines can be operated in three voltage and reactive power control modes: voltage control, reactive power control, or power factor control. Operating in voltage control mode is considered to be the most efficient way to use their static and dynamic reactive power capability, which can reduce the burden on other synchronous generators on the power system.

These control modes can be implemented either at the individual turbine level, or at farm level. Farm-level control is generally a slow SCADA-based control with an action time of one second or more. Faster acting, closed loop voltage control at wind turbine level is more likely to meet the automatic access standards.

Despite gradual enhancements in wind turbine reactive power capability, it is expected that many of the wind turbines installed in the NEM by 2020 will not be independently capable of meeting automatic access standards associated with voltage and reactive power control. It is currently common practice for NEM wind generators to either have negotiated access standards below the automatic level, or additional equipment to provide static and/or dynamic reactive power support.

A more challenging requirement is providing dynamic reactive power in South Australia, where current ESCOSA licence conditions for wind generators[5] impose connection standards closer to the automatic access standards than typically seen in other regions. To date, this challenge has been predominantly met by using dynamic reactive support plant, but fast turbine-level voltage control could potentially reduce or remove the need for dynamic reactive power support.

Observations for consideration outside of these wind integration study reports:

- Further investigate the effect the operation of wind farms in voltage control mode and power factor control on power system voltage control.
- Further investigate the effect of response speed of wind farm controls on power system performance.
- Further investigate the consequences of the current access standards in relation to power factor capability on power system voltage control.

3.1.3 Active power control

Control of active power, including ramping and curtailment, can be achieved with most type 3 and 4 wind turbines. The ramp rate of existing wind turbines during normal operating conditions ranges from 0.05 – 0.25 p.u./s, which would be sufficient to meet the automatic access standards. The only aspect of the automatic access standards that most type 3 wind turbines cannot meet is power reduction below a threshold of around 20–30% of nominal power.

Observations:

- AEMO has not identified issues around control of active power under normal power system conditions.

3.1.4 Inertial response

Displacement of synchronous generators with inherent inertial response can lower overall power system inertia levels, raising issues around the level of inertia that wind farms may be able provide. Comparisons between the inertial contribution of wind power generation and conventional synchronous generators commonly use two criteria: the inertia constant, and RoCoF.

From an inertial response perspective, wind turbines can be divided into fixed/semi fixed-speed turbines (types 1 and 2) and variable-speed turbines (types 3 and 4). Types 1 and 2 turbines provide some inherent inertial contribution; however the response is slower, and less, than similarly rated conventional synchronous generation.

Types 3 and 4 turbines do not inherently provide any inertial response, but can theoretically be supplemented with additional control systems or auxiliary equipment to do so. Two common methods described are curtailment of the wind turbine output below maximum achievable levels; and modification of converter control to increase the power temporarily when required by system conditions. Each of these methods has drawbacks.

Another mechanism to achieve inertial response is by using energy storage systems. Very recently, commercial wind turbines with integrated energy storage systems have entered the international market. Based on information identified for this review, it would seem reasonable to conclude that future wind farms may be able to deliver inertial

[5] ESCOSA. Available at: http://www.escosa.sa.gov.au/article/newsdetail.aspx?p=183&id=676&view=newsletter.

response should the need arise. There is no requirement to do so under current connection arrangements. Inertial responses are discussed further in Section 5.6.1

To be included in AEMO's subsequent wind integration study reports:

- Consider the impact of wind generation on power system inertial response.
- Identify methods of managing power system inertia if required.

Observations for consideration outside of these wind integration study reports:

- Further investigate wind turbines with modified converter control and integrated energy storage systems to better understand their potential inertial responses.

3.1.5 Governor response

A primary frequency response (or governor response) is a second, "active" stage of frequency support that follows the first "passive" inertial response. Provided that an inertial control is implemented for the wind farm, the turbines first respond in a manner directly proportional to the RoCoF experienced in the system. This is then followed by a governor response which aims to restore system frequency.

Governor response can be achieved with today's technology to the extent that the available wind allows. The inclusion of integrated energy storage systems provides additional opportunity to do this. This is discussed further in Section 5.6.2.

To be included in AEMO's subsequent wind integration study reports:

- Consider the impact of wind generation on the requirements for primary frequency response in the power system.

3.1.6 Connection to networks with low short circuit ratio

Wind farm connections create concerns when the Short Circuit Ratio (SCR) at the point of common coupling (PCC) drops below five. These concerns relate to the farm's ability to continue operating correctly under disturbance conditions. Assessing this issue requires high accuracy modelling, beyond the level available in most current wind turbine models.

The accuracy of most RMS-type models is typically proven for SCR values down to five. For lower SCR values, between three and five, RMS-type models may or may not be accurate. Under low SCR conditions, wind turbine controls may behave differently than under high SCR conditions. This may necessitate modifications in the turbine converter controls, and in particular coordination with other dynamic reactive support plant. Networks with low SCR have a strong dependency between voltage and reactive power.

Displacement of synchronous generators with wind and other forms of variable generation technology causes network fault levels to reduce. While issues associated with connections to low SCR networks currently only apply to remote connection points, large scale penetration of variable generation (and consequent displacement of synchronous generators) may give rise to more widespread network issues. Issues of low SCR networks are discussed further in Section 5.7.

Observations for consideration outside of these wind integration study reports

- Identify conditions where the use of electromagnetic transient (EMT) type models for assessing wind farm connections to weak networks may be required.
- Investigate and identify the minimum SCR requirements for secure and reliable power system operation with respect to wind generation.

3.2 Modelling methodology and challenges

To allow modelling of future wind generation, while avoiding known complications arising from existing project-specific wind generation mode, typical dynamic models of type 3 and 4 wind turbines, solar photovoltaic (PV), and STATCOMs are proposed for use in power system studies. These models are simpler than detailed manufacturer-specific models used for connection studies, but are believed to capture a range of important dynamic characteristics of wind generation.

A range of possible performance levels for type 3 and 4 turbines and solar PV were considered. These covered two scenarios relating to the rate of technology development: a lower performance scenario (a “plausible minimum” or “pessimistic” performance scenario), and an “optimistic” scenario, which assumes significant improvements in equipment grid performance capabilities to 2020.

The performance results in the optimistic scenario are generally sufficient to meet the respective automatic access standards, and ESCOSA licence conditions for wind generators in South Australia. The pessimistic scenario reflects performance that is only marginally better than recently installed wind farms. Meeting automatic access standards under the pessimistic performance scenario would require the use of further supplementary equipment inside the wind farm. These models are discussed further Chapter 7 and Appendix A.

Observations for consideration outside of these wind integration study reports:

- Obtain more accurate full three-phase EMT-type models for wind generation. Currently, positive sequence-type PSS®E models are predominantly used across the NEM. Full investigation of the detailed action of power electronics controls as used in wind turbines and utility scale PV systems will require the use of more detailed full three-phase EMT-type models. This will be particularly important for relatively weak regions in the NEM, such as Tasmania, or in more remote connection points on the mainland. Extensive penetration of power electronic-based components could give rise to adverse interaction of various controls; this can only be investigated with the use of EMT-type models.
- Conduct more accurate simulations of wind turbines behaviour during fault conditions to determine their injection of fault current in the network. Research indicates that existing positive sequence models may not provide accurate wind farm fault current calculations for all fault conditions.
- Develop more realistic dynamic load models to increase the accuracy of future wind integration assessments. Displacement of synchronous generators by variable generation technologies can reduce system fault levels, resulting in large voltage variations and increased importance of system load characteristics.

CHAPTER 4 - TECHNICAL AND HISTORICAL OVERVIEW OF WIND TURBINE AND PLANT TECHNOLOGIES

This chapter describes the technical characteristics of the different types of wind turbine technology installed in the NEM, and provides a comparison between them. The information presented in this chapter is drawn from published turbine information and specifications, discussions with selected manufacturers and wind farm developers, and AEMO's own technical knowledge.

The characteristics described represent AEMO's understanding of the typical capabilities for each turbine type, although there may be variances in individual models.

4.1 Wind turbine types

4.1.1 Type 1 wind turbines

A schematic diagram of a typical fixed-speed wind turbine, referred to as type 1, is shown in Figure 4-1. A squirrel cage induction generator is used for all practical installations of this type. This prevents access to the machine rotor terminals, as they are short circuited in this construction.

Type 1 turbines can only operate within a very narrow speed range above the synchronous speed, and this requires the turbine blades to rotate at a nearly constant speed. Control of active power above the rated speed is dealt with by a stall control. A blade pitch control, as applied to variable speed wind turbines, is not used for type 1 wind turbines.

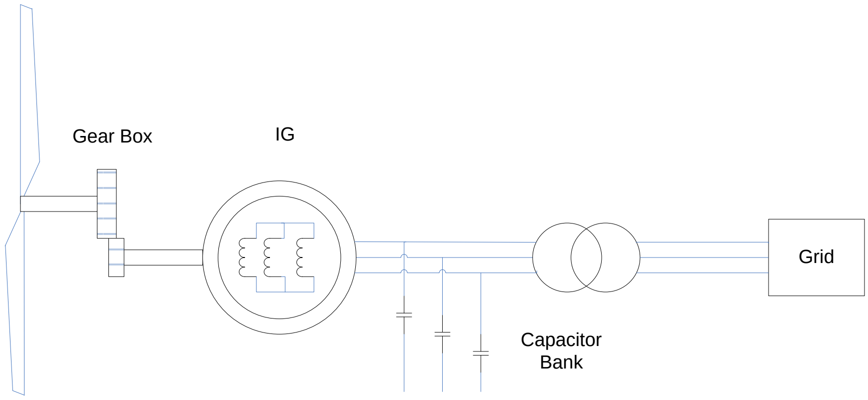
The simple induction machines used for type 1 turbines consume reactive power. To supply the required reactive power of the induction machine, shunt capacitor banks are installed at the turbine terminals. No other controls are typically used at the turbine level (aside from soft starter during energisation).

These turbines are generally run at a constant power factor, such that the exchange of reactive power at the turbine transformer LV terminals is practically zero. Additional dynamic reactive support plant is often installed at the wind farm collection grid to enable the wind farm to meet technical performance requirements.

As a result of being directly connected to the grid, wind speed variations are directly translated into voltage and power fluctuations at the grid connection point.

While these turbines are practically obsolete, they are used at a number of older wind farms in the NEM, and are not expected to be replaced by more modern wind turbines until they reach the end of their economic life, typically around 20 to 25 years from installation.

Figure 4-1 — Schematic diagram of type 1 wind turbine generator



4.1.2 Type 2 wind turbines

A schematic diagram of a typical semi variable-speed wind turbine, referred to as type 2 wind turbines, is shown in Figure 4-2. A wound rotor induction generator is used for all practical installations. This machine construction allows access to the rotor windings, enabling connection of a thyristor-controlled variable resistance to the machine rotor.

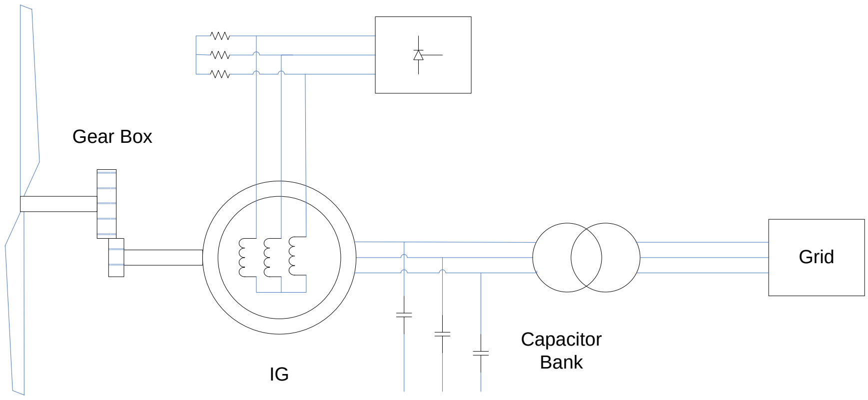
By adjusting this variable rotor resistance, the machine operating point can be adjusted across the torque-speed curve of the machine, which then allows a ‘semi variable’ speed operation of up to 10% above the synchronous rated speed. A blade pitch controller is used to control the active power.

Type 2 wind turbines are generally superior to type 1 with regards to converting a given wind resource into energy. However, the power system performance of the two as seen at the grid connection point is relatively similar. The requirement for dynamic reactive power support plant is similar for both turbine type 1 and type 2 wind generation.

Due to the installation of machine rotor resistance controls, issues associated with active power and voltage fluctuations are less pronounced compared with type 1 wind turbines, but high level of flicker may still be experienced, especially when connected to weak power systems with a low short circuit ratio (SCR).[6]

Type 2 wind turbines are practically obsolete, but there are numerous installations of type 2-based wind farms in the NEM. Similar to type 1, these are not expected to be replaced with more modern wind turbines until they expire.

Figure 4-2 — Schematic diagram of type 2 wind turbine generator



[6] SCR is defined as the ratio of the grid’s short circuit capacity at Point of Common Coupling (PCC) in MVA to the nominal power at the PCC in MW.

4.1.3 Type 3 wind turbines

A schematic diagram of a typical variable-speed type 3 wind turbine of is shown in Figure 4-3. These are sometimes referred to as doubly-fed induction generators (DFIG). A wound rotor induction generator is used for all practical installations.

Type 3 wind turbines have a connection between the machine rotor windings and the power system through a back-to-back voltage source converter. The key difference between type 2 and 3 wind turbines is the replacement of the controlled resistance used in type 2 with a four-quadrant, back-to-back voltage source converter in type 3. This has the capability to generate and consume active and reactive power in a controlled manner.

This rotor converter allows independent control of the wind turbine active and reactive power. It also eliminates the need for reactive compensation equipment as installed at the terminals of type 1 and 2 wind turbines. Bi-directional flow of active power through the rotor converter allows type 3 wind turbines to operate both above and below the machine's synchronous speed.

Above the synchronous speed, the rotor converter injects active power to the grid, whereas below the synchronous speed power is consumed in the rotor from the grid. The operating speed range depends on back-to-back converter ratings with respect to the generator ratings. For economic reasons it has been a common practice to size the rotor power electronic converter at around 25–35% of the generator rating, which provides an operating speed range of around ±25–35% of the rated speed.

Another advantage of type 3 turbines is that the mechanical drive train is largely decoupled from the electrical system via the back-to-back converter. This means that variations in the prime mover do not have a pronounced impact on the grid, resulting in reduced flicker levels.

The control of reactive power is managed by the rotor power electronic converter. For active power control, a combination of the converter control and turbine blade pitch controllers is used. The blade pitch controller is much slower than the rotor converter controls, and does not respond to first swing stability type events.

There are two separate 'sides' to the rotor power electronic converter: the machine side converter and the grid side converter. They have a DC connection between them. In most practical installations the control of active and reactive power is dealt with by the machine-side converter, with the role of the grid-side converter being to maintain a constant DC-link voltage. The grid-side converter typically runs at unity power factor, with no exchange of reactive power. However, type 3 wind turbines offered by at least one manufacturer use both grid-side and machine-side converters for reactive power control.

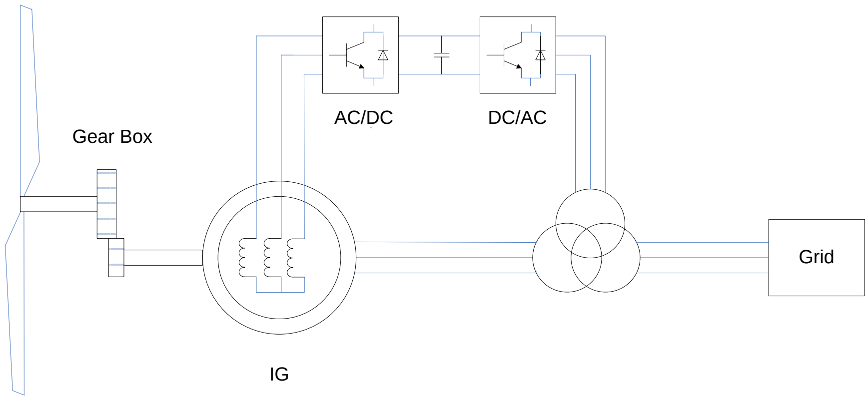
Type 3 turbine control systems are significantly more complex than type 1 and 2 turbines. The control system for both grid-side and rotor-side converters comprise fast inner loop and slow outer loop controls. The control of the rotor-side converter active and reactive current is performed at the inner control loop, whereas active and reactive power control is dealt with at the outer loop.

Wind turbine control during fault conditions is generally dealt with by the use of braking (energy dissipating) resistors, referred to as crowbars. Temporary blocking of the rotor converter can be used as a separate strategy, in conjunction with the use of braking resistors. No ancillary reactive compensation equipment is installed at the turbine terminals, but compliance with technical requirements sometimes necessitates the use of dynamic reactive support plant at the wind farm collection grid.

A known disadvantage of type 3 wind turbines is the use of brushes and slip rings to connect the rotor with its converter, resulting in higher maintenance requirements compared to simple squirrel cage induction machines. However, this does not affect the grid performance capability of these turbines.

Type 3 turbines have been the most widely used across the NEM for new installations in the last few years, and are considered likely to constitute a large portion of the generation mix for wind farms installed in the NEM by 2020.

Figure 4-3 — Schematic diagram of type 3 wind turbine generator



4.1.4 Type 4 wind turbines

A schematic diagram of a typical variable-speed, full rated converter Type 4 wind turbine is shown in Figure 4-4. Squirrel cage induction machines, wound field synchronous machines, and permanent magnet synchronous machines have all been used in practice for these turbines, with both geared and gearless (direct drive) options. Figure 4-4 shows the geared version.

The back-to-back voltage source power converter has the same rating as the generator, and the generator has no direct connection to the power system. This allows operation of the generator at any speed from zero to maximum rated speed, and provides an improved reactive power capability range compared with the type 3 wind turbines.

Due to the capabilities of the full rated power converters, type 4 turbines are slightly higher performing than type 3. They are also more expensive, due the need for a larger power converter rated to the same size as the generator.

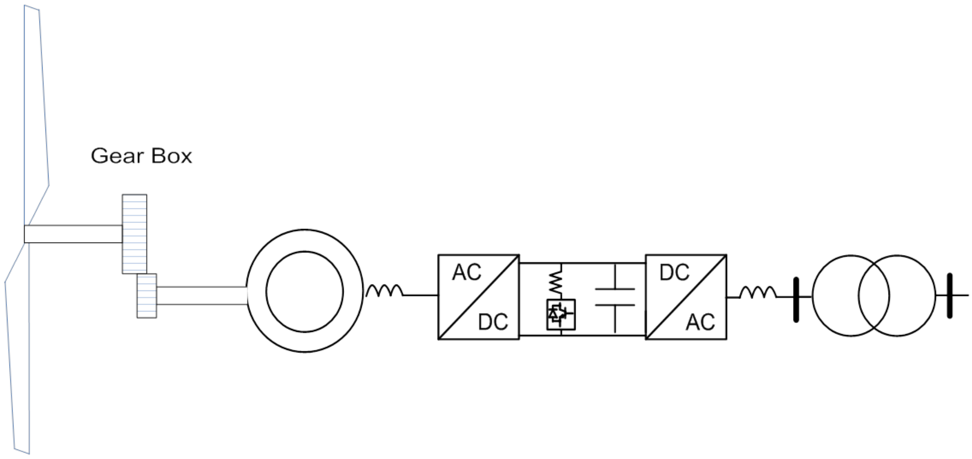
An advantage of type 4 wind turbines is that the power system and the generator are completely decoupled, unlike type 3 machines, where there is a loose coupling between the generator and grid through stator windings. The control of active and reactive power is completely determined by the converter, and can be performed even faster than type 3 wind turbines. The impact of power system voltage and frequency disturbances on the generator and mechanical drive train is negligible.

Most commercial type 4 wind turbines use a DC braking chopper resistor in parallel with the DC-link capacitor inside the power converted (refer to Figure 4-4). This resistor can dissipate any excess energy caused by temporary imbalances in the electrical and mechanical power during network fault conditions, when grid-side active power may temporarily need to drop to near zero.

The instantaneous peak and continuous sustained fault currents produced by the grid side of the power converter are comparable to the rated current of the machine. This may be an advantage or disadvantage, depending on the conditions of the grid to which the wind farm is connected. Due to their wider speed operating range, type 4 wind turbines can provide improved wind conversion efficiency, and are becoming more popular worldwide.

Based on trends in the connection process, it is expected that an increasing number of type 4 based wind farms will be installed in the NEM over the next few years, although due to their cost they will still comprise a smaller portion of overall capacity. It is assumed they will generally be preferred for the largest wind farm projects, where the increased cost of power converters forms a smaller portion of the overall project budget.

Figure 4-4 — Schematic diagram of type 4 wind turbine generator



4.1.5 Available turbine models

A range of wind turbine models of each type is shown in Table 4-1. The manufacturer, model designation, and rating (MW) are provided for each model. This is not a complete list of all commercially available wind turbines, but covers the models currently installed in the NEM, and provides several other examples for comparative purposes.

Table 4-1 — Overview of available wind turbines

Type 1	Type 2	Type 3	Type 4
Vestas NM64 1.5 MW	Suzlon S88 2.1 MW	Acciona AW1500 1.5 MW, AW3000 3.0 MW	Enercon E70 2.0 MW, E70 2.3 MW E82 2.0 MW, E82 2.3 MW E82 3.0 MW
Vestas NM72/NM82 1.65 MW	Vestas V66 1.75 MW	Vestas: V80 2.0 MW, V90 3.0 MW , V100 1.8 MW	Vestas V90 2.0 MW, V100 2.0 MW V112 3.0 MW, V126 3.0 MW
		Alstom ECO 100 3 MW, ECO 110 3 MW ECO 122 2.7 MW	Goldwind GW82 1.5 MW, GW100 2.5 MW
		REpower NM82/ NM92 2.05 MW NM100 2.0 MW, 3.0M122 3.0 MW	Siemens: SWT 82/93/101/108/113 2.3 MW SWT 101 3.0 MW
		Gamesa G9X 2.0 MW	Gamesa G10X 4.5 MW
		GE 1.5 MW, 1.6 MW, 1.7 MW, 3.6 MW	GE 2.5XL MW
		Suzlon S95 2.1 MW	

4.1.6 Comparison of wind turbine types

The various capabilities of wind turbines listed in Table 4-1 are summarised and compared, relative to each other, in Table 4-2.

Speed range

The first factor compared was speed range. As noted above, type 4 wind turbines allow operation over the largest possible speed range. In comparison, type 1 wind turbines offer a very limited operating speed range.

Active power rating

Type 1 and 2 wind turbines have similar output power ranges, with a maximum output of around 2 MW. While type 4 wind turbines have a slightly higher nameplate rating than type 3, both types are available with an output power of 6 MW or more.

Higher rated wind turbines (above 5 MW) are primarily intended for offshore wind farms, given the desire to minimise maintenance requirements by using fewer turbines. These very large turbines are not expected to be used extensively for NEM wind farm installations by 2020.

Reactive power capability

Type 1 and 2 wind turbines do not have any inherent ability to generate reactive power, and even with the use of shunt capacitors, the turbine is normally run at near unity power factor.

The four-quadrant power control capability of the voltage source converters used in type 3 and 4 wind turbines allows them to either generate or consume reactive power over a wide range of active power conditions. The type 4 turbines have a relatively higher reactive power capability due to the full scale converters, compared to the partial scale converters used with type 3.

Installation in the NEM

Approximately 35% of current NEM wind farm installations use type 3 turbines, with about 20% using type 4. A significant number of type 1 and type 2-based wind farms have been installed in the past, and are expected to continue operation beyond 2020.

Improved grid performance capability of type 4 turbines may be a motivator for wind farm developers to use them in future projects. That said, type 4 wind turbines are not always considered superior to type 3. This is because both types offered by various manufacturers have a capability range, rather than specific capabilities. For example, a high performing type 3 wind turbine performs better than a low performing type 4 wind turbine, and vice versa.

Dynamic performance

Type 1 and 2 wind turbines offer inferior performance with respect to voltage and reactive power control, and fault ride-through capability. All type 1 and 2 installations in the NEM have required installation of ancillary equipment to meet fault ride through requirements, typically in the form of dynamic reactive power support plant.

Type 3 and 4 wind turbines require less ancillary equipment. With gradual improvement in type 3 and 4 grid performance capability, future wind farms developments using type 4 turbines may be able to meet the NER automatic access standards without any ancillary equipment at all.

Cost and maintenance

Type 4 turbines use full-scale converters, which make them more expensive than all other turbine types. Type 1 and 2 turbines use minimal (or no) power electronic converters, so they are substantially cheaper, especially compared with type 4. Type 1 wind turbines are low cost and low maintenance, but their inferior grid performance capability combined with poor conversion of wind resources today outweighs their lower cost.

Type 2 and 3 wind turbines use wound rotor induction machines, and require some maintenance for the slip rings and brushes. Type 4 wind turbines do not have this equipment, although power electronic converters also require ongoing minor maintenance.

Grid support and interaction

Type 1 and 2 wind turbines do not provide any network stability support, whereas type 3 and 4 wind turbines are considered to be capable of positively contributing to several aspects of system stability. Type 4 wind turbines are generally understood to provide superior performance in this respect than type 3. The absence of fast responding power electronic converters means that type 1 and 2 wind turbines respond more slowly to system disturbances compared with types 3 and 4.

Full decoupling of the generator from the power system in type 4 wind turbines eliminates the impact of the generator and mechanical drive train in system dynamics. In type 3 wind turbines, the loose coupling between stator windings and wind turbine terminals can result in the contribution of generator time constants and mechanical drive train to the wind turbine's overall dynamic response.

Table 4-2 — Overall comparison of various wind turbine types

	Type 1	Type 2	Type 3	Type 4
Speed range	(Red)	(Orange)	(White)	(Green)
Power range	(Orange)	(Orange)	(Yellow)	(Yellow)
Reactive power generation capability	(Red)	(Red)	(White)	(Yellow)
Numbers installed	(Orange)	(Orange)	(Yellow)	(White)
Self-sufficiency for provision of dynamic and static performance	(Red)	(Red)	(White)	(Yellow)
Initial cost	(Green)	(Yellow)	(White)	(Orange)
Maintenance costs	(Green)	(White)	(White)	(Yellow)
Network support capability	(Red)	(Red)	(White)	(Yellow)
Speed of response	(Red)	(Red)	(White)	(Green)

Rating (relative to others)		Colour
Excellent	(Green)	
Very Good	(Yellow)	
Good	(White)	
Moderate	(Orange)	
Poor	(Red)	

4.2 Additional wind farm equipment

Aside from wind turbines, complete wind farm projects involve the use of additional balance-of-plant (BOP) components. These include dynamic reactive power support plant such as SVCs, STATCOMs, and synchronous condensers, and static reactive power support plant such as shunt capacitors and reactors. Other BOP components include cables, transformers, and switchgear.

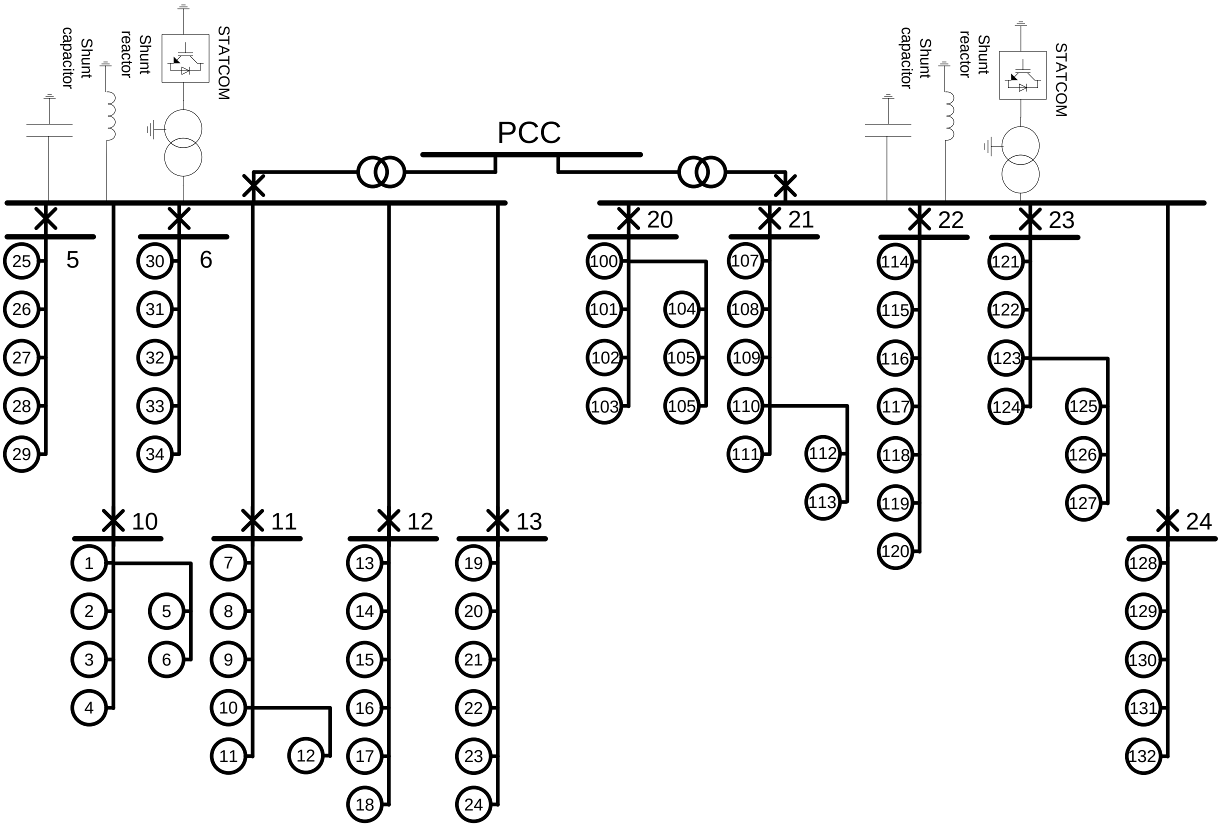
A schematic diagram of a typical wind farm comprising wind turbines, shunt capacitors and reactors, and STATCOMs is shown in Figure 4-5. Depending on the connection point, the wind turbine type chosen, and technical performance requirements for each particular wind farm, all or none of the dynamic and/or static reactive support plant may be necessary.

Many recently installed wind farms in the NEM use a central park level control system (normally provided by the wind turbine manufacturer) to dispatch active and reactive power across the individual turbines installed in the wind farm. This is also used to control reactive power production by other BOP components.

Usually, communication between the central park level control system and individual wind turbines happens via relatively slow supervisory control and data acquisition (SCADA) systems. Given the slow response time of these SCADA systems, the park level controller does not respond to rapid system transients. There are, however, a few known wind farms where the central controller is fast enough to be active during transients. This is more common with type 4 wind turbines.

In most applications the central park level control system is used as a master control dealing with the wind farm's active and reactive power control. Some installations exist in the NEM where the central park level control offered by the turbine manufacturer is used as a slave control, and is supervised by a dynamic reactive support plant which acts as a master control. In these cases, the park level control system is only responsible for coordinated control of the active power, but reactive power control is managed through the dynamic reactive support plant.

Figure 4-5 — Simplified example of wind farm single line diagram



CHAPTER 5 - EXISTING AND FUTURE NEM WIND TURBINE INSTALLATIONS

This chapter provides a summary of existing wind turbines installed in the NEM, and discusses existing and likely future turbine performance characteristics. This analysis will form the basis for the wind turbine performance capabilities assumed for new wind generation in the NEM by 2020.

As for Chapter 4, the information presented in this chapter is drawn from published turbine information and specifications, discussions with selected manufacturers and wind farm developers, and AEMO's own technical knowledge.

Unless otherwise stated, the capabilities discussed in Sections 5.3 to 5.7 relate to type 3 and 4 turbines, which are expected to be used in all new installations out to 2020. These observations represent AEMO's understanding of the typical capabilities for each turbine type, although there may be variances in individual models.

5.1 Existing NEM wind generation

Table 5-1 shows a summary of existing wind farms across the NEM, including several projects where construction is expected to commence during 2013. Note that this table excludes small wind farms below 5 MW. The table includes the following information:

- Wind farm name and size, and state and region of installation.
- Wind turbine size and type.
- Wind farm status and operating data (if applicable).

As at May 2013, operating wind generation capacity is around 2,560 MW. Of the currently operating capacity, around 1,160 MW or 45% of the installations are type 1 or 2 wind turbines; type 3 comprise around 880 MW (35%); and the remaining 520 MW (20%) are type 4. Including capacity under construction, the total installed capacity at the end of 2013 is estimated to be around 3,130 MW.

This mixture of turbine types is expected to change, with all future installations expected to be type 3 or 4. A large number of proposals currently under consideration by AEMO and network service providers (NSPs) use type 3 wind turbines.

Approximately 80% of existing installations are located in South Australia and Victoria. AEMO's 2012 NTNDP projects that these two states are expected to receive the majority of wind farm MW capacity out to 2020, with increasing penetration also seen in New South Wales and Tasmania[7]. Most recent installations use wind turbines with a nominal power in the range of 2–3 MW. This trend is expected to continue, with marginal increases in the nominal turbine power expected.

[7] http://www.aemo.com.au/Electricity/Planning/National-Transmission-Network-Development-Plan/Overview

Table 5-1 — Summary of NEM wind farm installations over 5MW

Name	Region	Capacity (MW)	Turbine Manufacturer	Model	Turbine Size	Type	Status	Built
Blayney Wind Farm	NSW	9.9	Vestas	V47	0.66 MW	II	Operating	2005
Capital Wind Farm	NSW	140.7	Suzlon	S88	2.1 MW	II	Operating	2009
Cullerin Range Wind Farm	NSW	30	REpower	8xMM82, 7xMM92	2 MW	III	Operating	2009
Gunning Wind Farm	NSW	46.5	Acciona	AW 1500	1.5 MW	III	Operating	2011
Woodlawn Wind Farm	NSW	48.3	Suzlon	S88	2.1 MW	II	Operating	2011
Windy Hill Wind Farm Stage 1	QLD	12	Enercon	E40	0.6 MW	IV	Operating	2000
Starfish Hill Wind Farm	SA	34.5	NEG Micon	NM64	1.5 MW	I	Operating	2003
Mount Millar Wind Farm	SA	70	Enercon	E70	2 MW	IV	Operating	2005
Canunda	SA	46	Vestas	V80	2 MW	III	Operating	2005
Lake Bonney Stage 1 wind farm	SA	80.5	Vestas	V66	1.75 MW	II	Operating	2005
Wattle Point Wind Farm	SA	91	Vestas	V82	1.65 MW	I	Operating	2005
Cathedral Rocks Wind Farm	SA	66	Vestas	V80	2 MW	III	Operating	2007
Hallett 1 (Brown Hill Range Wind Farm)	SA	94.5	Suzlon	S88	2.1 MW	II	Operating	2008
Lake Bonney Stage 2 wind farm	SA	159	Vestas	V90	3 MW	III	Operating	2008
Hallett 2 (Hallett Hill Wind Farm)	SA	71.4	Suzlon	S88	2.1 MW	II	Operating	2009
Lake Bonney Stage 3 wind farm	SA	39	Vestas	V90	3 MW	III	Operating	2009
Clements Gap Wind Farm	SA	57	Suzlon	S88	2.1 MW	II	Operating	2010
Waterloo Wind Farm	SA	111	Vestas	V90	3 MW	III	Operating	2010

Name	Region	Capacity (MW)	Turbine Manufacturer	Model	Turbine Size	Type	Status	Built
Hallett 5 (Bluff Range Wind Farm)	SA	52.5	Suzlon	S88	2.1 MW	II	Operating	2011
Hallett 4 (North Brown Hill Wind Farm)	SA	132.3	Suzlon	S88	2.1 MW	II	Operating	2011
Snowtown Wind Farm	SA	100.8	Suzlon	S88	2.1 MW	II	Operating	2009
Snowtown Wind Farm, Stage 2	SA	270	Siemens	SWT-3.0	3 MW	IV	Under construction	2013/14
Woolnorth Wind Farm Stage 1 (Bluff Point)	TAS	10.5	Vestas	V66	1.75 MW	II	Operating	2002
Woolnorth Wind Farm Stage 2 (Bluff Point)	TAS	54	Vestas	V66	1.75 MW	II	Operating	2004
Woolnorth Wind Farm Stage 3 (Studland Bay)	TAS	75	Vestas	V90	3 MW	III	Operating	2007
Musselroe Wind Farm	TAS	168	Vestas	V90	3 MW	III	Under construction	2013
Codrington Wind Farm	VIC	18.2	AN Bonus		1.3 MW	I	Operating	2001
Toora Wind Farm	VIC	21	Vestas	V66	1.75 MW	II	Operating	2002
Challicum Hills	VIC	52.5	NEG Micon	NM64	1.5 MW	I	Operating	2003
Wonthaggi Wind Farm	VIC	12	REpower	MM82	2 MW	III	Operating	2005
Yambuk Wind Farm (Portland Wind Farm Stage 1)	VIC	30	NEG Micon	NM72C	1.5 MW	I	Operating	2007
Cape Bridgewater Wind Farm (Portland Wind Farm Stage 2)	VIC	58	REpower	MM82	2 MW	III	Operating	2008
Waubra Wind Farm	VIC	192	Acciona	AW 1500	1.5 MW	III	Operating	2009

Name	Region	Capacity (MW)	Turbine Manufacturer	Model	Turbine Size	Type	Status	Built
Cape Nelson South Wind Farm (Portland Wind Farm Stage 3)	VIC	44	REpower	MM82	2 MW	III	Operating	2009
Morton's Lane Wind Farm	VIC	19.5	Goldwind	GW82	1.5 MW	IV	Operating	2012
Oaklands Hill Wind Farm	VIC	63	Suzlon	S88	2.1 MW	II	Operating	2012
Macarthur Wind Farm	VIC	420	Vestas	V112	3 MW	IV	Operating	2013
Mount Mercer Wind Farm	VIC	131.2	REpower	MM92	2.05 MW	III	Under construction	2013/14

5.2 Wind turbine grid performance capability

5.2.1 Low voltage ride-through capability

Low voltage ride-through (LVRT) capability refers to the ability of the wind turbines to withstand credible fault conditions, and support to network voltage recovery by injecting reactive current.

Depending on the wind turbine design, a LVRT threshold is defined at around 0.8 – 0.9 p.u. When the turbine voltage drops below this threshold, the turbine suspends normal operation and starts injecting reactive current, while control of active power is given lower priority. The LVRT setting is programmable and can be adjusted to suit each project as required.

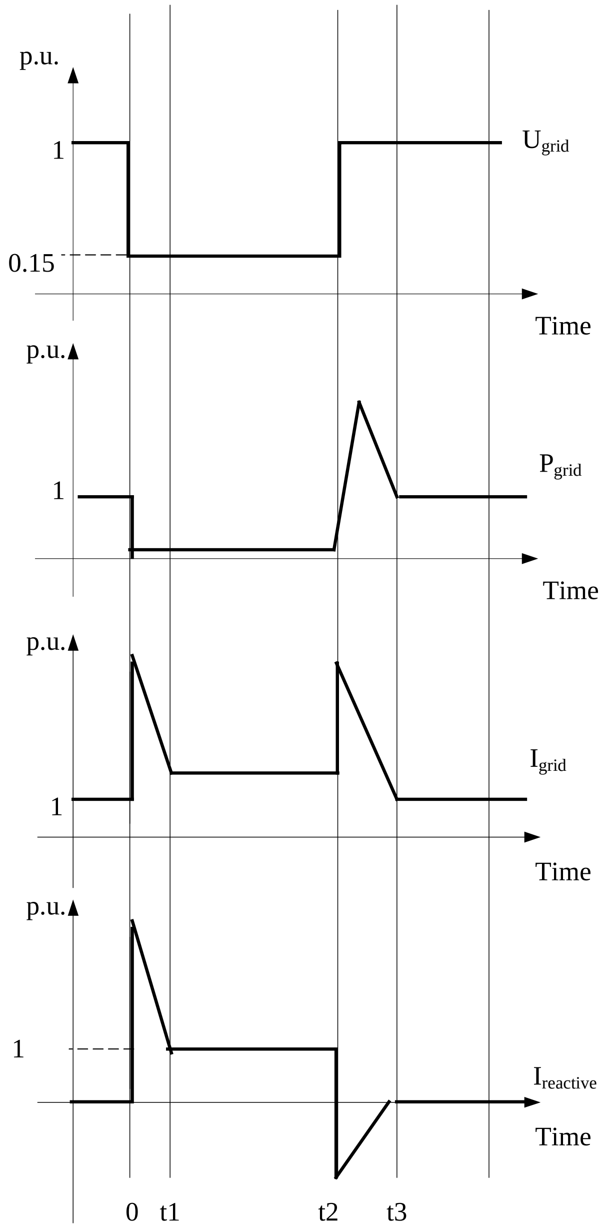
The behaviour of type 3 and 4 wind turbines during fault conditions can be summarised as follows, and is depicted in Figure 5-1.

During low voltage events, turbine voltage drops, and active power drops as a function of the voltage dip. When a fault occurs at t=0, the wind turbine initially provides a high fault current contribution, ramping down until the time t1. At that stage, the turbine converter takes control and the fault current is maintained at around the rated current.

From time t1 through to t2, the wind turbine injects sustained reactive current to assist network voltage recovery. As the voltage returns to normal at t2, active and reactive currents start to ramp back to their pre-fault values.

The turbine blade pitch controller may become active for long-duration faults, and reduces mechanical power input to the turbine to reduce the imbalance between the turbine and grid connection point active power levels.

Figure 5-1 — Wind turbine behaviour during low voltage events



Most existing wind turbines are designed to withstand zero voltage at their terminals for 150 ms or longer. The requirement for fault ride-through capability as specified in clause S5.2.5.4 of the NER is assessed for faults occurring at high-side of network transformer, which will result in a less significant voltage reduction measured at the turbine terminals. LVRT requirements do not apply for faults between the wind turbine generator (WTG) terminals and the high voltage side of the wind farm.

The LVRT tolerance curve provided by various wind turbine manufacturers specifies the permissible operating range of the WTG at its LV terminals, whereas compliance is generally assessed at the PCC. Accounting for interconnecting lines and cable impedances, and network and collector grid transformers, a 100% voltage drop at the PCC would translate into residual voltage in the order of 10–15% at the WTG terminals.

The requirement specified in clause S.5.2.5.5 of the NER to tolerate a 100% voltage drop for 430 ms can be met by several wind turbines.

Some designs of wind turbines have a short-term overload capability in the range of 1.15 – 1.35 p.u. of apparent power, which helps recovery from fault conditions. Due to mechanical limitations, it is the WTG that limits the active current, and the converter limits the reactive current due to thermal limits. In the future, it is expected that the short-term reactive current capability of wind turbines will increase slightly, but no improvement is expected in the short-term active current capability.

While wind turbine LVRT capability has been improving over the past few years, there are some current wind turbine designs, primarily type 3, which cannot meet the LVRT requirements independently, without installing additional dynamic reactive plant in the wind farm.

Wind turbine LVRT function is normally dealt with by the turbine converter control, but for long-duration faults, contribution from the turbine blade pitch controls may be also necessary to manage real power imbalances. Blade pitching strategies need to be designed to consider the forces they impose on the turbine tower.

Improved LVRT capability can be achieved by applying a dynamic braking resistor, or chopper, in parallel with the DC-link capacitor, with a higher rated resistor resulting in higher LVRT capability. Using braking resistors can reduce the need for additional dynamic reactive support, and is a standard feature for type 4 WTGs. Braking resistors may also be installed in the power converters on type 3 WTGs.

Unlike many other grid codes, which specify a three phase fault, the LVRT requirements set out in clause S5.2.5.4 of the NER identify a two-phase-to-ground fault as the most onerous contingency a wind farm must withstand. This has historically been considered less onerous than a full three phase fault. The modelling and simulation tool used in the NEM is a positive sequence tool (PSS®E), so two- and three-phase-to-ground faults are treated in essentially the same way.

In general, NER requirements are not considered particularly stringent from an LVRT capability perspective, so no relaxation of these requirements is expected in the future. An area which has posed challenges for some wind turbines—including some type 4 turbines—is LVRT for long-duration shallow voltage dips, e.g., ride-through of voltage dips in the range of 10–20% for 10–12 seconds.

5.2.2 High voltage ride-through capability

High voltage ride-through (HVRT) capability up to 1.2 p.u. is possible with practically all commercial type 3 and 4 wind turbines. Some commercial wind turbines have a higher HVRT capability. The requirement set out in clause S5.1a.4 of the NER for withstanding high voltages of up to 1.3 for 50 ms is considered one of the most stringent of all grid codes, and several existing wind turbine types are not compliant.

Precise investigation of the HVRT capability requires more detailed models than those normally available for wind farms in the NEM. This question is not considered further in this study.

5.2.3 Reactive current injection during disturbances

The automatic access standard stipulated in clause S5.2.5.5 of the NER specifies that: *"To assist the maintenance of power system voltages during the application of the fault, 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 operating generating units (in the absence of a disturbance) for each 1% reduction (from its pre-fault level) of connection point voltage during the fault''*.

Practically all modern wind turbines can respond within one cycle from fault initiation, and provide full reactive current at the low voltage side of the wind turbine transformer within two to three cycles.

The maximum reactive current which can be provided for a sustained periods under fault conditions is 1 p.u., but this may increase in the future with advances in the ratings of voltage-fed semi-conducting switching devices. The NER requirement states that 1 p.u. reactive current injections can be realised when the grid connection point voltage drops by only 25%, which may occur for relatively distant faults. This allows the WTG to provide reactive current support even for distant faults. The level of support provided by WTGs for shallow faults can be equal to or better than that provided by synchronous generators.

The requirement for providing reactive current injection applies to both balanced and unbalanced fault conditions. A more complex control scheme is required for unbalanced fault conditions to ensure that no reactive current is injected into the healthy phases. While the NER requirements are very similar to other grid codes, one difference is that some grid codes require a variable reactive current injection between 1–10% voltage reduction. Several practical wind turbines are capable of providing reactive current injection with higher slopes, but this compromises active power recovery.

5.2.4 Active power recovery

The active power recovery rate of existing wind turbines typically ranges from 1–10 p.u./s, with a higher rate indicating faster active power recovery. A fast active power recovery is generally desirable, and can be used when connecting to strong transmission networks, but if active power recovery is too fast, it can give rise to network stability issues and deteriorating voltage recovery when connecting to weak power systems with low SCR.

Most type 4 wind turbines can achieve a recovery of 10 p.u./s, although even faster recovery rates can be potentially achieved. In most cases, type 3 wind turbines exhibit recovery rates towards the lower to middle range specified above. The difference between type 3 and 4 WTGs stems from the fact that with type 4 WTGs active power control is solely managed by the converter control and is not dependent on the electro-mechanical response of the turbine (which exhibits a very fast response time), while type 3 turbines also include some effects due to electro-mechanical response.

The most common slope currently found among wind turbines is around 2 p.u./s, which corresponds to a power recovery of one second for a 100% drop in active power. The automatic access standard specified in clause S5.2.5.5 of the NER requires active power recovery to at least 95% of the level existing just prior to the fault within 100 ms after disconnection of the faulted element. This requires a recovery rate of 10 p.u./s. Such fast active power recovery may be undesirable when connecting wind farms to weak points in the network, but can potentially be achieved with most commercially available type 4 wind turbines.

5.2.5 Rate of change of frequency

Power system disturbances that result in a substantial imbalance between demand and generation can produce rapid changes in power system frequency. The initial rate of change of frequency (RoCoF) is determined by the overall power imbalance and the power system inertia.

The maximum acceptable RoCoF for existing wind turbines is in the range of 2–4 Hz/s for 200–300 milliseconds. Less rapid changes, such as 1 Hz/s, can be tolerated for a longer duration; in the range of one second or more. This limitation on permissible RoCoF stems from the use of a phase-locked loop in the converter controls of type 3 and type 4 wind turbines, which can lose tracking of the voltage phase angle—and therefore the power system frequency—for more rapid changes in power system frequency. In the future it is expected that all wind turbines will have a withstand capability of 4 Hz/s and above. The automatic access standard for the RoCoF, as specified in clause S5.2.5.3 of the NER, is ±4 Hz/s for 250 milliseconds.

The displacement of synchronous generators by type 3 and 4 wind turbines can result in higher RoCoF, because wind turbines do not inherently provide any inertial response. This may potentially be an issue in the NEM in regions with high wind penetration, particularly Tasmania and South Australia. However, as wind turbines can tolerate high RoCoF for a couple of hundred milliseconds, sufficient time would be provided for the wind farm’s synthetic inertia (if such a provision is made) to respond and alleviate frequency deviations. Without this high RoCoF ride-through, the wind farm’s synthetic inertia would not be used as the control as it is not fast enough to mitigate the initial frequency peak.

RoCoF relays may be used to protect and trip wind generation with high levels of RoCoF, however studies have identified that this approach can be cumbersome and should be abandoned as it prevents the use of synthetic inertia. Other challenges associated with RoCoF relays include difficulties in filtering the noise present in the measured frequency, and sensitivity of the RoCoF relays to switching events.

5.2.6 Unbalanced disturbances

Most modern wind turbines are able to ride through asymmetrical voltage dips caused by unbalance network faults. While this is usually less onerous, one issue associated with unbalanced faults is that power injected into the grid contains power oscillations with a frequency twice that of fundamental frequency, i.e., negative sequence. Large oscillations in grid voltage can be observed in these circumstances.

Additionally, the negative sequence component that will arise from single and two-phase faults will generate a second harmonic current in the rotor circuit of type 3 wind turbines. This will, in turn, generate a second harmonic ripple torque in the generator, and asymmetrical turbine currents. When the asymmetrical fault is cleared, the ripple torque disappears, and the phase currents are controlled towards symmetrical values again. Long and severe two-phase faults may lead to a temperature rise in the generator, rotor and chopper circuit; this could lead to generator disconnection if not correctly considered in the plant design.

Additionally, the magnitude of the positive sequence component and therefore the voltage support capability in terms of reactive current injection decreases during unbalanced faults. Some later model wind turbines are designed to control the negative sequence component; this eases the thermal stress and provides a higher degree of controllability on the positive sequence components.

With type 3 wind turbines, management of the negative sequence component at both grid-side and machine-side is needed. The capability to control the negative sequence component for machine-side is not widely used at present, but appears to be technically feasible for wind turbines installed by 2020.

Using positive sequence tools such as PSS®E can cause inaccurate results when determining system response to unbalanced disturbances. AEMO has not been able to address this issue further in the current study, because precise investigation of the issue would require high accuracy EMT-type models, which are not generally available for wind generation currently installed in the NEM.

5.2.7 Wind turbines vs. synchronous generators during disturbances

An advantage of wind farms from a transient stability perspective is that no direct connected synchronous generator is involved. This means the rotor angle instability is not a direct concern. However, this statement only holds true when there are sufficient synchronous generators in the system to provide sufficient inertia.

Compared to synchronous generators, wind turbines generally provide a faster response to voltage dips, but the 1 p.u. limit for sustained reactive current injection of the wind turbines (based on the rating of the converter electronics) is significantly lower than the synchronous generator limit (typically around 2-3 p.u.) depending on the synchronous machine design.

For shallower voltage dips, wind farms can generally achieve a similar or larger reactive current injection response than synchronous generators; but for severe voltage dips, wind farm support to the network can be less effective. This limitation will be more pronounced for connections to networks with a low short-circuit ratio. Additionally, using full reactive current injection during a disturbance imposes a limit on the active power recovery due to the limited overall converter capability.

An advantage of wind turbines is that rapid reduction in reactive power, in the order of a few milliseconds, is possible when needed during fault clearance. Synchronous generators can take a few hundred milliseconds to reduce the reactive power by entering the under-excited mode.

5.3 Voltage and reactive power control

5.3.1 Control schemes

In general, wind turbine control of voltage and reactive power can be performed in one of the following three modes:

- Constant voltage control (at the wind farm HV, the turbine LV, or a combination of the two (compound)).
- Constant reactive power control.
- Constant power factor control.

A combination of these modes is sometimes used where, during steady-state operation, the wind farm is operated with constant reactive power or constant power factor. Immediately after a network disturbance, the control is switched over to a voltage control to assist system recovery from network disturbance.

Operating the wind turbine in voltage control mode is considered to be the most efficient way of using the available static and dynamic reactive power capability of the turbine and wind farm overall. This can reduce the reactive power requirements of synchronous generators. Reactive power and power factor controls may be the preferred mode of operation when connecting to very strong transmission systems, but for other conditions it can give rise to under-utilisation of the wind turbine reactive power capability.

Voltage and/or reactive power control can either be implemented at the turbine-level, or at farm-level. Farm-level control is generally a slow SCADA-based control with an action time of one second or more, which will not provide a fast response for providing dynamic reactive power. ESCOSA licence conditions for wind generators in South Australia mandate that 50% of the available wind farm reactive capability is provided with a high speed of response. As this cannot be achieved with slower SCADA-based control strategies, either additional fast-acting dynamic reactive support plant (such as STATCOMs), or closed-loop turbine-level voltage control will be needed to meet this requirement.

Currently, turbine-level fast voltage control has not been very widely used, so fast-acting dynamic reactive support plant is the most common solution. Most type 4 wind turbines, and some recently introduced type 3, can provide fast turbine-level voltage control. This is achieved with fast inner control at the turbine level, and slower outer control at the farm level.

With type 3 and 4 wind turbines, active and reactive power can be controlled independently. For example, a change in active power dispatch set-point will not result in a change in the reactive power. With type 1 and 2 wind turbine the active and reactive power are correlated.

In some recent wind farm developments in the NEM, the practice has been to give higher priority to active power control during normal operating conditions. Priority is given to reactive power immediately after a fault and up to several hundred milliseconds thereafter, to expedite network voltage recovery. Adjustment may be needed when connecting wind farms to networks with a very low short-circuit ratio; this requires very careful consideration of post-fault active and reactive power recovery strategies.

5.3.2 NER requirements

The automatic access standard set out in clause S5.2.5.13 of the NER specifies the following settling times for a step change of voltage set-point or voltage at an agreed location:

- *Active power, reactive power and voltage less than 5.0 seconds for a 5% voltage disturbance with the generating unit synchronised, from an operating point where the voltage disturbance would not cause any limiting device to operate; and*
- *In respect of each limiting device, active power, reactive power and voltage less than 7.5 seconds for a 5% voltage disturbance with the generating unit synchronised, when operating into a limiting device from an operating point where a voltage disturbance of 2.5% would just cause the limiting device to operate.*

These requirements can be achieved using SCADA systems with an action time of one to four seconds, or using fast turbine level closed loop voltage control. Several recent wind farm installations are compliant with these automatic access requirements.

Additionally, the generating system is expected to regulate voltage at the connection point or an agreed location in the power system (including within the generating system) to within 0.5% of its set-point. This criterion is generally achievable through close control of reactive power, and most existing wind farms are capable of meeting this requirement. The only exception arises when relatively small wind farms with limited reactive capability are connected to a strong point on the transmission network.

5.3.3 Reactive power capability

Overall capability

It is expected that a wind farm can be operated at any point within the reactive capability curve specified in the wind farm connection agreement. Actual wind turbine reactive power capability depends on the turbine's internal voltage, temperature, current limitations, and active power level, with wind turbines operating at partial load often technically able to provide a higher level of reactive power support.

Wind turbine capability charts outlining the relationship between active and reactive power can be either triangular, rectangular, or D-shaped. Turbines with rectangular or D-shaped capability charts can provide reactive capability even when they are not generating any active power. This capability potentially exists for the entire operating range of most type 4 wind turbines, with suitable control settings.

A number of existing type 3 wind turbines have been designed such that the reactive power capability reduces when active power drops below approximately 0.2 p.u. This results in limited or no reactive capability at zero or very low power outputs. In some cases the turbine may be paused (not rotating) during low wind conditions, which results in reduced reactive power capability. AEMO understands that some type 3 wind turbines may become commercially available that have a reactive power generation capability at zero active power.

Typically, reactive power capability is defined when operating the turbine at nominal voltage, and operating at other voltages can result in reduced reactive power capability. For this reason some grid codes specify a capability curve outlining the relationship between voltage and reactive power, as well as the typical active – reactive power capability curve.

High terminal voltage limitation may also prevent wind turbines from generating reactive power under some operating conditions. Cable charging within a wind farm can exacerbate the issue, with turbines at the end of a long cable string not delivering any reactive power because of their over-voltage limit. Reactive power capability is generally specified at the point of interconnection, though it can also be specified at the generator terminals.

Static capability

The automatic access standard set out in clause S5.2.5.1 of the NER requires the plant to provide reactive power of 0.396 p.u. at any level of active power output for voltages within 0.9 – 1.1 p.u. No commercially available wind turbine types that are currently capable of delivering this requirement without additional reactive support plant were identified during this review. Negotiation of access standards, or the use of static (capacitors) and/or dynamic (STATCOMs) reactive power support are typically required.

The main factor limiting wind turbine reactive power capability is the rating of the power electronic devices used in modern type 3 and type 4 turbines. These devices have a limited voltage and current capability; that said, their ratings are expected to marginally increase in the future.

Wind turbine reactive power capability can be increased by uprating the main semiconducting switching devices (such as IGBTs) in the back-to-back power electronic converter; or by using multi-level converters, which results in an increase in turbine voltage and current capability.

Dynamic capability

Wind turbines can provide fast acting dynamic reactive power support in the same fashion as synchronous generators, but at a comparatively lower level. There are no specific NER requirements with respect to response time (dead time) and rise time of the dynamic response, but the NER does state the settling time for both limited and non-limited response, and the halving time.

ESCOSA licence conditions for wind generators in South Australia set out dynamic reactive requirements for wind generation by specifying a response time (dead time) of 0.2 seconds and a rise time of one second. Response time and rise time definition are given in clause S5.2.5.13 of the NER.

Additionally, ESCOSA licensing conditions specify that wind farms in South Australia must provide dynamic reactive power at a level of at least 50% of the overall reactive power delivered at the PCC. This can be achieved either with turbines that use fast wind turbine level control, or through dynamic reactive support (STATCOMs). ESCOSA licence conditions for wind generators in South Australia can be met by using short-term overload capabilities of dynamic reactive plant such as STATCOMs for up to two seconds. Currently these devices have a short time overload capability around 2.5 – 3 p.u., which helps reduce the overall STATCOM size.

Comparison with synchronous generators

Although wind turbine reactive power capability has been evolving in recent years, in general wind turbines exhibit a lower reactive power capability range compared to synchronous generators. Most large synchronous generators are capable of complying with the automatic access standards; this does not generally hold true for existing wind turbines.

Installation of sufficient static and/or dynamic reactive power support can allow any level of reactive requirement to be met; however the incentives for wind farm developers have not generally been sufficient to encourage wind farms to comply with the automatic access standards in the NER.

Future wind farms—especially those based on type 4 wind turbines—are expected to exhibit improved static and dynamic reactive power capability. It is likely that some of these turbines will come close to meeting both the automatic access standards and ESCOSA licence conditions for wind generators in South Australia, with minimal or no additional reactive equipment requirements.

Another differentiator is that with synchronous generators, reactive power is directly injected into the transmission grid, providing a more efficient means of controlling voltage relative to wind farms. In wind farms, reactive losses occur across various transformers and cables/lines, significantly reducing reactive power delivered to the PCC.

As discussed previously, reactive power generation capability reduces when power drops below a certain limit. Similar limitations apply to synchronous generators. Although conventional generators may be capable of operating as synchronous condensers, they are often restricted from operating between zero and minimum load conditions.

5.4 Active power control

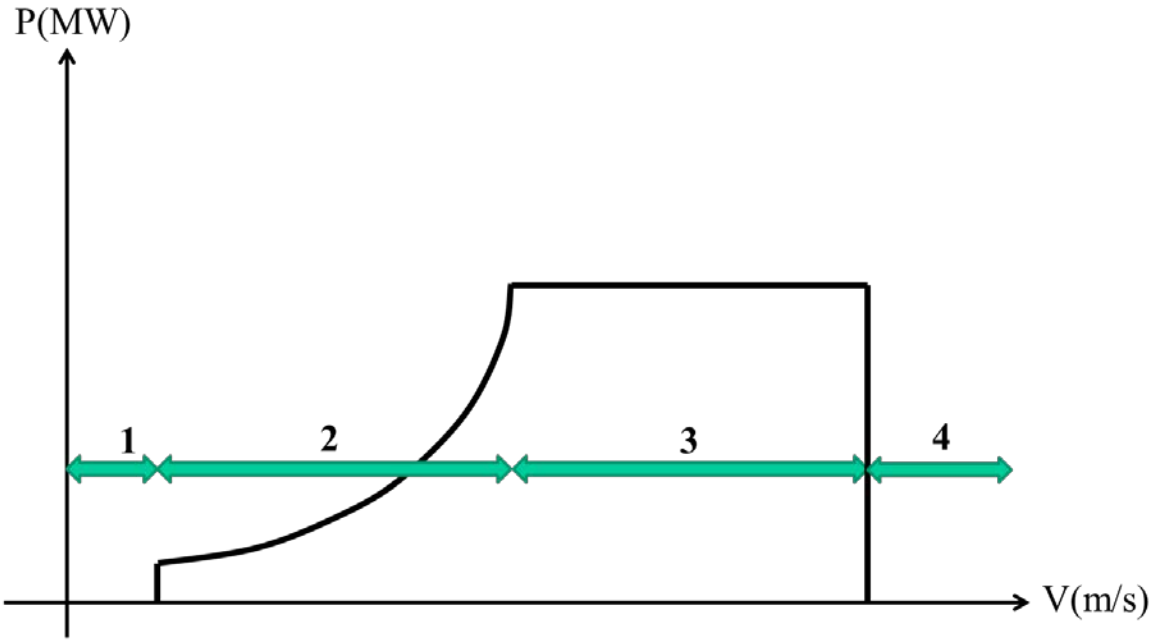
For pitch-controlled wind turbines, three distinct operating modes can be identified, depending on the available wind speed as shown in Figure 5-2.

Region 1 encompasses operation from start-up to cut-in wind speed, where the generator is turned on and generates power. The cut-in wind speed for modern wind turbines is typically in the range of 3 – 5 m/s. Differences are to some extent related to the specific IEC wind class for which the wind turbine has been designed. IEC standard 61400-1 classifies wind turbines into class I, II and II based on the average annual wind speed at the hub height, which is 10 m/s, 8.5 m/s, and 7.5 m/s respectively for the classes.

Region 2 covers partial power operation where the intent is to extract as much energy from the available wind as possible. Depending on the IEC class and turbine design, nominal rated wind turbine power is achieved around the end of this region, at around 10–16 m/s wind speed.

In region 3, generator power is limited at nominal rated power by adjustment of the turbine blade pitch. Operation in region 3 can be sustained for wind speeds up to 20–28 m/s. Above these speeds the turbine needs to be shut down to protect itself from mechanical damage. The corresponding wind speed is referred to as cut-out wind speed.

Figure 5-2 — Turbine power vs. wind speed for pitch controlled wind turbines



Wind turbines can be operated from zero to nominal power without any restriction, and will generally aim to produce maximum active power subject to the available wind speed. When curtailing the generated power to allow for frequency regulation ability, there is generally a minimum production limit based on current wind conditions, which is determined by the turbine design.

For most type 3 wind turbines this minimum is around 20–30% of the nominal power, so curtailing the generated power below that level is not possible. With type 4 machines, active power is completely controlled by the converter. Some type 4 wind turbines can be physically curtailed down to zero power, but in many cases this will not be practical due to the internal consumption of auxiliary loads and the generator losses.

Clause S5.2.5.14 of the NER specifies the following automatic access standard requirements for active power control for semi-scheduled generating systems such as wind farms:

- *(i)* *Automatically reducing or increasing its active power output within five minutes at a constant rate, to or below the level specified in an instruction electronically issued by a control centre.*
- *(ii)* *Automatically limiting its active power output, to or below the level specified above.*
- *(iii)* *Not changing its active power output within five minutes by more than the raise and lower amounts specified in an instruction electronically issued by a control centre.*
- *(iv)* *Ramping its active power output linearly from one level of dispatch to another.*

The ramp rate of existing wind turbines during normal operating conditions ranges from 0.05 to 0.25 p.u./s, which would be sufficient to meet these requirements. The only automatic access standard which cannot be met by most type 3 wind turbines is power reduction below a threshold of around 20-30% of nominal power.

Power run-back schemes are included in some wind farm installations. Power run-back allows the system operator to send a remote signal to instruct the wind farm to reduce active power with a certain minimum ramp down rate to a predetermined power level and to stay there until the run-back signal is cleared. These schemes can protect the power system against loss of thermal transfer capability or transient angle instability.

Most modern wind farms use a central park level control system to send active power targets to individual wind turbines. These controls can be designed to maintain a fixed value (absolute power constraint), keep a fixed relationship to the available power (delta production constraint), or limit the RoCoF (power gradient constraint).

5.5 Frequency control

In general, frequency support in power systems can be divided into three stages:

1) Inertial response.
2) Primary frequency control.
3) Automatic generation control (AGC).

This report focuses on the inertial response and the primary frequency control response from wind generation.

Inertial response to a frequency disturbance is fast, and has no dead-band, while primary frequency response is slower, and is often implemented with a dead-band.

The main function of the primary frequency control is to limit to minimum frequency, i.e., the bottom point of the frequency curve, within acceptable values. In the NEM, these values are specified in the Frequency Operating Standards. While the requirement for providing primary frequency control by generation is established in several grid codes, no quantifiable requirements were found with respect to wind farm inertial response.

5.5.1 Inertial response

Background

Power system inertia is a natural characteristic that limits the grid frequency rate of change when there is an imbalance between the total generation and consumption of power in the system. The imbalance can be caused by various network events such as faults, loss of lines or interconnectors, or loss of generation. In simple terms, inertia refers to short-term storage of the energy often characterised by the inertia constant (H). High system inertia means a lower RoCoF, and a more stable system.

With conventional synchronous generation, rotational speed is directly related to electrical frequency. Any frequency variation will be seen as a rotational speed variation of all the synchronous machines connected to the grid. For example, in the event of a generating unit loss the resulting power imbalance in the grid will cause the frequency to drop. This will increase the load angle of all connected synchronous generators, which will then increase their power production and decrease the frequency excursion. In general, synchronous generators provide a natural inertial response; but the response speed and level of inertial contribution cannot be controlled. This is because the inertia is directly related to the machines' physical masses and associated prime mover.

Displacing conventional synchronous generators with asynchronous generation, such as wind and solar PV, raises concerns about power system inertia levels. This is because without sufficient synchronous generation containing inherent inertial response, managing power system frequency and stability may become more difficult.

Comparisons between the inertial contribution of wind generation and conventional synchronous generators can be based on two criteria: the inertia constant (H), and the rate of change of frequency (RoCoF). The suitability of each of these options to assess inertial contribution of wind farms is discussed later in this section.

Wind turbine inertial contribution

From an inertial response perspective, wind turbines can be divided into fixed/semi fixed-speed turbines (type 1 and 2), and variable speed turbines (type 3 and 4). When there is a sudden drop in the frequency of type 1 wind turbines, the rotor speed does not change instantaneously (due to turbine inertia), but the generator power-speed characteristic changes due to the change in power system frequency. This increases the generator's electromagnetic (electrical) power output.

This causes a mismatch between the mechanical power and electromagnetic power of the turbine, and the rotational speed then decreases until a new balanced operating condition is reached. The kinetic energy stored in the turbine is transferred to the grid to help arrest the frequency decline. In this way, type 1 wind turbines provide some effective inertial contribution.

With type 2 turbines, the response to a disturbance is characterised by a constant output power, as the external rotor resistance will control the output power at rated. In this case, it is the generator speed that changes, not the active power. The net inertial contribution of type 1 and type 2 wind turbines is similar.

In general, the response of induction machine-based fixed-speed wind turbines is slower and less than synchronous generators of equivalent rating. This is because fixed-speed turbines have a lower coupling of induction generator rotational speed to system frequency, and a marginally smaller inertia constant. The inertia constant of synchronous generators is typically between two and nine seconds, while for wind turbines it ranges from two to six seconds. The contribution of type 1 and type 2 wind generation to power system inertia is currently ignored in NEM operations.

Variable speed wind turbines, including types 3 and 4, are essentially treated as wind turbines without any inertia. This is because fast control of power electronic converters maintains a practically constant output power irrespective of changes in grid frequency, effectively producing a zero inertia characteristic.

There is a subtle difference between type 3 and type 4 wind turbines from a grid coupling perspective: type 4 turbines feature full decoupling between the electrical generator and the grid, so the electrical generator inertia is practically unseen by the grid; type 3 wind turbines have some loose coupling from the rotor windings to the grid via back-to-back power electronic converters.

Despite this, current control system designs practically decouple the generator rotational speed from the system frequency, so from an inertial response perspective there is little difference between types 3 and 4.

Wind turbine synthetic inertia

To emulate the inertial response of synchronous generators, or to appear as though they have inertia, wind turbines need to adjust their active power output as a function of grid frequency deviations. While most modern wind turbines can rapidly reduce power in the event of a grid frequency rise, the challenge is providing inertia in response to grid frequency declines. This requires a rapid increase in active power output, ultimately requiring additional mechanical power from the turbine.

This issue can be managed primarily by curtailing the wind turbine generation below maximum possible production at all times, and releasing the withheld capacity only when the grid frequency dips. Although this approach has already been adopted in some power systems outside the NEM, there is currently no incentive to do so in the NEM. This is because there is no obligation for wind generation to either provide inertia or participate in frequency control arrangements in the NEM. The economic implications resulting from lost wind energy generation mean that this approach would not be supported by wind farm generators or network service providers.

Other possible approaches for providing ‘emulated’ or ‘synthetic’ inertia to address falling grid frequency are either the temporary extraction of energy from the generator rotor, or adjustment of the turbine blade pitch. The choice would depend on the prevailing wind speed and turbine operating point, as outlined below.

Below rated wind speed

Stored kinetic energy from the turbine generator rotor can be temporarily extracted and given to the grid, and the generator rotor speed drops. This energy is recovered later from the grid. Over longer timeframes this form of emulated inertial response is essentially energy neutral; a period of increased electrical power is followed by a period of decreased electrical power to restore the generator rotor speed to normal.

Higher wind speeds

At higher wind speeds (greater than rated), rather than extracting energy from the generator rotor, blade pitch control can be used to increase the captured wind power and increase electrical power output, temporarily exceeding the steady-state rating of the generator.

At present, power electronic converters and mechanical components of wind turbines have a marginal overload capability; however, providing significant inertial response would require uprating these to temporarily carry higher active power above the continuous rating.

This approach has been already applied to type 3 wind turbines, and AEMO understands that prototype models have demonstrated successful operation [4]. It appears that while this method can effectively control the RoCoF, the frequency recovery time is longer relative to synchronous generators.

It has also been shown that [17] obtaining inertial response from a large number of turbines produces a better nadir than when fewer turbines are contributing to the response, although recovery time is slightly slower given the deeper aggregate recovery period associated with more turbines operating below the rated speed and fewer above it.

As the inertial response is achieved through the converter control response speed, the level of 'synthetic' inertia provision is relatively controllable; however the available inertial response can vary according to wind turbine loading conditions.

An advantage of variable-speed wind turbines in providing emulated inertial response is that generator speed is not limited to the typical 0.95 p.u. limit allowed by the under-frequency relays typical on conventional synchronous generators.

Type 3 wind turbine generator speed can drop as low as 0.7 p.u, depending on the controls installed, allowing up to 5.25 times more kinetic energy to be obtained compared to conventional synchronous machines of similar ratings. Type 4 wind turbine speeds can vary anywhere from zero to full speed, so the kinetic energy available is generally greater than type 3 wind turbines, with their more limited operational speed range.

Variable speed type 3 and 4 wind turbines provide advantages in this regard over fixed-speed (type 1 and 2) wind turbines, as fixed-speed wind turbines' maximum permissible speed variation is only around 5–8%. This means that the energy available from fixed speed wind turbine by slowing down their rotors is lower than from variable speed wind turbines.

Providing emulated inertial response requires a very fast control, which is only available through fast wind turbine level control. Such action is provided through a coordinated inner loop wind turbine level control, and outer loop park level control where the park level control system coordinates the response of individual wind turbines. This is because spatial distribution of wind in a wind farm results in each wind turbine generating different levels of power, so the inertial contribution of each individual wind turbine is not identical.

Given that a central park level control system caters for this potential difference in the active power level of individual wind turbines, traditional wind turbine aggregation methods may not be adequate for assessing collective wind farm inertial contribution.

Identified limitations associated with wind turbine synthetic inertia

Disadvantages identified with these methods of providing synthetic inertia include the extra heat from additional power generation, and stress on mechanical components. These issues are well understood among wind turbine manufacturers, who expect to overcome them in the next 3 – 5 years. To avoid frequent operation of inertial control and the associated stress on mechanical components, controls can be designed to respond only to large under-frequency events (not to over-frequency events, or minor under-frequency events that do not deteriorate system stability).

Another area of concern, especially with type 3, is that wind turbines can only be typically curtailed down to a level of 15-25% of the rated power depending on wind turbine design. To avoid rotor stall during low power conditions, wind turbines can neither provide an emulated inertial response nor be curtailed to provide a governor response. Above these low levels, the energy which can be delivered is dependent on the degree of the initial curtailment, the available wind power at the time of the event, and the tuning of the inertial response control structure.

In general, there is a limit which determines the maximum inertial contribution of the wind turbine. This primarily applies to type 3 wind turbines, especially those controlling active power rather than electromagnetic torque. Excessive extraction of kinetic energy from the rotor would bring the electromagnetic torque close to its breakdown value, possibly causing the turbine to stall.

Other methods for provision of inertia

Aside from providing inertial response via wind turbine controls, other solutions can include integrating energy storage devices into the wind turbine, using energy storage devices at the DC-side of STATCOMs, and using synchronous condensers with high overload capability. Very recently, commercial wind turbines with integrated energy storage systems have become commercially available.

Quantification of inertial requirements

As discussed, inertia provision by wind turbines can be assessed using an inertia constant, or by assessing the effect on RoCoF. In general, variable speed turbine inertial response depends on local wind speeds, and cannot be quantified deterministically by system operators. Specifying a fixed emulated inertia constant for a wind turbine is therefore not a practical approach for all conceivable operating conditions and credible contingencies.

It is suggested that fully replicating the inherent inertial action of synchronous generators is not possible, nor is it necessary. Instead, carrying out extensive power systems simulation studies to determine the maximum RoCoF which can be experienced in the system would provide a baseline regarding the level of inertial support required by wind farms under high wind penetration scenarios.

5.5.2 Governor response

A primary frequency response, or governor response, is the second stage of frequency support after the initial inertial response. Provided that an inertial control is implemented for a wind farm, this inertial control will respond first, proportional to the RoCoF experienced in the system.

This is then followed by a governor response, which aims to restore system frequency. A governor control changes the active power set-point of the wind turbines to provide the active power required in response to a frequency deviation. It is a common practice to use a central park level controller to send the required set-point change to individual wind turbines within a wind farm.

As discussed, one way to provide inertial response from the wind turbines is to curtail them at all times so they can increase their power output as needed. This incurs a loss of energy available from each turbine, but might be justifiable if the combination of inertia response and governor response necessitate this. It has been shown that emulating the inertial response can cause double dip conditions when wind turbines decelerate, but this can be largely eliminated by implementing the governor response.

Aside from responding to under-frequency events, a governor response can also be effective in mitigating over-frequency conditions. These are generally power run-back types of control aiming to relieve thermal overloading of certain lines during credible contingencies. This occurs when the wind farm reduces its power in response to the set-point change signal from the grid operator.

With today’s technology, implementing a governor response capability sufficient to allow participation in NEM frequency control arrangements in the turbine or wind farm controls would likely be quite straightforward, as it already exists for a few commercial wind turbine designs. The extent to which the governor response can be provided depends on the available wind.

5.6 Connection to networks with low short circuit ratio

Short circuit ratio (SCR) is generally used to assess network strength, and is defined as the ratio of the three-phase RMS fault level in MVA at the PCC to the wind farm’s nominal power (MW). For wind farms, the short circuit ratio can also be determined as the inverse of the impedance seen from the aggregate wind turbine terminals to the point of common coupling.

This means that the SCR seen at the aggregate wind turbine terminals would be smaller than the SCR at the point of interconnection. For example, considering typical impedances for a wind farm of 100–200 MW, an SCR of 5 at the PCC would translate to an SCR of about 3 at the aggregate wind turbine terminals.

The disadvantage of defining the SCR at the PCC is that the equivalent impedance from the aggregate wind turbine terminals to the PCC varies between projects. It would therefore be more appropriate to define and assess the SCR at the equipment terminals. However, this information is considered as proprietary by some wind turbine manufacturers. Consequently no universal information is available to compare minimum design values of the SCR at wind turbine terminals.

For wind farm connections, concerns increase as the short circuit ratio at the PCC drops below five. The accuracy of most RMS-type models is typically proven for SCR values down to five. For the SCR region between three and five, the RMS-type model may or may not accurate. Benchmarking the model against the respective detailed

EMT-type model may be necessary to confirm performance. Aside from model validity, another issue is the suitability of equipment installed onsite for such low short circuit conditions. For low SCR conditions, wind turbine control may behave unreasonably and may necessitate turbine converter control modifications, in particular coordination with other dynamic reactive support plant. Such networks have a strong dependency between voltage and reactive power. This results in the voltage deviation being greater for the same level of reactive power injection or absorption than that experienced when connecting to strong transmission networks.

It is understood that wind turbines (particularly type 4) provide a marginal contribution to the network fault current, typically exceeding the nominal rated current by just 10–20%. Displacement of synchronous generators by wind and other forms of variable generation technology causes network fault levels to reduce. For this reason, although issues associated with connections to low SCR networks currently only apply to remote connection points, large scale penetration of variable generation—and consequent displacement of synchronous generators—may give rise to network-wide issues.

The effects of low SCR on system disturbances are higher voltage drops and slower voltage recovery compared to systems with higher SCRs. This means an increased risk of system instability, even when using wind turbines with LVRT capabilities. Another issue is that aside from the fundamental frequency components, higher order harmonics can be observed in the system response. These types of temporary over-voltages (TOVs) can be mitigated by using a higher voltage control gain, but this could cause un-damped or poorly damped oscillation modes.

For low SCR conditions, coordinated wind farm level control should be designed to create a trade-off between active and reactive power recovery following disturbances. When connecting to strong transmission networks the priority is for a fast yet stable voltage recovery, and active power recovery is second priority. For networks with low SCRs and little local load, this strategy cannot be adopted. This is because a too fast recovery gives rise to temporary over-voltages, and secondly, the energy deficit after the fault clearance can be significant. A higher rate of active power recovery can alleviate both of these problems and also assist in mitigating the risk of experiencing un-damped or poorly damped oscillation modes.

Other issues attributed to connections to weak networks include the risks of harmonic resonance, sub-synchronous interaction, and control interactions in general. These issues can only be investigated using detailed EMT-types models, and are excluded from the Wind Integration Project scope.

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CHAPTER 6 - TECHNOLOGY TRENDS

This chapter provides a brief summary of emerging technology trends in wind turbines. The information presented in this chapter is drawn from published turbine information and specifications, discussions with selected manufacturers and wind farm developers, and AEMO's own technical knowledge.

6.1 More efficient wind turbines

At present several newer commercial wind turbines are available with a nominal power of 5 MW and above. AEMO understands that design concepts have been proposed to realise larger wind turbines in the range of 8–10 MW. Most of these wind turbines are intended for use in offshore wind farms, or high-wind onshore sites (IEC class I).

Type 4 design is expected to be predominantly used for these new larger wind turbines. The use of multi-level converters combined with a synchronous generator (either wound field or permanent magnet) is expected to be the dominant design. From a NEM perspective, AEMO does not currently expect that any wind farms installed by 2020 will use wind turbines above below 5 MW.

Several DC-connected wind farms are being proposed in Northern Europe, with either point-to-point or multi-terminal high voltage DC (HVDC) links. There is currently no formal connection application for any DC-connected wind farm in the NEM, but a number of high wind sites exist which may favour point-to-point DC connection rather than AC connection. Commercial type 3 and type 4 wind turbines suitable for DC connection are available, and high power dedicated DC-connected wind turbines are in development by a number of manufacturers.

Most of these newer wind turbine types are suitable for IEC class I and class II wind sites. Installation at sites with lower wind speed conditions (IEC class III) will compromise the energy yield. Development of dedicated wind turbines for low wind speed sites is an area of recent attention for wind turbine manufacturers and wind farm developers. When deciding on the most appropriate site, it might be economically justifiable to choose IEC class II or III sites with little network congestion rather than the class I wind sites with high network congestion.

These newer wind turbines commonly use the same control system as older wind turbine designs, while up-scaling the turbine blade and tower height. The up-scaling applied by various wind turbine manufacturers ranges from 10–40%; larger up-scaling means higher production gains. A production gain of up to 50% has been reported by some manufacturers when using IEC class I wind turbines for an IEC class I wind site compared to using conventional IEC class III wind turbines. The original generator is generally maintained. Type 3 and type 4 wind turbines for IEC class III sites are already commercially available.

This review has identified an increasing trend towards direct drive (gearless) wind turbines, especially for offshore wind farms. These turbines generally have fewer components than the geared counterparts. This reduces the possibility of component failure and associated maintenance requirements, and enables faster replacement of failed electronic components. The main drawbacks are that they are more expensive than geared wind turbines of comparable performance, and that long-term supply of rare earth materials used in permanent magnet generators is a concern. (Geared permanent magnet wind turbines require a fewer rare earth materials.) These turbines are available from several manufacturers, and the first large scale wind farm based on direct drive wind turbines is currently under construction in the NEM.

6.2 Control changes

SCADA systems are commonly used for data acquisition, remote monitoring, and wind farm level controls. While fast-acting SCADA systems are available with a resolution of one sample per second, most SCADA systems used in practice have a slower action time of 4–10 s. This results in under-utilisation of wind turbines' reactive power capability. SCADA systems enhancements, or more accurate, faster-acting alternatives such as phasor measurement units (PMUs), will provide opportunities for better utilisation of wind farm capability, in particular voltage and reactive power capabilities.

A challenge associated with the operation of a power system with significant penetration of variable generation technologies is that their intermittent nature means a correlation between generation and demand cannot be readily established. This can be somewhat alleviated by using advanced generation forecasting and load forecasting, and by the availability of sufficient conventional generating systems to compensate for sudden variations in wind farm output power.

Displacing synchronous generators with variable generation technologies will diminish this buffering capability, although this could be partly replaced with the use of energy storage systems. Storage systems can also be used to augment system stability by providing inertial response and primary frequency control, and assist in network fault condition recovery. This avoids the need for wind turbine curtailment or temporary deceleration, as other alternatives are currently available for providing wind turbine inertial response. High capital cost has previously been a barrier to large scale integration of energy storage devices in wind farms, but commercial wind turbines with integrated energy storage have recently entered the international market.

AEMO understands that imminent developments in wind plant grid performance capability include improved static and dynamic reactive power capability, provision of fast turbine level voltage controls (which would assist compliance with ESCOSA licence conditions for wind generators), faster recovery of active and reactive power after fault clearance, and possibility of inertial response. Features such as providing damping of small-signal oscillations has been discussed in research literature [47, 48], but are less likely to be included in commercial wind plants commissioned by 2020.

CHAPTER 7 - WIND PLANT CAPABILITY MODELLING METHODOLOGY

This chapter outlines the assumptions that AEMO intends to use for modelling a 2020 NEM power system considering the possible wind generation development forecast in the 2012 NTNDP, based on the findings and observations described in the preceding chapters.

These include assumptions about the possible mix of wind turbines which could reasonably be expected to be installed in the NEM by 2020, and the possible performance range these wind turbines may exhibit.

This chapter also provides modelling information to represent these different generation models in PSS®E.

7.1 Wind turbine type mix

Table 7-1 shows two potential wind turbine mixes considered possible for wind farms installed in the NEM by 2020, including existing and future installations. The mixes reflect two scenarios:

- A pessimistic scenario, with a greater mixture of wind turbines of lower performance.
- An optimistic scenario, with a greater mixture of wind turbines of higher performance.

While type 1 and 2 wind turbines are likely to be obsolete for new installations in the NEM, the existing fleet of these turbines will remain in service, and will not be replaced by type 3 or type 4 based wind turbines before 2020.

Table 7-1 — Wind turbine type mix for 2020

Turbine type	Pessimistic scenario	Optimistic scenario
Types 1 and 2	10%	10%
Type 3	60%	30%
Type 4	30%	60%

Investigating issues associated with large scale wind integration in the NEM requires a sufficiently accurate representation of the NEM, including solar PV farms installed by 2020. For this reason a simplified solar PV inverter model is also presented later in this section. The solar PV model has generally the same structure as the type 4 wind turbine model.

For each of the generation models (types 1 and 2, type 3 and type 4 wind turbines, and solar PV), AEMO has developed a representative lower performing model variant (Type A), and a higher performing model variant (Type B). By selecting different mixes of the wind turbine types, and various levels of assumed performance from the different model types, different wind generation performance scenarios can be examined. Technical descriptions of these different models are provided in the rest of this chapter.

7.2 Wind turbine type allocation

It is assumed that type 1 and 2 wind turbines have comparable grid performance characteristics, and can be represented by type 2 wind turbines.

It is assumed that the largest NEM wind farms will be based on type 4 wind turbines, as these turbines have the following characteristics:

- Typically have a higher nameplate rating compared to type 3; AEMO is aware of only one manufacturer offering a type 3 turbine that exceeds 4 MW for the European market.
- Offer higher reliability and lower maintenance partly due to the elimination of slip rings that exist in type 3 turbines. This justifies using type 4 for offshore farms where reliability and maintenance are crucial factors.
- Eliminate or at least minimise the need for dynamic reactive support equipment which tends to occupy a larger footprint as the wind farm size increases.
- Have marginally higher efficiency at full load compared to type 3 turbines, but significantly higher efficiency at partial load conditions. This makes them more suitable for low wind speed sites.

Higher costs of type 4 compared to type 3 turbines, and recent provision of dedicated type 3 turbines from several manufacturers for low wind speed conditions may make type 3 turbines preferable for smaller projects in low wind speed sites.

7.3 Wind farm layout

Figure 7-1 and Figure 7-2 show the single line diagram of the modelled wind farm collection grid, and integration to the point of interconnection. The main differences between the two diagrams are as follows:

- Type 1 and 2 wind turbines operate such that the exchange of reactive power at the turbine LV terminals is around zero, and the turbine does not contribute to system dynamics. Turbine representation can be simplified to a resistive load; this is because the capacitive impedance of the shunt capacitor installed at the turbine terminals and the inductive impedance of the generator cancel each other out.
- Type 1 and 2 based wind farms are represented with dynamic reactive support, which is provided by STATCOM, but no STATCOM is included in the single line diagram of type 3 and 4 based wind farms. This is because it is understood that most type 3 and 4 turbines installed by 2020 will have improved static and dynamic reactive power capability, and will achieve the required performance without additional dynamic reactive power support.
- Most type 1 and 2 based wind farms installed in practice include shunt reactors at the 33 kV collection grid to manage reactive power control at light load conditions. For simplicity, these reactors have not been represented in Figure 7-1, but can be readily represented by assuming that their rating is identical to the 33 kV capacitors.

In Figure 7-1 and Figure 7-2:

- Wind farms are represented as single aggregated wind turbines and a fixed shunt capacitor at the MV collection grid.
- Type 1 and 2 based wind farms also have a STATCOM included at the MV collection grid. The STATCOM is represented as a single aggregated device.
- The wind farm collection grid is assumed to be 33 kV.

The detailed modelling methodology for each component of the wind farm collection grid is discussed in subsequent sections. The data required for representing the substation transformer and HV overhead line/underground cable would be chosen by the user for each specific connection point.

In Figure 7-1 and Figure 7-2, the following three busbars can be identified:

- xxxx: representing the LV side of aggregated wind turbine terminals.
- yyyy: representing the HV side of aggregated wind turbine terminals.
- zzzz: representing the point of interconnection.
- ssss: Representing the LV side of the STATCOM terminals.
- gggg: Medium voltage wind farm collection grid.

When entering data into the PSS®E dynamic data file, the correct busbar number should be inserted with consideration given to the specific connection point, and consistent with the corresponding load flow set-up.

Figure 7-1 — Single line diagram of the wind farm collection grid with type 1 and 2 wind turbines, and integration to the point of interconnection

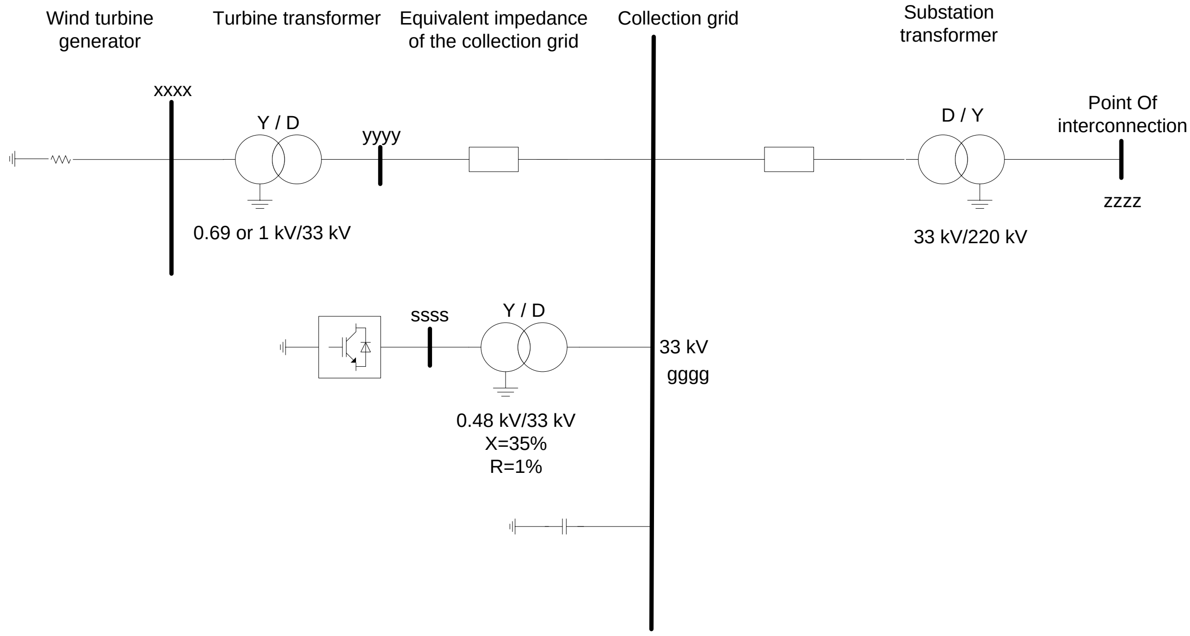
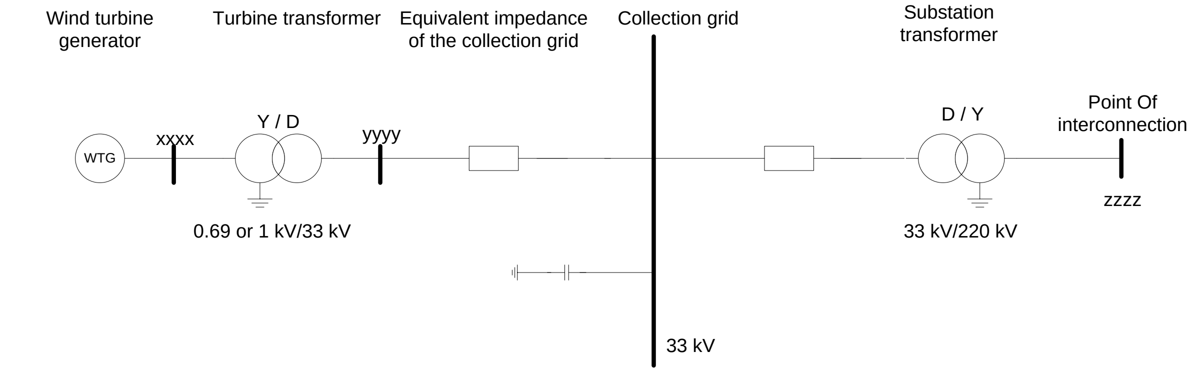


Figure 7-2 — Single line diagram of the wind farm collection grid with type 3 and 4 wind turbines, and integration to the point of interconnection



Note: For solar PV farms the single line diagram shown in Figure 7-2 remains valid except that the PV terminal voltage is changed to 0.48 kV. Additionally, most solar PV farms tend to be connected to networks with lower voltage levels. The primary or secondary voltages for either of the two transformers may need adjustment to account for these differences.

7.4 Reactive power and voltage control capability

7.4.1 Assumptions

Voltage/power factor control assumptions

- All type 1 and 2 based wind farms are operated at a constant power factor control mode without any farm level controller.
- All future wind farms will employ a central farm level controller. Existing wind farms with this feature include Waubra, Macarthur and Musselroe.

- All existing and future wind farms based on type 3 and 4 turbines and solar PV inverters will be operated on voltage control mode, except Macarthur which uses a power factor control mode.
- High performance type 3 (3B) based wind farms will include a fast closed-loop turbine-level voltage control mode, but the pessimistic scenario machines (3A) will use a slow acting plant-level voltage control with an action time of 1–5 s.
- All existing and future type 4 based wind farms will employ a fast closed-loop turbine-level voltage control scheme.

Reactive power capability assumptions

- For the type 1 and 2 based wind farms, wind turbines cannot generate any reactive power, and need to consume reactive power. Static reactive support is generally provided by installation of shunt capacitor banks at the turbine LV terminals.
- All type 1 and 2 based wind turbines are operated such that the reactive power flow at the turbine terminals is around zero.
- Additional dynamic reactive support is provided for type 1 and 2 based wind turbines by installation of the STATCOM rated at 0.12 p.u. of the wind farm apparent power in MVA. It is assumed that the STATCOMs have a short-term overload capability of 2.67 p.u. for 2 s consistent with the capability of currently installed STATCOMs.
- For type 1 and 2 based wind farms, the 33 kV shunt capacitor is rated at 0.5 p.u. of the wind farm nominal power.
- The reactive power capability of type 3 based wind farms will vary from having a power factor of 0.95 in the pessimistic scenario (A) to a power factor of 0.85 in the optimistic scenario (B), which is typical of synchronous generators. The power factor is defined at 1 p.u. voltage.
- The power factor assumed for the pessimistic scenario is derived considering the average power factor of currently installed type 3 wind turbines, which ranges from 0.985 to 0.9. A power factor of 0.95 can therefore be assumed for existing type 3 based wind farms.
- The pessimistic scenario is considered to be a type 3 wind turbine with a rated power factor of 0.95 without fast acting turbine level voltage control (type 3A).
- Figure 7-3 illustrates the reactive power capability of type 3- and type 4-based wind farms for the optimistic and pessimistic scenarios. For the pessimistic scenario wind turbines (type 3A) it is understood that the reactive power capability is often reduced when operating at light load (typically below 0.2 p.u.), or high load (above 0.8 p.u.). This is highlighted with dashed lines in Figure 7-3.
- The typical type 3 wind turbine model used does not, however, allow for adjusting the reactive power as function of the operating active power. For this reason the active vs. reactive power chart for all type 3- and 4-based wind farms is assumed to have a rectangle shape.
- Reactive power capability of all wind turbines is considered to be symmetrical, i.e., Qmin=-Qmax.
- Reactive power losses from the wind turbine LV terminals through the point of interconnection will be approximately 50% of the reactive power generated at the terminals.
- Table 7-2 summarises the reactive power generated by the wind turbine, and the size of the capacitor bank required at the 33 kV for various wind turbine types and mix scenarios. The size of capacitor bank is calculated such that:
- For all scenarios other than wind turbine type 3A and PV type A, the reactive power generated at the point of interconnection amounts to 0.395 p.u. as required by the automatic access standard.
- For wind turbine type 3A,and PV type A, the reactive power delivered at the point of interconnection is assumed to be 0.3 p.u.
- Increasing the turbine terminal voltage from 1 to 1.05 p.u. gives rise to a 50% decrease in the reactive power generated by the wind turbine. Similar net impact can be expected when reducing the voltage from 1 to 0.95 p.u.

- All future wind farms will have the capability to generate some reactive power at zero and light load conditions.
- Solar PV inverters will exhibit a true rectangle shape reactive power capability similar to type 4 wind turbines but with reduced capability. For this reason it is assumed that solar PV type A and B will have the same reactive power capability as wind turbines of type 3A and 3B, respectively.

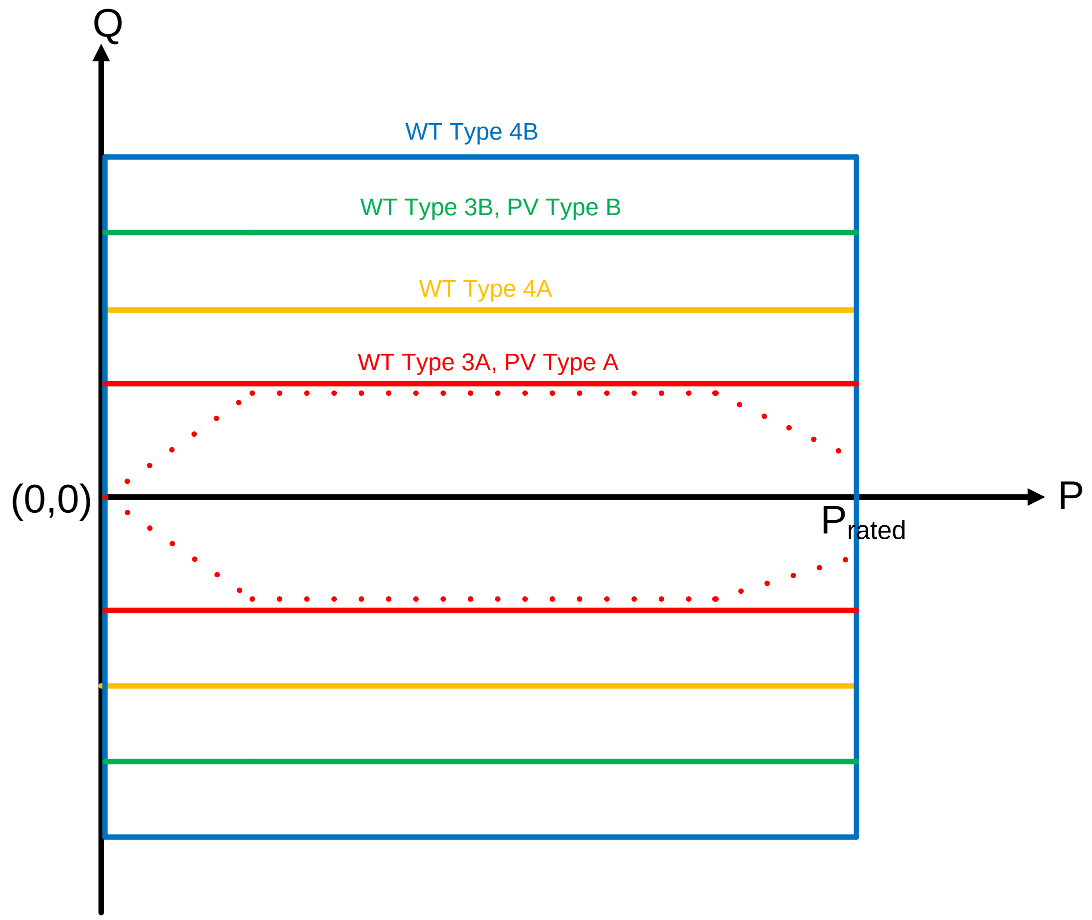
Table 7-2 — Assumed wind turbine reactive power capability at 1 p.u. voltage

Equipment	Qmax, WTG, 0.69 kV (p.u.)	Qmax, WTG, at POI (p.u.)	QMSC, 33 kV (p.u.)	QSTATCOM (p.u.), 33 kV	Fast closed-loop wind turbine-level voltage control	Compliance with automatic access standards/ ESCOSA generation licence conditions
WTG type 2	0.5	0	0.5	0.12	No	Yes
WTG type 3A	0.328	0.164	0.136	0	No	No
WTG type 3B	0.62	0.31	0.085	0	Yes	Yes
WTG type 4A	0.58	0.29	0.105	0	Yes	Yes
WTG type 4B	0.79	0.395	0	0	Yes	Yes
PV type A	0.328	0.164	0.136	0	Yes	No
PV type B	0.62	0.31	0.085	0	Yes	Yes

Table 7-3 — Assumed wind turbine reactive power capability at 1.05 p.u. voltage

Equipment	Qmax, WTG, 0.69 kV (p.u.)	Qmax, WTG, POI (p.u.)	QMSC, 33 kV (p.u.)	QSTATCOM (p.u.), 33 kV	Fast closed-loop wind turbine-level voltage control
WTG type 2	0.5	0	0.5	0.12	No
WTG type 3A	0.164	0.082	0.218	0	No
WTG type 3B	0.31	0.155	0.24	0	Yes
WTG type 4A	0.29	0.145	0.25	0	Yes
WTG type 4B	0.395	0.1975	0.1975	0	Yes
PV type A	0.164	0.082	0.218	0	Yes
PV type B	0.31	0.155	0.24	0	Yes

Figure 7-3 — Assumed reactive power capability of different wind turbines and solar PV



7.5 Fault ride-through capability assumptions

- The low voltage ride-through (LVRT) capability for type 3 and 4 wind turbines and solar PV inverter is enabled when the wind turbine terminal voltage drops below 0.9 p.u. Users can adjust this value.
- The static and dynamic reactive power capability of type 3 wind turbines are determined with the same parameters (Qmax and Qmin) whereas type 4 wind turbines include additional parameters to account for the turbine converter's dynamic overload capability. The dynamic reactive power capability of type 4 based wind farms is characterised by the parameters Imax TD, Iphl, Iqhl, and max FRT Iq as indicated in Table A-3. For type 4B wind turbines, these parameters are larger relative to the type 4A wind turbines implying a higher short-term dynamic reactive power capability.
- For all wind farms, reactive power control is given priority over active power control. This means that during disturbances active power is limited such that initially the converter current and subsequently the turbine operating point are maintained within the reactive power capability chart.
- To cater for the momentary increase in turbine active power during fault recovery, the maximum turbine power production is set to 1.1 p.u. in all type 3 and 4 wind turbines.
- Type 3 wind turbine models used do not account for the reactive current injection capability during the fault. This capability is therefore only represented in type 4 based wind farms. In the pessimistic scenario, the wind farm is capable of injecting reactive currents up to 1 p.u. at a rate of 2% per each 1% drop in the turbine

terminal voltage. In the optimistic scenario the wind farm can inject reactive currents of up to 1.3 p.u. with a rate of 8% per 1% drop in the turbine terminal voltage.

- Type 3 wind turbine models used do not account for active power recovery rate upon fault clearance. This capability is therefore only represented in type 4 based wind farms. A recovery rate of 2 p.u./s and 10 p.u./s is assumed for the pessimistic and optimistic scenarios, respectively.
- To allow investigation of the impact of excessive voltage or frequency on the wider network, wind turbine over/under voltage and frequency protection relays are disabled.
- The response of solar PV inverters to voltage dips is similar to that of type 4 wind turbines except that the model used does not account for the reactive current injection capability of the inverter during disturbances.

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APPENDIX A - PSS®E REPRESENTATION

A.1 Wind turbine time-domain model

A.1.1 Load flow model

- All type 3 and type 4 based wind farms can be operated at any power output from zero to the rated power, i.e. Pmin=0.
- Pmax can be adjusted to reflect the full load or partial load conditions. Pgen should be equal or less than Pmax.
- For all turbine types and solar PV models Mbase is assumed equal to Pmax.
- The MVA and MW ratings of the aggregated wind turbine/solar PV inverter equals those of a single wind turbine/solar PV inverter multiplied by the number of wind turbines/solar PV inverters in the particular wind/solar farm.
- Reactive power limits should be set according to Table 6-2 and Table 6-3 with Qmin=-Qmax.
- For type 1 and 2 wind turbines Qmax=-Qmin=0.5*Pgen
- Source impedance data for various wind turbine types and solar PV inverters are shown in Table A-1.

Table A-1 — Source impedance data for wind turbines

Equipment	Rsource	Xsorce
Type 3 WT	0	0.8
Type 4 WT	0	9999
Solar PV	0	9999

A.1.2 Dynamic model

Dynamic data files include several parameters for both type 3 and type 4 machines, however, only those parameters which may need to be adjusted by the user are shown in Table A-2 through Table A-4.

The differences between scenario A and B are also highlighted in the tables. All other parameters now shown in the tables will remain identical for scenario A and B.

The nameplate rating of the type 3 wind turbine dynamic model used is 1.5 MW, with the number of aggregate wind turbines set with CON (J+26) in the user model WT3E. The turbine size selected is not material for the overall model performance as seen at the aggregate wind turbine terminals, and was selected based on typical settings used for this particular dynamic model.

For the type 4 wind turbine and solar PV models the aggregation can be done in the load flow case, and no turbine size is required in the dynamic data file.

Close inspection of Table A-3 and Table A-4 reveals that the two models are similar, except that the dynamic model of the PV inverter does not provide user adjustable settings for reactive current injection.

Table A-2 — Adjustable dynamic model parameters for type 3 wind turbine

WT3G			
xxxx 'USRMDL' ID 'WT3G' 1 1 1 4 4 4 0 CON(J) to CON(J+3)		Value	
CONS	**Description**	type 3A	type 3B
J+9	QMX, max limit in voltage regulator(p.u.)	+0.328	+0.526
J+10	QMN, min limit in voltage regulator (p.u.)	-0.328	-0.526
J+26	N, Number of original wind turbines lumped to this equivalent WT	nnnn	nnnn
WT3E			
xxxx 'USRMDL' ID 'WT3E' 4 0 7 33 10 13 ICON(M) 0 ICON(M+2) to ICON(M+6)			
CON(J) to CON(J+32) /			
ICONS	**Description**	type 3A	type 3B
M	Remote bus # for voltage control; 0 for local control	zzzz	xxxx
M+2	VARFLG: 0 – constant Q control; 1 – use Wind Plant reactive power control emulator; -1 – constant power factor control	1	1
M+3	VLTFLG : 1 = Use closed loop terminal voltage control; 0 if VARFLG=0 or -1	0	1
M+4	From' bus of the interconnection transformer	xxxx	xxxx
M+5	To From' bus of the interconnection transformer	yyyy	yyyy
WT3T			
0 'USRMDL' 0 'WT3T' 8 0 3 8 4 5 xxxx '1 ' 0 CON(J) to CON(J+7) /			

Table A-3 — Adjustable dynamic model parameters for type 4 wind turbine

W4EUR2			
xxxx ' USRMDL' ID 'W4EUR2' 4 0 4 34 11 4 List of ICONs List of CONs/		Value	
CONS	**Description**	type 4A	type 4B
J+20	ImaxTD, Converter current limit	1.115	1.7
J+21	Iphl, Hard active current limit	1.25	1.25
J+22	Iqhl, Hard reactive current limit	1.085	1.25
J+26	FRT_Droop, FRT droop (%)	0.000	0.000
J+27	FRT_Iq_Gain, FRT Iq Gain (%/%)	2.000	8.000
J+28	Max FRT Iq, Max FRT Iq (p.u.)	1.000	1.30
ICONS	**Description**		
M	Remote bus # for voltage control; 0 for local control	xxxx	xxxx
M+1	PFAFLG: 1 if PF fast control enabled 0 if PF fast control disabled	0	0
M+2	VARFLG: 1 if Qord is provided by WindVar 0 if Qord is not provided by WindVar if VARFLG=PFAFLG=0 then Qord is provided as a Qref=const	1	1
M+3	PQFLAG, P/Q priority flag: 0 Q priority 1 P priority	0	0
W4GUR2			
xxxx 'USRMDL' ID 'W4GUR2' 1 1 0 9 3 5 List of CONs /			
CONS	**Description**		
J+7	RIp_LVPL, Rate of LVACR active current change	2.000	10.000
WT4PLT			
0 'USRMDL' 0 'WT4PLT' 8 0 2 0 0 3 xxxx '1 ' /			

Table A-4 — Adjustable dynamic model parameters for PV model

GEPVE			
IBUS 'USRMDL' ID 'GEPVE' 4 0 8 27 8 8 ICONs from (M) to (M+7) CONs from (J) to (J+26) /			
CONS	**Description**	Type A	Type B
J+5	QMX, max limit in voltage regulator(p.u.)	Qmx_A	Qmx_B
J+6	QMN, min limit in voltage regulator(p.u.)	Qmn_A	Qmn_B
J+18	ImaxTD, Converter current limit	1.12	1.7
J+19	Iphl, Hard active current limit	1.12	1.25
J+20	Iqhl, Hard reactive current limit	1.12	1.25
ICONS	**Description**		
M	Remote bus # for voltage control; 0 for local control	xxxx	xxxx
M+2	PFAFLG: 1 if PF fast control enabled 0 if PF fast control disabled	0	0
M+3	VARFLG: 1 if Qord is provided by WindVar 0 if Qord is not provided by WindVar if VARFLG=PFAFLG=0 then Qord is provided as a Qref=const	1	1
M+4	PQFLAG, P/Q priority flag: 0 Q priority 1 P priority	0	0
GEPVG			
xxxx 'USRMDL' ID 'GEPVG' 1 1 2 13 3 5 0 ICON(M+1) CONs from (J) to (J+12) /			
CONS	**Description**		
J	Rated power of the PV plant, MW	rrrr	rrrr
J+7	RIp_LVPL, Rate of LVACR active current change	5.000	10.000

A.2 Balance of plant component model

A.2.1 Mechanically switched capacitor

As discussed in Table 7-2 and Table 7-3.

A.2.2 STATCOM

Table A-5 — Source impedance data for STATCOM

Equipment	Rsource	Xsorce
STATCOM	0	9999

Table A-6 — Adjustable dynamic model parameters for STATCOM model

CDVAR1		
ssss,'USRMDL',1,'CDVAR1',1,1,20,68,3,36,0,0, mmmm,1,zzzz,gggg,gggg,zzzz,-1,0,0,0,0,0,0,0,0,0,0,0, 1.05,0.04,0,0,0.01,0,0,70,0,0,0.04,0.04,0.03,0.02,0.04,0.03,400,2.67,2,0.5,0.5, 1,1,1,1,1,4,0,0,0,0,0,0,0,0, -1,2000,-0.52,30000,1,2000,0.52,30000,55,0,0,0,0,0,0,0,0,0,0,0, 0,0,0,0,0,0,0,0,0,0,0,0,0,0/		
ICONS	**Description**	Value
M+2	STATCOM Mvar Rating	mmmm
M+3	Control Mode 0 - Voltage Control; 1 - Power Factor Control; 2 - Constant Susceptance Output; 3 - Constant VAR Output	1
M+4	bus number for Regulation Voltage control	zzzz
M+5	bus number for Transient Voltage control	gggg
M+6	From bus number for defining the CT01 flow. It is only needed if the Power Factor or Constant VAR regulation modes are desired	gggg
M+7	To bus number for defining the CT01 flow. It is only needed if the Power Factor or Constant VAR regulation modes are desired	zzzz
CONS	**Description**	Value
J	STATCOM's regulation voltage target (p.u.) - referred to as Vref. For a flat STRT, set Vref to the p.u. voltage of the generator's VOLT REG BUS#	1.05

A.2.3 Transformers

- The MVA rating of the equivalent transformer equals that of an individual turbine transformers multiplied by the number of wind turbines.
- It is assumed that the wind farm is connected to the grid via two identical transformers. The impedance values indicated in Table A-7 therefore represents two parallel connected transformers.
- The source impedance information for the transformer and the corresponding Mbase is indicated in Table A-7.
- The MVA rating of aggregated turbine transformer, and therefore the value of source impedance needs to be adjusted to reflect the actual rating of the aggregated transformer, which is $N*P_{WTG}$.

Table A-7 — Source impedance data for the equivalent wind farm transformer

Transformer impedances	Rsource	Xsorce	Mbase
Turbine transformer	0.008	0.06	100
Collector grid transformer	0.008	0.06	100
STATCOM transformer	0.01	0.35	100

A.2.4 Equivalent impedance of the collection grid

Table A-8 shows typical values of collector system impedance in p.u. (Mbase).[1]

Table A-8 — Collector system impedance in p.u. (Mbase)

Plant Size (MW)	Voltage (kV)	Feeder	R pu (pu)	X pu (pu)	B pu (pu)	B/X pu	X/R pu	B/R pu
50	34.5	All UG	0.014	0.011	0.032	2.33	0.77	3.02
100	34.5	All UG	0.017	0.014	0.030	1.79	0.83	2.16
100	34.5	33% OH	0.018	0.079	0.030	1.67	4.37	0.38
100	34.5	All UG	0.012	0.011	0.036	3.14	0.91	3.43
110	34.5	All UG	0.013	0.012	0.033	2.59	0.92	2.83
103	34.5	All UG	0.009	0.018	0.044	4.59	1.88	2.45
112	34.5	All UG	0.007	0.005	0.019	2.79	0.72	3.89
114	34.5	All UG	0.012	0.015	0.037	3.12	1.25	2.49
116	34.5	All UG	0.012	0.016	0.039	3.13	1.30	2.40
200	34.5	Some OH	0.013	0.051	0.028	2.07	3.79	0.55
200	34.5	25% OH	0.021	0.078	0.050	2.38	3.73	0.64
230	34.5	All UG	0.012	0.016	0.038	3.12	1.28	2.44
300	34.5	Some OH	0.020	0.078	0.050	2.56	4.02	0.64
300	34.5	Some OH	0.015	0.060	0.028	1.94	4.08	0.47

[1] Final Project Report WECC Wind Generator Development, prepared for CIEE by National Renewable Energy Laboratory, March 2010.

LIST OF ABBREVIATIONS

Abbreviation	Term
AEMO	Australian Energy Market Operator
BOP	Balance of plant
DC	Direct current
DFAG	Doubly fed asynchronous generator
DFIG	Doubly fed induction generator
EMT	Electromagnetic transients
ESCOSA	Essential Services Commission of South Australia
FRT	Fault ride through
HVDC	High voltage direct current
HVRT	High voltage ride through
IEC	International Electrotechnical Commission
IGBT	Insulated gate bipolar transistor
LVRT	Low voltage ride through
NEM	National Electricity Market
NER	National Electricity Rules
NSP	Network service provider
PCC	Point of common coupling
PMU	Phasor measurement unit
PSS®E	Power System Simulator for Engineering
RoCoF	Rate of change of frequency

Abbreviation	Term
rms	Root mean square
SCADA	Supervisory control and data acquisition
STATCOM	Static compensator
SLD	Single line diagram
SVC	Static var compensator
TOV	Temporary overvoltage
WTG	Wind turbine generator

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