Draft Final

Wind Generation Technical Characteristics for the NYSERDA Wind Impacts Study

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November 24, 2003

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1 INTRODUCTION

NYSERDA has commissioned an extensive study of the effects of substantial wind generation on the performance, reliability, and economics of operation of the New York State Bulk Power System. This forward-looking study is to both qualitatively and quantitatively assess a range of potential technical and economic impacts of a prospective wind generation development scenario over the planning years 2006 through 2013.

1.1 Purpose of document

Wind generation technology is expected to continue its evolution up to and through the defined study period. The current fleet of wind turbines used in large U.S. wind plants represents what is really the initial generation of commercial offerings. Experience is already accumulating as to the shortcomings of these turbines, and most wind turbine vendors are well underway with product changes and plans to address these defined needs. With the study period designated to commence more than two years beyond the date of completion for this assessment, there is a high probability that the prospective wind plants to be considered in the study will have characteristics that will enhance overall integration with the bulk electric system.

So as not to skew the qualitative and quantitative assessments to be performed in this study by the NYSERDA contractor to either the benefit or detriment of wind generation, this document has been prepared by the NYSERDA Special Purpose Contractor (SPC) to define the characteristics and assumptions regarding wind generation technology to be used in the various technical assessments. It is to be used as a reference for developing the models and characterizations for the wind plants in the various calculations and simulations that comprise the overall assessment.

1.2 Scope

Wind turbine and wind plant characteristics as viewed from the bulk transmission network are important for this study. Details of the aerodynamic and mechanical aspects of individual turbine operation are important only to the extent that they influence the electrical behavior of the turbine or plant.

This document defines baseline wind turbine and wind plant technologies that will form the basis for wind generation facilities added to the NYSBPS in the early years of the study period. By the latter stages of the study period, significant evolution in wind turbine and wind plant technology and design is presumed to occur, such that wind generation facilities added in the later years of the study will exhibit characteristics that improve prospects for satisfactory integration with the bulk power system.

1.3 Rationale for definition of baseline technologies

Most developments in wind turbine technology over the past decade have been focused on reducing the levelized cost of energy. A relatively few of these myriad changes and enhancements have been for the specific purpose of improving interconnection or integration with the bulk electric power system.

Similarly, the objectives for and constraints on wind plant designs have been relatively simple, due in substantial part to fairly simple requirements for performance of the wind plant at the point of interconnection to the bulk power system.

Now that wind generation has become major presence in many areas of the U.S., there are moves underway to address through requirements and interconnection standards some of the existing and emerging technical issues, such as the recent industry focus on wind turbine low-voltage ride-through capability. This movement will increase in intensity as wind becomes a larger fraction of the generation portfolio, pushing turbine vendors and wind plant developers to evolve their products in ways that will enhance the interoperability with the grid.

The definition of baseline wind turbine and wind plant technologies for the beginning of the study period is a way to reflect the likely outcome of changes already underway in the industry. As wind penetration grows further, the challenges related to interconnection and integrations will likely increase, which will further motivate vendors and developers to evolve and enhance their products. For this reason, the document also lays out a vision of what wind turbine and wind plant technology is likely to become by the end of the study period.

2 BACKGROUND- EXISTING WIND TURBINE TECHNOLOGY

Models for conventional power system elements such as generators and their various control systems, switched and static compensation devices, load, and transmission network elements are well understood by power system analysts. Wind plants, however, pose several new challenges. The fundamental nature of a commercial bulk wind plant, with large numbers of relatively small turbines interconnected by a substantial medium-voltage network, requires equivalencing and simplification without loss of important detail. For some phenomena, the wind plant can be treated as a single entity – transmission power flow is an example, where definition of real and reactive power injection at the point of interconnection with the transmission system at an instant in time provides adequate representation. In dynamic studies, it would be desirable to treat the wind plant as a single large plant, but such treatment may not represent the full range of dynamic behavior or be appropriate for all types of system disturbances. Because each individual wind turbine is a relatively sophisticated machine, determining the dynamic behavior of the aggregate plant model can be difficult.

The technology employed in commercial wind turbines deviates from the much better understood conventional generation equipment. Induction machines, rather than synchronous generators, are used in nearly all U.S. commercial wind turbines. Further, some of the turbine designs employ sophisticated power electronic controllers that alter the fundamental behavior of the induction machines in both steady state and dynamic operation. The characteristics of other wind turbine elements and wind plants that may have an influence on the design, operation, or security of the bulk power system, such as the rotational inertias and torsional constants of the mechanical systems or the variation of real and reactive power output as functions of time, are unknown to power system analysts.

For analytical studies of large power systems, the time frames of interest range from tens of milliseconds to steady state. Device and component models, therefore, must accurately reflect behavior over the entire bandwidth, and properly account for any phenomena outside of the simulation bandwidth that may have an "aliasing" effect on the time frame of interest. Because the purpose of the models is to facilitate investigation of electrical power system issues, certain details of the mechanical system or energy conversion process may not be represented if they have no impact on electrical performance. In conventional models for large power plants, for example, details of the mechanical system, e.g. combustion process, steam cycle control, governor, etc., are included only to the extent that they influence the electrical behavior of the plant during the time frames of interest in a particular study.

2.1 Current commercial wind turbine designs

Almost all of the wind turbines deployed in large wind generation facilities in the U.S. over the past decade can be generally described by one of the following configurations:

- Stall-regulated (fixed-pitch) blades connected to a hub, which is coupled via a gearbox to a conventional squirrel-cage induction generator. The generator is directly connected to the line, and may have automatically switched shunt capacitors for reactive power compensation and possibly a soft-start mechanism which is bypassed after the machine has been energized. The speed range of the turbine is fixed by the torque vs. speed characteristics of the induction generator.
- A wound rotor induction generator with a mechanism for controlling the magnitude of the rotor current through adjustable external rotor circuit resistors, and pitch regulation of the turbine blades to assist in controlling speed. The speed range of the turbine is widened because of the external resistors.
- A wound rotor induction generator where the rotor circuit is coupled to the line terminals through a four-quadrant power converter. The converter provides for vector (magnitude and phase angle) control of the rotor circuit current, even under dynamic conditions, and substantially widens the operating speed range of the turbine. Turbine speed is primarily controlled by actively adjusting the pitch of the turbine blades.

While not represented in the present fleet of commercial turbines for application in the United States, the variable-speed wind turbine with a full-rated power converter between the electrical generator and the grid deserves mention here. The first utility-scale variable-speed turbine in the U.S. employed this topology, and many see this configuration reemerging for future large wind turbines. The power converter provides substantial decoupling of the electrical generator dynamics from the grid, such that the portion of the converter connected directly to the electrical system defines most of the characteristics and behavior important for power system studies.

2.2 Overview of operation

A generalized wind turbine model is shown in Figure 1, and illustrates the major subsystems and control hierarchy that may influence the behavior of a single wind turbine in the time horizon of interest for large power system studies.

A wind turbine converts kinetic energy in a moving air stream to electric energy. Mechanical torque created by aerodynamic lift from the turbine blades is applied to a rotating shaft. An electrical generator on the same rotating shaft produces an opposing electromagnetic torque. In steady operation, the magnitude of the mechanical torque is equal to that of the electromagnetic torque, so the rotational speed remains constant, real power (the product of rotational speed and torque) is delivered to the grid. Since the wind speed is not constant, a variety of control mechanisms are employed to manage the conversion process and protect the mechanical and electrical equipment from conditions that would result in failure or destruction.

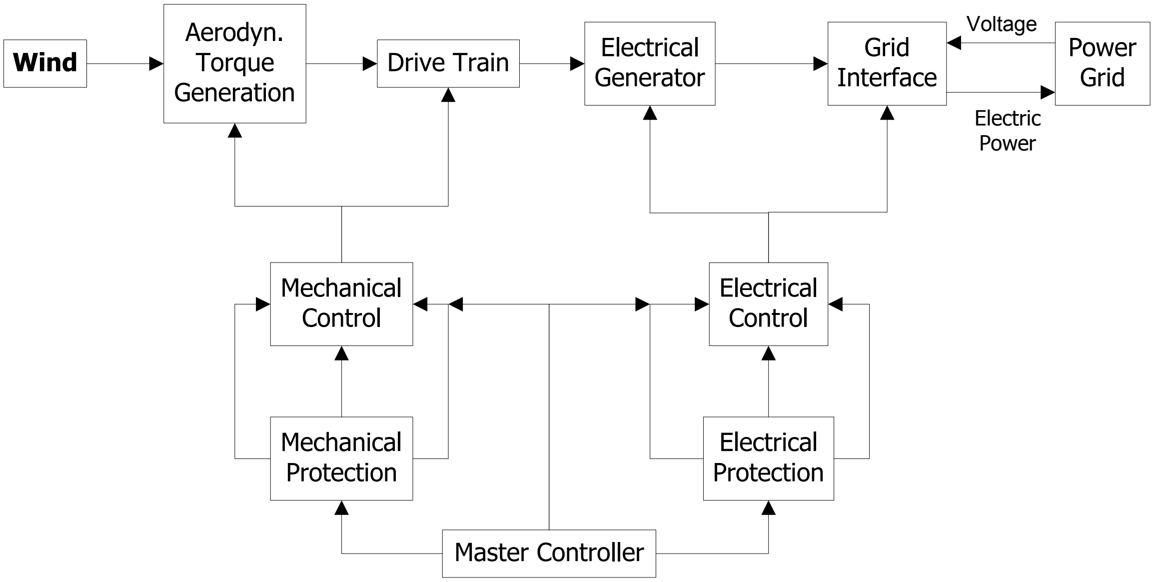

Figure 1: Generalized wind turbine model with control elements and hierarchy.

2.2.1 Mechanical Systems and Control

Mechanically, the turbine must be protected from rotational speeds above some value that could lead to catastrophic failure. Mechanical brakes are provided for stopping the turbine in emergency conditions, but are not used in normal operations. Controlling the power (and hence, torque) extracted from the moving air stream is the primary means for protecting the turbine from over-speed under all but emergency shutdown conditions.

In fairly steady conditions, the power extracted from the air stream by the turbine blades can be characterized by Equation 1:

$$P = \frac{1}{2} \cdot \rho \cdot \pi \cdot R^2 \cdot \upsilon^3 \cdot C_p \qquad \text{Equation 1}$$

where

ρ = air density (nominally 1.22 kg/m^3)

R = radius of area swept by the turbine blades

υ = speed of moving air stream

C_p = "coefficient of performance" for the composite airfoil (rotating blades)

C_p itself is not a constant for a given airfoil, but rather is dependent on a parameter λ, called the tip-speed ratio, which is the ratio of the speed of the tip of the blade to the speed of the moving air stream.

Since wind speed and air density cannot be controlled, and the radius of the blades is fixed, the performance coefficient is the only means for torque control. In some wind turbines, blades are designed so that C_p falls dramatically at high wind speeds. This method of aerodynamic torque control is known as *stall regulation*, and is limited to preventing turbine over-speed during extreme gust conditions and limiting maximum shaft power to around the rating value in winds at or above the rated value.

Large wind turbines employ a more sophisticated method of aerodynamic torque regulation that has benefits in addition to preventing mechanical over-speed. The performance coefficient can also be changed by adjusting the "angle of attack" of the blades, as is done on some modern propeller-driven aircraft. Figure 2 shows C_p as a function of λ for a modern wind turbine. Blade pitch adjustment allows the energy capture to be optimized over a wide range of wind speeds (even if the rotational speed of the shaft is relatively constant), while still providing for over-speed protection through large adjustments in pitch angle.

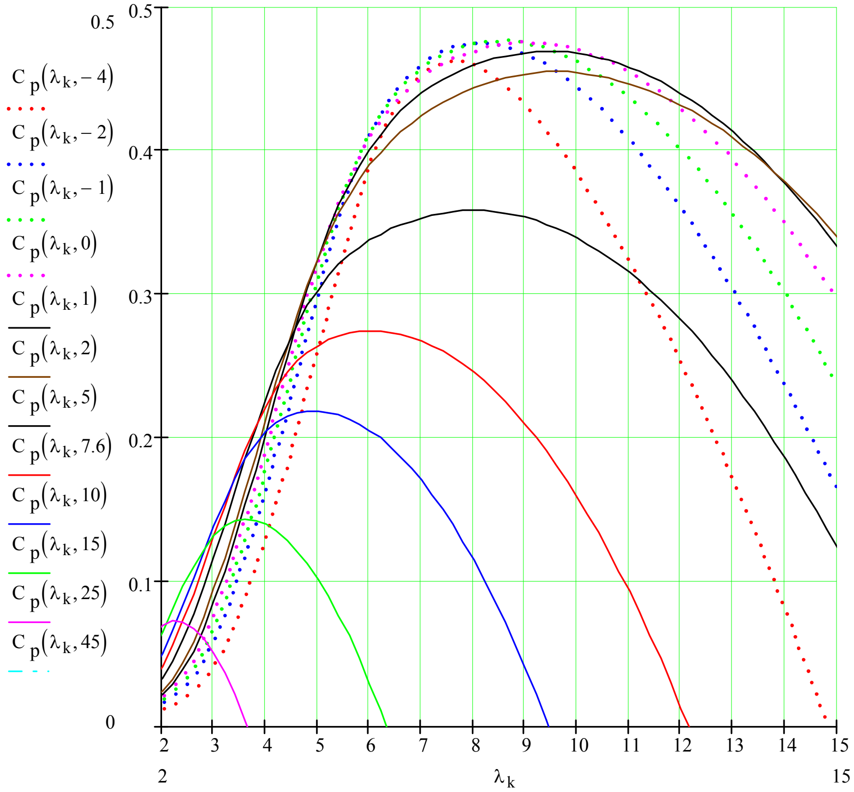

Figure 2: Coefficient of performance (C_p) for a modern wind turbine blade assembly as a function of tip-speed ratio (λ) and blade pitch (β, in degrees).

The pitch of the turbine blades is controlled by an actuator in the hub that rotates each blade about a longitudinal axis. The inertia of the blade about this axis and the forces opposing such a rotation of the blades are not negligible. Pitching of the blades, therefore, does not happen instantaneously, with the dynamics governed by the longitudinal inertia of the blades, forces acting on the blade (which can be wind speed and pitch dependent), and the torque capability of the pitch actuator mechanism.

The characteristic shown in Figure 2 is a "quasi-static" depiction of the blade performance, in that is does not account for turbulence effects, blade vibration with respect to the average speed of rotation, or other asymmetries such as tower shadowing. It does, however, provide a much simpler means of incorporating the otherwise very complex details of the aerodynamic conversion process into models for electrical-side studies of the turbine.

The overall conversion of wind energy to electric power is normally described by a turbine "power curve", which shows turbine electrical output as a function of steady wind speed (Figure 3). Such a representation is accurate only for steady-state operation, since the inherent dynamics of the mechanical and electrical systems along with all possible control functionality is neglected.

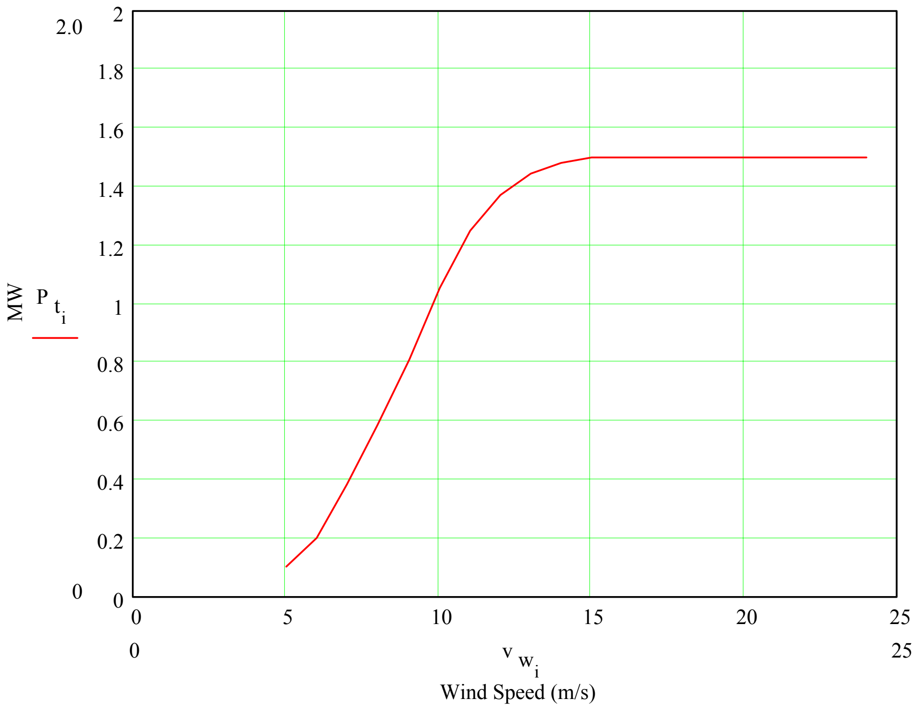

Figure 3: Power curve for a variable-speed, pitch-controlled wind turbine. Note "flatness" of output for wind speeds at or above rated value.

Rotational speeds of large wind turbines are limited by maximum tip-speed ratios, and so for megawatt-class turbines with long blades are relatively low, in the 15 to 30 rpm range. With conventional electrical generators, a gearbox is necessary to match the generator speed to the blade speed. The resulting mechanical system, then, has low-speed and high-speed sections, with a gearbox in between, as shown in Figure 4 (top). An even simpler representation is shown at the bottom of Figure 4, where the gearbox inertia is added to the inertia of the generator, and all components are referred to the high-speed shaft by the square of the gear ratio.

For megawatt-scale turbines, the mechanical inertia is relatively large, with typical inertia constants (H) of 3.0 seconds or larger (the inertia constant for the generator only will typically be about 0.5 s). The mechanical inertia is an important factor in the dynamic behavior of the turbine, because the large inertia implies relatively slow changes in mechanical speed for both normal variations in wind speed and disturbances on the grid. In addition, the various control systems in the turbine may utilize turbine speed as an input or disturbance signal, so that large inertia will then govern the response time.

With a two-mass mechanical model, there will be one oscillatory mode. With relatively flexible drive shafts in large wind turbines, the natural frequency of this primary mode of oscillation will be in the range of 1 to 2 Hz.

2.2.2 Electrical Systems and Control

Induction machines are the energy conversion devices of choice in commercial wind turbine design. In addition to their robustness and reliability, they provide a "softer" coupling between the grid and the mechanical system of the turbine. Wind turbine manufacturers have also moved beyond the basic induction generator systems with technologies for improving control and overall efficiencies. These technologies have a definite impact on the electrical and dynamic performance of wind turbines, even to the extent of masking or overriding the dynamic characteristics that would normally be associated with rotating machinery. The four major types of generator technologies used in today's commercial wind turbines are discussed in the following sections.

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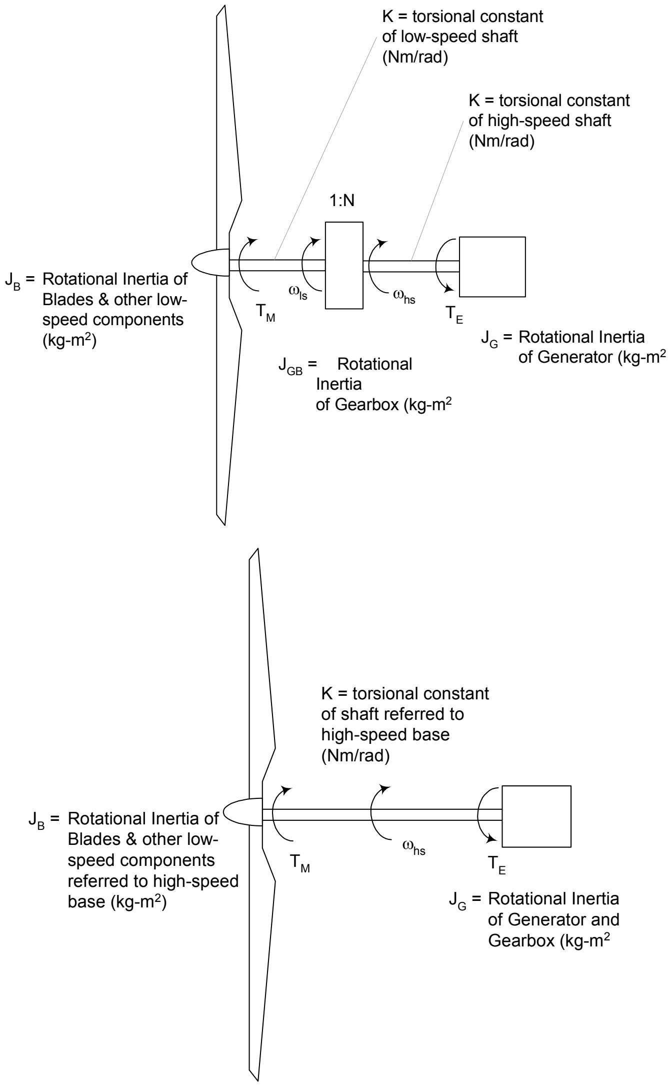

Figure 4: Simplified model of wind turbine mechanical system. Two mass model with gearbox (top) and model with equivalent gearbox inertia and reference of all components to high-speed shaft (bottom).

2.2.2.1 *Direct-Connected Induction Generators*

Wind turbines with squirrel-cage induction generators connected directly to the line are the simplest electrically. While for purposes of aerodynamic efficiency they operate at nearly constant speed, the slight variation of speed with torque (and power) can significantly reduce mechanical torque transients associated with gusts of wind and grid-side disturbances.

The speed range of the turbine is dictated by the torque vs. speed characteristic of the induction generator (Figure 5). For large generators in today's commercial turbines, slip at rated torque is less than 1%, which results in very little speed variation over the operating range of the turbine. For a given wind speed, the operating speed of the turbine under steady conditions is a nearly linear function of torque, as illustrated by the torque vs. speed characteristic of Figure 5. For sudden changes in wind speed, the mechanical inertia of the drive train will limit the rate of change in electrical output.

Because the induction generator derives its magnetic excitation from the grid, the response of the turbine during a grid disturbance will be influenced by the extent to which the excitation is disrupted

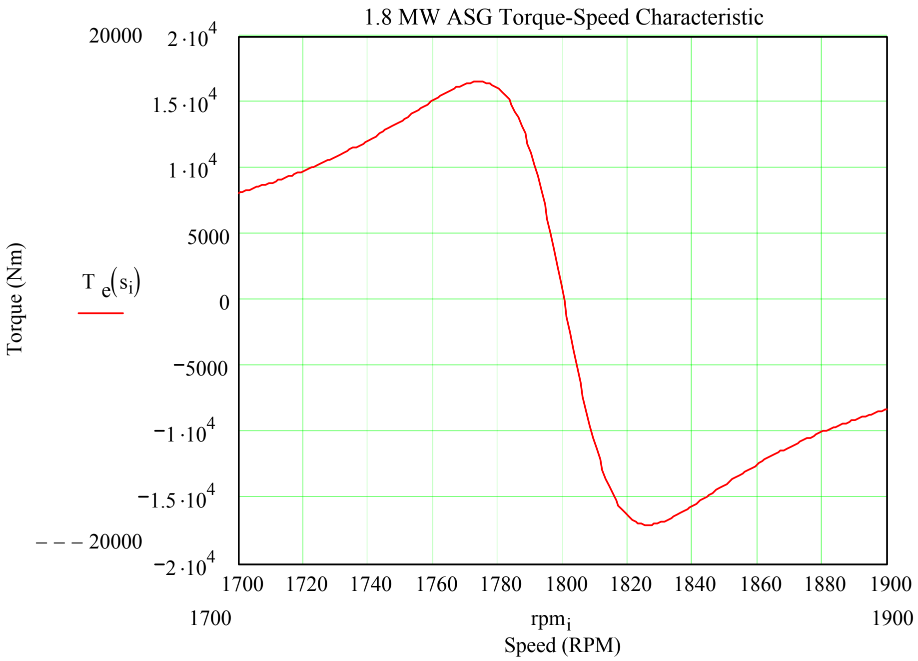

Figure 5: Torque vs. Speed characteristic for an induction machine used in a commercial wind turbine.

2.2.2.2 *Wound-Rotor Induction Generator with Scalar Control of Rotor Current*

In a squirrel-cage induction generator, the rotor "circuits" are fictitious and not accessible external to the machine, and the induced currents responsible for torque generation are strictly a function of the slip speed. The turbine shown in Figure 6 utilizes a wound-rotor induction machine, where the each of the three discrete rotor winding assemblies is accessible via slip rings on the machine shaft. This provides for modification of the rotor circuit quantities and manipulation of the rotor currents, and therefore the electromagnetic torque production. The Vestas turbines for domestic application (e.g. V47 and V80) utilize a patented system for controlling the magnitude of the rotor currents in the induction generator over the operating speed range of the turbine. The system (Vestas Rotor Current Controller, or VRCC) consists of an external resistor network and a power electronics module that modulates the voltage across the resistors to maintain a commanded rotor current magnitude. The operation of the VRCC is quite fast, such that it is capable of holding the turbine output power constant for even gusting winds above rated wind speed, and significantly influences the dynamic response of the turbine to disturbances on the grid.

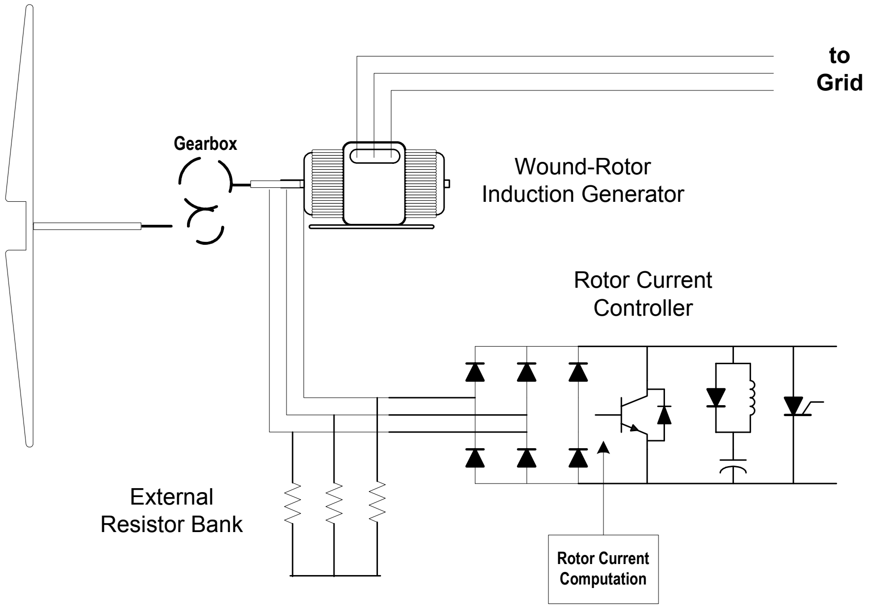

Figure 6: Configuration of a Vestas turbine for domestic application. Diagram illustrates major control blocks and Vestas Rotor Current Controller (VRCC).

The 750 kW and 1.5 MW turbines (and the 3.6 MW prototype for offshore applications) from GE Wind Energy Systems employ an even more sophisticated rotor current control scheme with a wound-rotor induction generator (Figure 7). Here, the rotor circuits are supplied by a four-quadrant power converter (capable of real and reactive power flow in either direction) that exerts near-instantaneous control (e.g. magnitude and phase) over the rotor circuit currents. This “vector” control of the rotor currents provides for fast dynamic adjustment of electromagnetic torque in the machine. In addition, the reactive power at the stator terminals of the machine can also be controlled via the power converter.

Field-oriented or vector control of induction machines is a well-known technique used in high-performance industrial drive systems, and its application to wind turbines brings similar advantages. In an earlier version of this turbine, the torque command (and therefore the magnitude of the rotor current component responsible for torque production) was linked to the speed of the machine via a “look-up” table. The field-orientation algorithm effectively creates an algebraic relationship between rotor current and torque, and removes the dynamics normally associated with an induction machine. The response of the power converter and control is fast enough to maintain proper alignment of the torque-producing component of the rotor current with the rotor flux so that the machine remains under relative control even during significant grid disturbances.

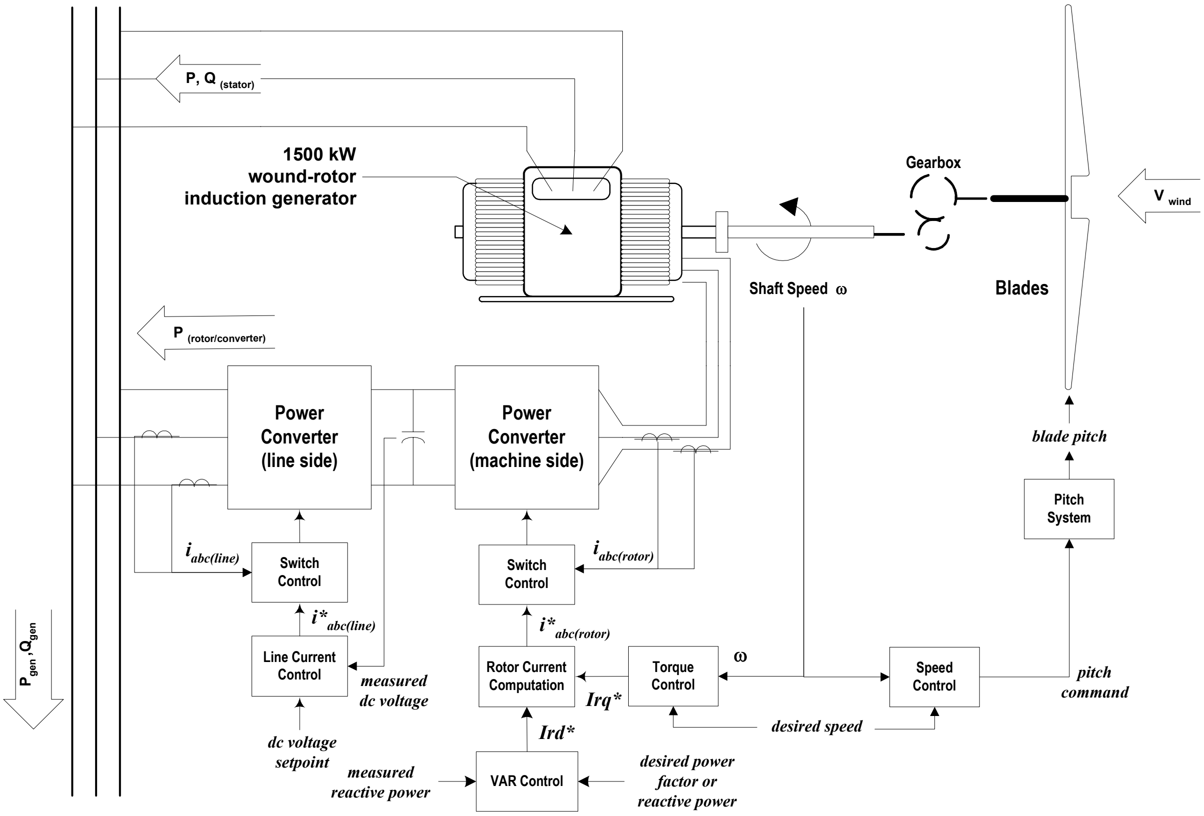

Figure 7: Configuration of GE with four-quadrant power converter supplying rotor circuit of a wound-rotor induction generator. Control blocks for torque control also shown.

2.2.2.3 *Static Interface*

The Kenetech 33 MVS, introduced commercially in the early 1990's, was the first utility-scale (i.e. large) variable-speed wind turbine in the U.S. The turbine employed a squirrel-cage induction generator with the stator winding supplied by a four-quadrant power converter (Figure 8). Because all of the power from the turbine is processed by the static power converter, the dynamics of the induction generator are effectively isolated from the power grid.

A modern static power converter utilizes power semiconductor devices (i.e. switches) that are capable of both controlled turn-on as well as turn-off. Further, the device characteristics enable switch transitions to occur very rapidly relative to a single cycle of 60 Hz voltage – nominal switching frequencies of a couple to several kHz are typical. This rapid switching speed, in combination with very powerful and inexpensive digital control, provides several advantages for distributed generation interface applications:

- Low waveform distortion with little passive filtering
- High-performance regulating capability
- High conversion efficiency
- Fast response to abnormal conditions, including disturbances, such as short-circuits on the power system
- Capability for reactive power control

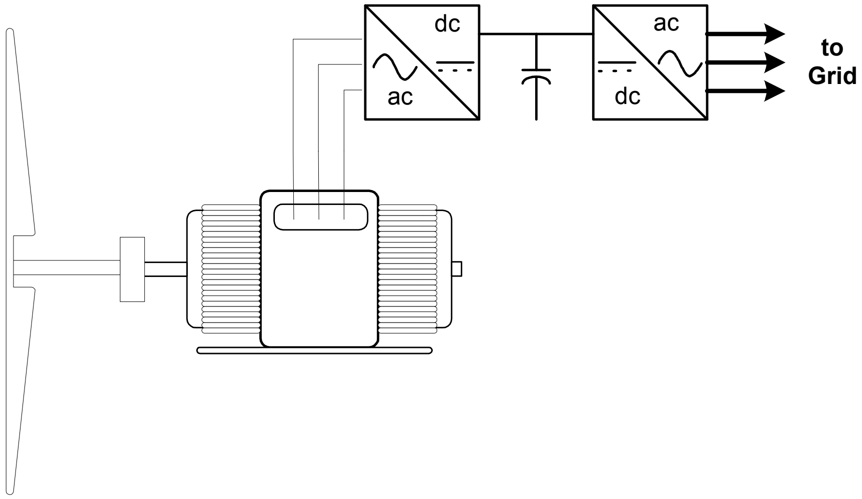

Figure 8: Variable-speed wind turbine with static power converter grid interface.

Because the effective switching speed of the power semiconductor switches is quite fast relative to the 60 Hz power system frequency, it is possible to synthesize voltage and current waveforms with very little lower-order harmonic distortion. Most modern converters easily meet limits on these harmonics found in the IEEE 519 standard.

Figure 9 depicts a simplified control schematic for a static power converter in grid-parallel operation. Since wind turbine is likely small relative to the short-circuit capability of the supply system, the voltage magnitude at the interconnect point is cannot be influenced to a great degree by the turbine. The control scheme, therefore, is designed to directly regulate the currents to be injected into this “stiff” voltage source.

The ac line voltages, dc link voltage, and two of the three ac line currents – for a three-wire connection - are measured and provided to the main controller. The ac voltage and line currents are measured at a high resolution relative to 60 Hz, so that the controller is working with instantaneous values. By comparing the measured dc voltage to the desired value, the controller determines if the real power delivered to the ac system should be increased, decreased, or held at the present value. Such a simple regulation scheme works because there is no electric energy storage in the converter (except for that in the dc filter capacitor), so the energy flowing into the dc side of the converter must be matched at all times to that injected into the ac line. If these quantities do not match, the dc link voltage will either rise or fall, depending on the algebraic sign of the mismatch.

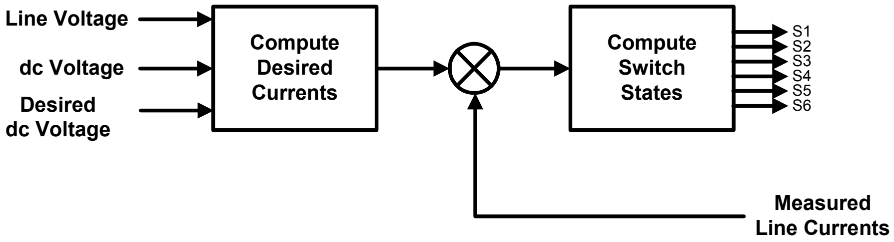

Figure 9: Simple output current control stage for a static power converter in a grid-tied DG application.

The error in the dc voltage is fed into a PI (proportional-integral) regulator to generate a value representing the desired rms magnitude of the ac line currents. Another section of the control is processing the instantaneous value of the ac line voltage to serve as a reference or "template" for the currents to be produced by the converter. The desired instantaneous value of the line current is computed by multiply the desired rms current magnitude by the present value from the template waveform. In the next stage of the control, often times called the "modulator" section, the desired instantaneous value of line current is compared to the measure value (in each phase). The modulator then determines the desired state of the six switches in the matrix based on the instantaneous current error in each phase of the line currents. The states are transmitted to the IGBT gate drivers, which then implement the state of each IGBT in the matrix as commanded by the controller. The process is then repeated at the next digital sampling interval of the overall control.

The process is repeated thousands of times per single cycle of 60 Hz voltage. By using the line voltage as a template for the shape of the currents to be synthesized, synchronism is assured. Additionally, if there is no intentional phase shift introduced in the control calculations, the currents will be almost precisely – save for small delays introduced by the control itself - in phase with the line voltages, for unity power factor operation.

Figure 10 depicts the output of a current-regulation scheme that might be employed in a grid interface converter in a wind turbine. Here, the modulator will only change the state of the switches if the absolute value of the difference between the desired and actual line currents exceeds a certain value. The small errors that are continually corrected by the action of the converter control are clearly visible. Because of the high switching speed, however, the distortion of the current waveform is very low, well within IEEE 519 limits.

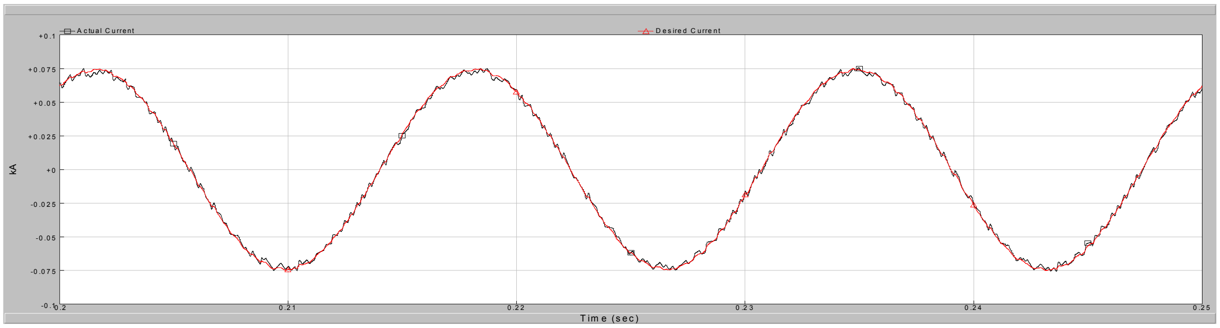

Figure 10: Static power converter output current showing reference (desired) current and actual current.

By modifying the control scheme just described to incorporate a commanded "shift" in the reference or template waveforms, reactive power flow to or from the line may also be controlled. Since the net energy flow from the reactive currents is zero (apart from very small conductive and switching losses), the dc voltage will be unaffected. Reactive power may be adjusted independently of real power flow up to the thermal limits of the switches and passive components in the converter. Reactive power generation with zero real power is also possible.

The significance of the previous discussion from the modeling perspective is that, unlike rotating machinery whose behavior is bound by fairly well-know physical principles, the response of the wind turbine static power converter equipment to events on the power system is almost entirely dictated by the embedded control algorithms. How a static power converter contributes to short-circuits, for example, cannot be deduced from the topology or values of passive elements such as tie inductors or dc link capacitors.

2.3 Grid Interface

Current commercial wind turbines use low-voltage generators (<1000 V), and connected to the medium voltage public distribution feeder or wind plant collector system through a three-phase transformer. The transformer connection may is usually wye on the low-voltage side to serve turbine loads. The medium-voltage side may be either wye or delta. The transformer may be supplied by the turbine vendor, and in some cases can be located "up tower" – in the nacelle of the turbine to reduce cabling losses. Pad-mount transformers near the base of the turbine tower are also common.

All commercial wind turbines have either power factor correction or some type of power factor control. Direct-connected induction generators and those with scalar rotor current control use staged/switched shunt capacitors to correct power factor across the operational range of the turbine.

Advanced machines are capable of power factor control via the advanced rotor power converter. The converter itself may have a small L-C network on its terminals for filtering noise resulting from the fast operation of the semiconductor switches.

2.4 Protection Systems

Commercial wind turbines incorporate sophisticated systems for protection of electrical and mechanical components. These turbine-based systems respond to local conditions, detecting grid or mechanical anomalies that indicate system trouble or potentially damaging conditions for the turbine. Some are computer-based, as with those associated with the high-performance static power conver, or run as algorithms in the master turbine controller, and therefore can respond almost instantaneously to mechanical speed, vibration, voltages, or currents outside of defined tolerances.

In addition, conventional multi-function relays for electric machine protection are also provided to detect a wide variety of grid disturbances and abnormal conditions within the machine.

3 WIND PLANT DESIGN AND CONFIGURATION

Wind turbines are just one (albeit an important) component of bulk wind plants. With individual turbine sizes now exceeding 1 MW, nameplate ratings for single wind plants of many tens to hundreds of MW are common. The geographic extent of the wind plant must be large enough to not only accommodate the dozens to a hundred or more turbines, but also allow optimal spacing and utilization of local terrain features that will maximize energy production. The infrastructure for connecting a large number of widely distributed turbines to a single point of interconnection with the transmission system has important influence over the electrical characteristics of the wind plant.

The installed and proposed utility-scale wind plants in the U.S. have some common design characteristics that offer potential simplifications for constructing aggregated models for transmission system studies. These commonalities stem from practicalities and optimizations regarding the local wind regime, micro-siting of individual turbines, electric system design, and operations and maintenance economies. The result is that, from the power system modeling perspective, large wind plants have the following features in common:

A single turbine type – Since wind turbines are complex machines that require preventative, predictive, and on-demand maintenance to achieve the highest availability, it is better from a maintenance and operations perspective to utilize the same turbine throughout the wind plant and have a maintenance and operations staff that specializes in all aspects of this single turbine design.

- **Medium voltage collector systems and interconnect equipment** – The electrical infrastructure which "collects" power generated by each turbine in the plant and delivers it to the transmission system utilizes standard overhead and underground medium voltage (15 to 35 kV) equipment and design practices. Some variations from standard utility practice for medium voltage design are necessary, however, as the operation of wind turbines varies significantly from the distributed end-use loads for which the utility practice is optimized. For example, voltage regulation and protection schemes must be modified to account for generation, rather than load, distributed along the collector lines. The collector lines are an integral part of the wind plant; i.e. they are not utilized to serve non-wind plant load or other electric utility customers.
- **Reactive compensation** – Maintaining voltages within tolerances at individual turbines within a wind plant while at the same time meeting power factor or voltage regulation requirements at the point of interconnection with the transmission system requires careful management of reactive power. Typical locations for reactive power compensation within a wind plant are 1) at each individual turbine, dependent on the reactive power requirements and characteristics of the rotating machinery in the

turbine; 2) at the interconnect substation in the form of switched shunt capacitor banks; and 3) at locations along the medium voltage collector lines depending on the layout of the plant. Some plants have the ability to dynamically control reactive power from each turbine, which offers the possibility of reactive power management for transmission system considerations to be accomplished by the turbines themselves. Terminal voltages at individual turbines, however, may be a constraint on the amount of reactive power that can be delivered to the interconnect substation during periods of high wind generation. In addition, when reactive power is required at the point of interconnection to the transmission network to support voltage, substantial reactive power may be "lost" in the medium voltage collector system between individual wind turbines and the interconnect substation.

- **SCADA and Plant Control** – Large wind plants typically have fairly extensive means for remote operation of individual turbines and collection of high-resolution operating data. Interfaces to power system operations centers are also being implemented, allowing automated implementation of control area operator commands during certain system conditions – e.g. automatic curtailment.

The most important influence of the wind plant infrastructure on the interconnection bus bar characteristics of the wind plant is on the net reactive power capability of the wind plant. Voltage profiles along the collector lines are an internal issue. For purposes of characterizing the plant for transmission studies, the static, dynamic, and load-dependent effects of the collector system on the net reactive power at the interconnection substation must be characterized. Figure 11 illustrates this influence with an example from an operating wind plant. Wind plant generation and net reactive power requirements are shown as functions of wind speed. In the figure, the net reactive power is entirely a function of reactive losses in the lengthy overhead collector lines, since the turbines are assumed to be operating at unity power factor. The stepped line shows how staged shunt capacitor banks on the collector lines might be deployed to account for this load-dependent reactive loss. Not shown on the diagram is how such as scheme would contribute to the dynamic nature of the plant. As wind speed – and power output – vary, so will the net reactive requirements. Details of the capacitor switching scheme are critical here, since there will be time delays and hysterisis associated with the capacitor bank controls. These parameters must be selected with some knowledge of the time variation of wind generation on the collector line to prevent unnecessary capacitor switching operations and potentially associated voltage flicker.

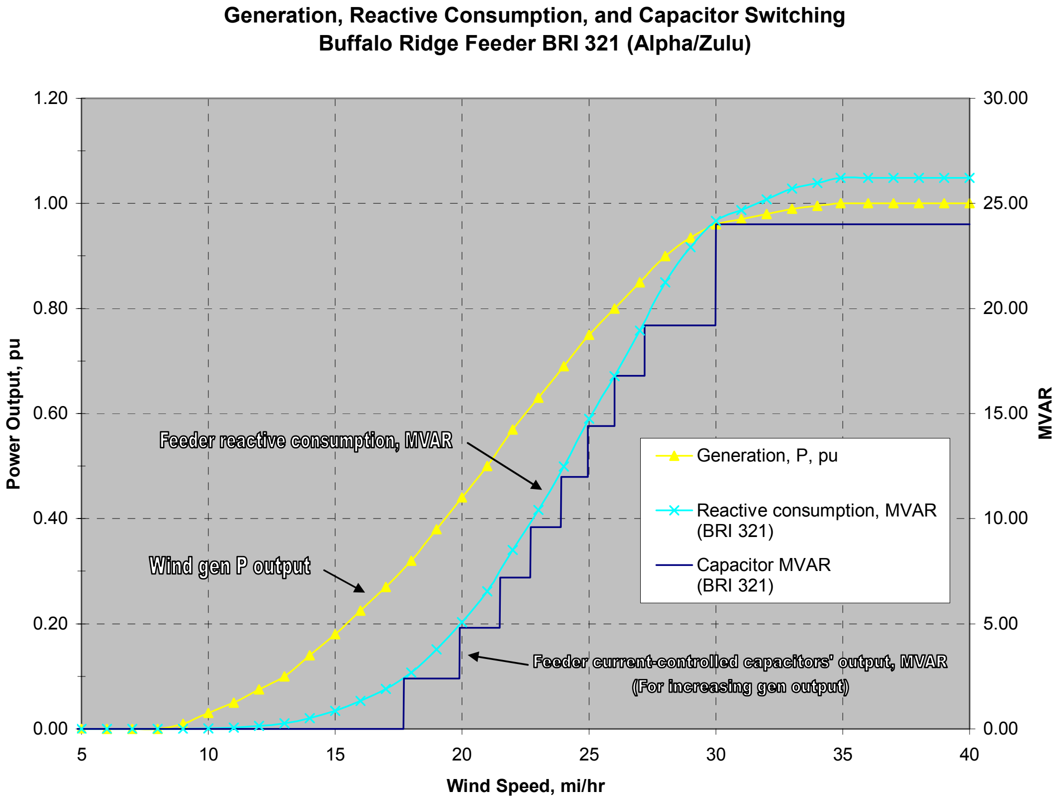

Figure 11: Illustration of the impact of collector line reactive losses on the net reactive power capability of a large wind plant.

4 WIND PLANT PERFORMANCE CHARACTERIZATION FOR POWER SYSTEM STUDIES

Models that capture the aggregated behavior of all components in a wind plant as seen from the interconnection point to the transmission network are the most useful and sometimes practically required for large power system studies. This section

4.1 Steady-State and Small-Signal Behavior

For power flow calculations, a wind plant can obviously be represented as a single generating unit at the interconnection substation. Determining the equivalent "reactive capability" of the plant, however, can be complicated since it will be a function of a large number of elements within the plant – turbine reactive compensation, reactive losses in collector lines, auxiliary compensation equipment such as collector line capacitor banks, etc. While fairly standard and well-known for conventional generating units, this characteristic has not been considered explicitly for many of the plants developed over the past decade.

Net reactive power is also a function of voltage if shunt capacitors are present as part of the plant reactive compensation scheme.

The dynamic nature of the wind resource can introduce a new dimension to power system studies, especially where the transmission interconnection is weak. Reactive power support for maintaining target voltages at the transmission interconnection will vary with the real power injected. Temporal variation of wind plant aggregate power is a very complicated function of a number of plant parameters and variables, but it also can be a defining factor for the dynamic characteristics of the reactive compensation system.

Additionally, the reactive compensation devices within the plant – turbines (shunt capacitors or advanced control), collector line capacitor bank, and possibly interconnect substation-based deviced – are dynamic devices themselves, with set points and delay for toggling on or off of switched devices and continuous control for static var capabilities.

Some of the factors that influence the variability of the aggregate production of a wind plant include

- Variations in wind speed at each turbine location in the plant;
- Topographical features that introduce turbulence and shear into the moving air stream across the geographical expanse of the wind plant;
- The mechanical inertia of individual turbines, which influences how the wind speed variations, turbulence, and wind shear affect the output of individual turbines

- The wind turbine control scheme, including the generator control and pitch regulation systems that determine how the electric power at the terminals of the turbine is influenced by fluctuating prime mover input;
- The number of turbines within the plant, since a larger number of turbines implies a larger geographical area for plant, and more statistical diversity in the local characteristics that contribute to output fluctuations;
- The grouping of turbines within the plant – if turbines are grouped into "strings", rather than more uniformly distributed over the area of the plant, local fluctuations in wind speed will affect more than a single turbine at an instant of time.

Wind generation is often characterized as "intermittent", but, to better understand how it can impact power system operations, it is useful to consider the output variability is more detail.

On the shortest time scales, say tens of seconds to minutes, the output of a wind plant can fluctuate because of varying wind speeds at the individual turbines comprising the plant due to effects of terrain and turbulence in the moving air stream. This is more likely the case in light to moderate winds, as modern wind turbines are capable of holding the output power "flat" for wind speed at or above the rated value. Measurement data shows that the fluctuations on this time scale as a fraction of the plant rating decrease in magnitude as the number of turbines in the plant increases.

Over longer time periods – tens of minutes to hours – wind plant generation will again exhibit fluctuation, and may also trend down or up as the larger scale meteorology responsible for the wind changes. Passage of a weather front is an example. Experience is showing that these trends can be predicted, but the accuracy of the prediction degrades quickly with time. Forecasts for the next hour, for instance will be much better than those for several hours ahead.

Longer-term forecasting for the next day or week is even less accurate, especially when timing is important. Predictions of a weather front passing an area tomorrow can be relatively accurate, but the accuracy for predicting which hour it will pass will be much lower.

"Intermittent", as the term is applied to wind generation, encompasses both the fluctuating characteristics along with the degree of uncertainty about when the resource will actually produce. Both of these attributes are important for power system engineers and operators who have come to understand well the fluctuations and uncertainties inherent in conventional generating resources and system loads. Because wind generation is new, these characteristics are only beginning to be quantified, and procedure for dealing with them remained to be developed.

As of this writing, there are no practical analytical methods for characterizing the output fluctuations from a large wind plant. Direct measurements from operating wind plants are providing some important insights into the complicated interaction of the factors listed above. The National Renewable Energy Laboratory (NREL) launched a program in CY2000 to collect high-resolution electrical measurement data from operating wind plants across the U.S.

4.2 Dynamic Response

The electrical and mechanical technologies which comprise commercial wind turbines differ dramatically from the familiar synchronous generator and auxiliary systems that are used to represent almost all conventional generating equipment. And, instead of a small number of very large generating units, bulk wind plants can be made up of a very large number of relatively small machines. Until quite recently, these attributes have presented a difficult challenge to power system engineers engaged in evaluating transmission system impacts of large wind generation facilities.

Evaluating the dynamic response of the electric power system during and immediately following major disturbances such as faults is a critical engineering function for ensuring system security and reliability. Now that wind plants make up a non-negligible fraction of the generation assets in some control areas, their contribution to the system dynamic performance must be considered.

When subjected to a sudden and substantial change in terminal voltage or frequency, both the mechanical and electrical elements of the turbine along with the associated control systems influence its behavior. Consider the doubly-fed induction generator with flux vector control of torque via the power converter on the rotor circuit. When a fault on the transmission network causes the voltage at its terminals to sag to some fraction of normal,

- The magnitude of the main flux in the machine begins to decay in response to the reduced terminal voltage, and the position of the flux vector may suddenly change if there is a phase shift associated with the fault voltage
- The rotor power converter control instantaneously adjusts the quadrature axis rotor currents to "line up" with the new rotor flux vector.
- Since the rotor flux is not longer at the pre-fault value, the stator power of the machine is reduced accordingly. In response, the power converter control may try to increase the torque-producing component of rotor current.
- Because the electrical power output of the machine is now lower than the pre-fault value, there is net accelerating torque on the mechanical system which will increase the rotational speed of the machine.
- The increased rotational speed will cause the turbine blades to begin pitching to reduce the mechanical torque input to the machine and reduce speed

- When the fault is cleared and the terminal voltage returns to near normal, the rotor power converter control will readjust the position of the rotor current vector to again line up with the rotor flux vector
- Electric power output will jump back to (or slightly above, if the rotor current had been increased by the controller during the fault) the pre-fault value. Since mechanical power had been reduced by the pitch system, net decelerating torque on the mechanical system will cause rotational speed to decrease.
- The sudden changes in electromagnetic torque applied by the generator to the rotating shaft (at fault inception and clearing) excite the main mechanical resonance between the turbine blades and the generator inertia, such that these masses are now oscillating out of phase around the average speed of the rotating system.
- The oscillations in generator speed may be fed through the control system to produce oscillations in electric power at the stator terminals of the machine.

While there are similarities to the response of a synchronous generator to the same disturbance, the markedly different equipment and control comprising the wind turbine lead to a difference dynamic response. While the sequence above is only an example for one type of wind turbine, it is indicative of the behavior that needs to be represented in dynamic simulations of the entire power system.

In addition, the response described is for a single turbine. What is important from the perspective of the power system is the aggregate response of all the turbines in the wind plant, along with the influence of any other dynamic elements such as static compensation or switched elements.

Research is only beginning into electro-dynamic equivalents for wind plants. There is agreement on a few general guidelines and principles for developing these dynamic equivalents. For remote disturbances – those originating on the transmission network, not within the wind plant itself – individual turbines can be considered coherent, i.e. they response as if they were a large single machine of equivalent aggregate rating. This assumption is based on all turbines being of identical type and parameters, and that they "see" the disturbance at precisely the same instant and in roughly the same degree.

With some turbine technologies, there are nonlinearities in certain of the control blocks such that the response may be dependent on the pre-fault conditions at the turbine, namely the assumed generation level as a fraction of the rated value. If maximum generation conditions are being studied, then all turbines at the same pre-fault generation level is a good one. If for some reason partial generation conditions are of interest, aggregate dynamic performance of the plant could depend on how the total generation is allocated to individual turbines.

Because of the extensive medium voltage collector system that is part of many large wind plants, there is potentially an issue with differing pre-fault terminal voltages at turbines dependent on generation level and electrical location within the plant. And, as with the steady-state and small signal characterizations, the response of the plant in terms of reactive power may also be difficult to capture, unless the behavior at the interconnection bus bar is dominated by a single device such as a static var compensator located at the substation.

Fortunately, most of these detailed questions are of likely of secondary importance, especially where the focus is on the power system as a whole and not some particular aspect of the wind plant response. Until new research findings indicate otherwise, relatively simple dynamic equivalents consisting of a single or small number of equivalent machines at the interconnection substations is the recommended approach.

4.3 Transient

Dynamic simulations and studies of the interconnected power system are based on a number of assumptions that allow some simplifications in the representation of the dynamic components of the system. For some investigations, such simplifications are not valid or can obscure the aspects of the system model critical for the study.

Studies of sub-synchronous torsional interaction, control interactions, inadvertent islanding, etc. may requires models with more detail than those used for system dynamic studies. Full transient models of all but the simple wind turbine technologies require information and engineering detail that can only be obtained from the wind turbine manufacturer. Studies of these types should be conducted collaboratively with technical personnel from the turbine designer.

4.4 Short Circuit Contributions

Little guidance exists for calculating short-circuit contributions from large wind generation facilities. Analytical approaches are complicated for the following reasons:

- Commercial wind turbines employ induction machines for electromechanical energy conversion, which do not strictly conform to the standard procedures and assumptions used in calculaton of short-circuit contributions on the transmission network.
- Generator control technologies employed in wind turbines– e.g. scalar or vector control of rotor current in a wound-rotor induction machine - can substantially modify the behavior of the induction machine in response to a sudden drop in terminal voltage, further complicating calculation of terminal currents during such conditions
- Windplants are composed of large numbers of relatively small generators, interconnected by an extensive medium-voltage network that itself influence fault contributions

The short-circuit behavior of a squirrel-cage induction generator is fairly well known, and procedures are spelled out in the technical literature (such as the IEEE Brown Book) for considering these machines in short-circuit studies. These recommendations, however, apply most directly to fault studies within large industrial facilities, and may require adaptation for transmission system fault studies.

In the remaining cases of the wound-rotor induction machines, the external components and accompanying control have very significant influence on the machine under network fault conditions, assuming that the control systems themselves are not bypassed or rendered inoperative as a consequence of reduced terminal voltage at the turbine.

The following paragraphs are intended as a qualitative description of the characteristics of the various wind turbine generator technologies under network fault conditions.

4.4.1 Direct-Connect Squirrel Cage Induction Generator

Induction generators are essentially induction motors that are driven at speed above their nameplate synchronous speed by some prime mover. Magnetic excitation necessary for torque production and power flow is drawn from the power supply system. The electric current necessary for magnetizing the iron core is responsible for much of the reactive power required by an induction machine.

When the source of excitation is removed from an induction machine, the main flux field collapses and torque production or power flow is no longer possible. It does take a finite amount of time for this field to collapse, however, during which time an induction machine will contribute current to a short-circuit on the power system. Also, if voltage is just reduced rather than removed completely as the result of a downstream fault, the main flux will decay to some new value, but provide necessary excitation for the machine to contribute to the fault. Contributions from induction motors are rarely considered in utility fault studies, but can be an important consideration for protective device coordination and rating within some industrial facilities. The IEEE Brown Book (Standard 399-1997) "IEEE Recommended Practice for Industrial and Commercial Power Systems Analysis" details procedures for calculating induction motor and generator contributions to short-circuits within facilities.

Figure 12 illustrates the behavior of a wind turbine employing a line-connected induction generator during a fault on the supply network. In the first cycle following fault inception, stator currents quickly build up to a value several times the rated current of the machine. The contribution during the first cycle can be estimated as the sum of: 1) a sinsusoidal component approximately equal to the pre-fault terminal voltage divided by the sum of the subtransient reactance of the generator and the reactance of the equivalent network to the point of fault, and 2) a uni-directional (dc) component that depends on the reactance to resistance (X/R) ratio of the equivalent system impedance and the precise point on the terminal voltage wave where the fault is initiated. Both components decay in magnitude as the fault persists. The dc component decays at a rate governed by the X/R ratio. The decrease in the magnitude of the sinusoidal component is due to the decay in the main flux of the machine.

After a few cycles, the dc component has vanished, and the sinusoidal component has decreased in magnitude. It should be noted here that precise calculation of the short-circuit contribution requires a time-domain computer simulation with a relatively detailed differential equation representation of the induction machine. The aforementioned IEEE Brown Book acknowledges as much, and prescribes an approximate method for defining two equivalent reactances for the induction machine – one to be used for calculating the first cycle contribution, the other for a later time during the fault that would be associated with breaker clearing or interrupting requirements.

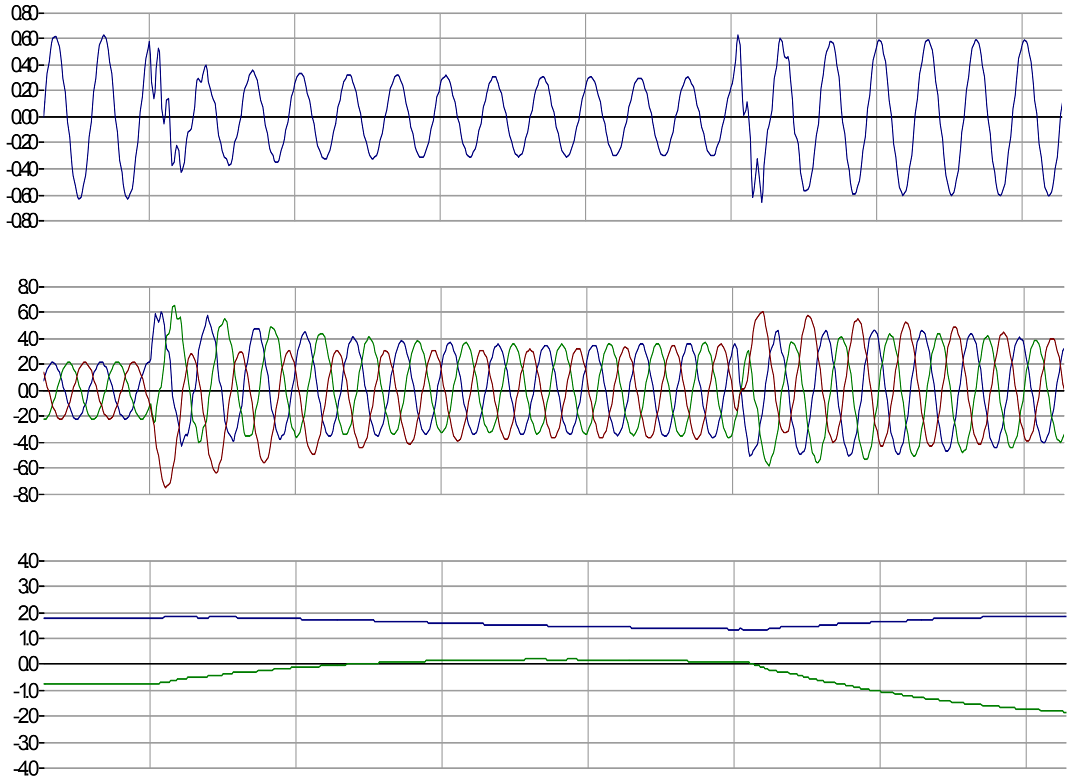

Figure 12: Contribution by a 2.0 MVA induction generator to a symmetrical three-phase fault. Shown are voltage at the machine terminals (top), stator currents (middle), and real and reactive power (generator convention) at the machine terminals (bottom).

4.4.2 Doubly-Fed Induction Generator with Vector Control of Rotor Currents

The 1.5 MW wind turbine from GE and its predecessor, the 750 kW turbines from Enron, are also based on a wound rotor induction generator. In these turbines, however, the rotor circuit is powered by a bi-directional static power converter. The fast response of the power converter coupled with sophistical algorithms in the turbine and converter controller sections allows for precise and continuous adjustment of the instantaneous currents in the rotor circuits of the induction machine. Nearly instantaneous control of electromagnetic torque and turbine power factor is possible with this scheme.

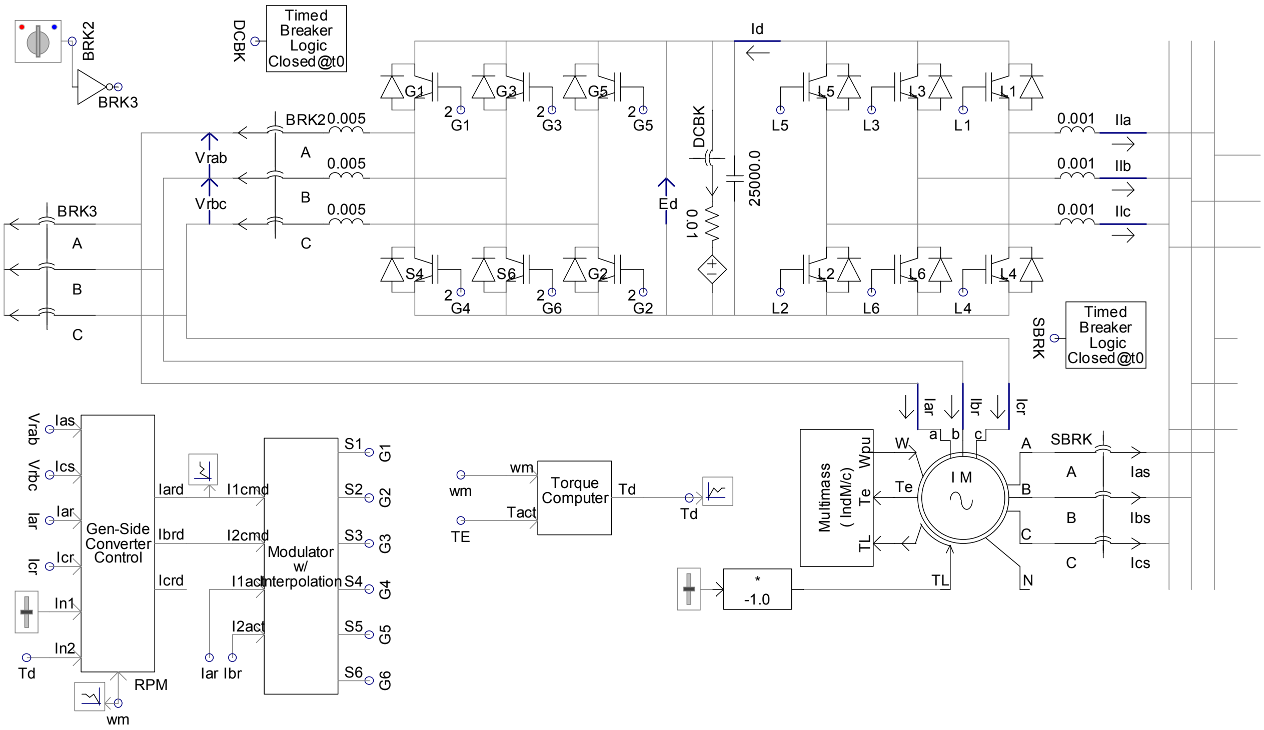

Figure 13: Transient mode of a doubly-fed induction generator with vector control of rotor currents.

The fast action of the turbine and converter controls can limit the stator currents during a fault on the grid. Figure 14 details the turbine operation during a 150 ms grid fault. When the fault is initiated, the sudden change in terminal voltage magnitude and phase angle causes the power converter to momentarily "lose control" of the rotor currents, which is manifested as a one-quarter cycle "surge" in the stator current. Control is regained quickly, and the stator currents settle down to near their pre-fault value for the duration of the fault event (The slight rise in stator current magnitude during the fault is due to control actions attempting to restore the electromagnetic torque to the pre-fault value). When the fault is cleared, the phase and magnitude of terminal voltage again change suddenly, inducing another short-duration transient in the stator current. Again, however, control is regained, and stator currents return to the level desired by the turbine control.

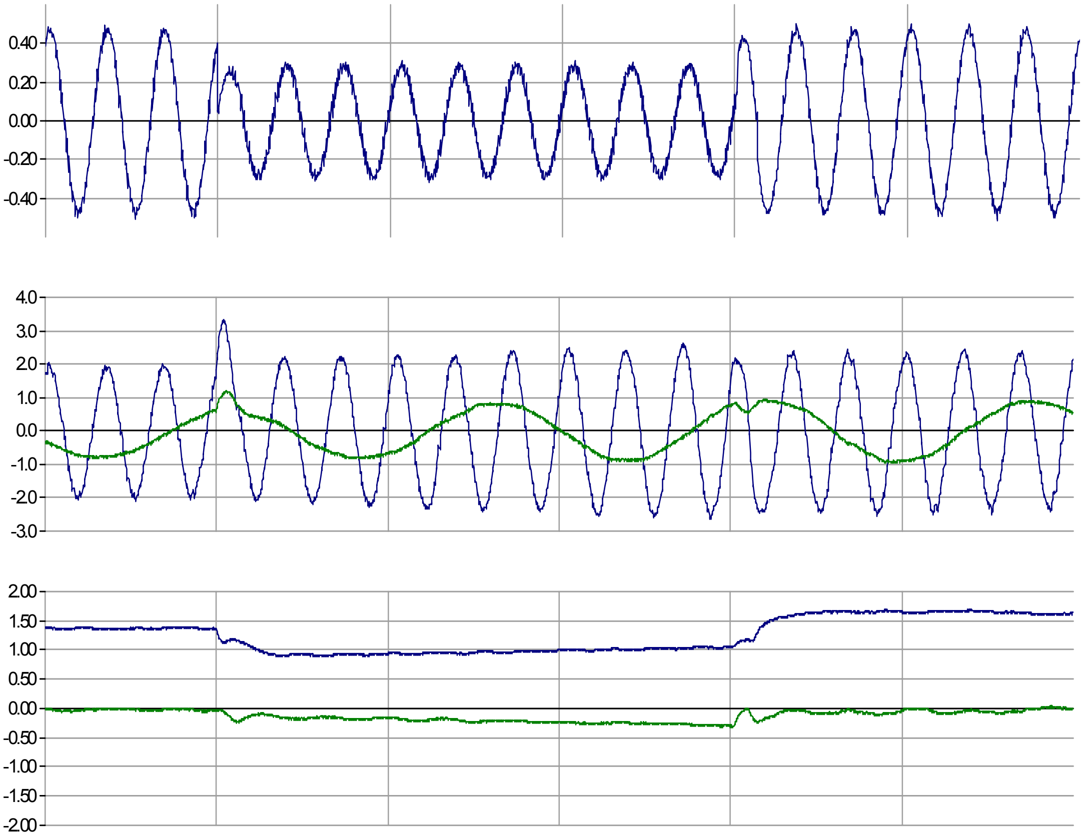

Figure 14: Short-circuit contribution from the GE 1.5 MW wind turbine for 150 ms grid fault. Shown are voltage at the machine terminals (top), stator currents (middle), and real and reactive power (generator convention) at the machine terminals (bottom).

It should be noted, however, that if the rotor power converter is bypassed, such as might be done to protect it from high rotor circuit voltage, the behavior of the turbine during the fault would be better characterized as a conventional induction machine. GE Power System Energy Consulting has developed an internal white paper specifying how the GE Wind Turbine would perform under conditions of rotor converter bypass.

5 WIND GENERATION TECHNOLOGY AND APPLICATION TRENDS

The turbine types described in Chapter 2 have served the U.S. wind industry from the beginning of the explosive growth in the mid 1990's. Newer, bigger turbine models have been introduced along the way, but the technological improvements and modifications in the new commercial introductions have not changed the basic electrical behavior of the turbines.

Reducing the cost of energy is still today the primary driver for ongoing developments in wind turbine technology. Experiences from large wind projects are, however, beginning to influence wind turbine developments, and are expected to have even more impact going forward. Wind turbine vendors now recognize that some features and enhancements to the electrical performance of their products are or will be demanded by customers and are critical for further expanding the overall market potential for wind generation in the U.S.

Wind plant design is always undergoing some evolution. Plant operators and project developers are gaining important experience from the first generations of large wind plants developed since the mid-1990's. Awareness is growing of the importance of the portion of the wind plant between the turbines and the interconnection point to the transmission network to plant availability, turbine performance, and successful operation with the grid.

Finally, with wind generation becoming a visible fraction of the generating assets in some control areas, transmission service providers are beginning a push for more stringent wind plant performance requirements and interconnection standards.

These influences will have a positive impact the characteristics of wind generation facilities as viewed from the transmission network over the coming years. This section describes technological changes that will lead to new wind plant features and capabilities over the coming years that will affect electrical performance and integration with the grid.

5.1 Wind Turbine Technology Trends

The value of variable speed technology for large wind turbines has been proven in the marketplace over the past decade, and will be the predominate technology going forward. Variable speed operation has benefits in terms of managing mechanical loads on the turbine blades, drive train, and structure. The grid-side benefits are also significant, and include dynamic reactive power control, increased dynamic control over electric power generation, and opportunities for further enhancement of grid-integration features of the turbine.

5.1.1 Topology

At present, the doubly-fed induction machine topology is favored both in the U.S. and globally. As the size of individual turbines continues to grow, there is an emerging consensus that future turbines will likely employ machines other than induction generators, possibly advanced synchronous or permanent magnet designs. For variable speed operations, these new machines will require that all of the electrical output flow through some type of power converter. This converter would almost completely define how the turbine "looks" to the power system, offering some new opportunities for improving interconnection and integration.

5.1.2 Electrical Robustness

Wind turbine vendors are now well aware of the need for improving turbine electric robustness, especially in terms of the ability to ride-through faults on the transmission system. Enhanced low-voltage ride through is already and option for several commercial turbines, and will likely be a standard feature in the coming few years. Farther down the road, it is expected that wind turbines will be no more sensitive in terms of tripping for transmission system faults than conventional generators, and will provide flexibility with respect to "programming" their shutdown modes for grid events.

5.1.3 Reactive Power Control

Dynamic reactive power control is an important feature, and provides the plant designer with an additional tool for managing collector line voltage profiles within the plant and the overall reactive power characteristics of the plant. It should be recognized, however, that turbine-based reactive power control is not a "magic bullet", especially in cases where reactive power is required to support the transmission system, since in this situation the reactive power is being produced as far away as possible from where it is needed. The fast dynamic response of turbine-based reactive compensation may be very important, however, for assisting with system voltage recovery following faults.

To realize the full value for dynamic reactive power control, future wind turbines must be able to make reactive power available even when not generating.

5.1.4 Real Power Control

At present, commercial wind turbines generally operate to maximize energy production. When winds are at or above the rated speed, electrical output is "capped" at the nameplate rating. In light to moderate winds, however, the turbine is operated to capture as much energy as possible, such that the output will fluctuate when wind speed fluctuates.

These fluctuations are not optimal from the perspective of the grid, as they can lead to voltage variations and potentially increase the regulation burden at the control area level. In future generations of wind turbines, it will be possible to "smooth" these fluctuations to a greater degree than is achieved now with mechanical inertia alone. More sophisticated pitch regulation schemes, improve blade aerodynamic designs, wider operating speed ranges may provide a way to limit the short-term changes in turbine output while at the same time minimizing the loss of production. Such a feature could be enable only where and when it has economic value in excess of the lost production.

Extending this type of control would allow wind turbines to participate in Automatic Generation Control (AGC). In this mode, the turbine would have to operate at a level somewhat below the maximum available from the wind to provide room for "ramping up" in response to EMS commands. Again, the value of providing this service would have to be evaluated against the cost in terms of lower production as well as the cost of procuring this service from a different source. Technically, though, such operation is possible even with some of the present commercial technology.

5.1.5 Dynamic Performance

The dynamic characteristics of the more advanced commercial turbine technologies are complicated functions of the overall turbine design and control schemes. Little consideration has been given thus far to what would constitute desirable dynamic behavior from the perspective of the power system. Much of the attention to date in this area has been focused on the ride-through question. Once that matter is resolved, there may be opportunities to fine-tune the dynamic response of the turbine to transmission network faults so that it provides maximum support for system recovery and enhances overall stability.

Given the sophistication inherent in the topology and control schemes of future wind turbines, it should be possible to program the response to a degree to achieve such stability benefits. Such a feature would allow a wind turbine / wind plant to participate in a wide-area Remedial Action Scheme (RAS) or Special Protective System (SPS) as is sometimes done now with HVDC converter terminals and emerging FACTS devices.

5.2 Wind Plant Design and Operation

Realizing the benefits of enhanced capabilities of wind turbines will depend in large part on the overall wind plant design, since the actions of a large number of relatively small wind turbines must be coordinated to have positive impacts on the overall power system.

5.2.1 Reactive Power Management and Dispatch

Because of the fast pace at which the wind industry has emerged and grown over the last decade, the reactive power characteristics of a wind plant are more often than not an "outcome" rather than a design requirement. With more stringent interconnection requirements, more attention and analysis will be given to this topic for plants built over even the next few years. The required reactive power capability of a wind plant will be determined from the results of the interconnection study, and will drive the overall wind plant design, possibly impacting even turbine selection.

Where the transmission system interconnection is weak or vulnerable, there will be more use of auxiliary equipment such as static var compensators. As design experience accumulates, the ability of the wind plant to provide for the needs of the transmission system at the point of interconnection will be much improved.

5.2.2 Communications and Control

The communications and control infrastructure of even present-day wind plants is quite sophisticated, with high-speed SCADA to each turbine and other critical devices or points within the collector system. This sophisticated infrastructure has yet to be exploited for purposes of improving the interconnection performance and integration of the wind plant with the power system; mostly it has been used for maximizing plant production and availability.

In the future, this infrastructure will be the foundation upon which many of the advanced features and capabilities will be based. The interface between the wind plant control center and power system control area operations will also be developed to a much higher degree. Advanced wind plant performance such as AGC participation will likely be accomplished by the control area EMS interacting with the wind plant control center, rather than from EMS to individual wind turbines. Such an interface would also facilitate other plant capabilities that could benefit power system security and reliability, such as automatic full- or partial-curtailment of wind generation under severe system contingencies.

5.2.3 Wind Plant Production Forecasting

While the fast fluctuations in wind plant output can create problems with respect to voltage flicker and reactive power management, somewhat longer term fluctuations in wind plant production appear to be of the most consequence for control area operators. More specifically, the uncertainty over what wind plant production will be during the next hour, or by hour for the next day is the major question. Planning conservatively to cover a possible reduction in wind plant generation results in higher reserve margins and higher cost if not needed. Backing down economic generation to accommodate a sudden increase in wind generation can also increase costs.

All of the analytical studies of the impacts of wind generation on power system operations have one theme in common: Better predictions of what wind generation will do at some time in the future allow the control area operators to better plan for the most economic set of resources to meet the remaining load. Much research work is ongoing in the area of wind production forecasting, and at least two commercial services have been launched to assist wind plant operators with sophisticated meteorological and statistical methodologies for improving the accuracy of production forecasts.

Wind generation forecasting has already been incorporated into the market rules for the California ISO, in exchange for preferable treatment with respect to settlement of imbalance energy and unscheduled deliveries. Continued focus on wind generation forecasting as a way to mitigate the uncertainty in future wind energy deliveries are expected to improve the science and methods that underlie these systems.

Assumptions about the ability to forecast wind generation at some time in the future can make a critical difference in the analysis of wind generation of power system operations and control. On shorter time scales, say for the next hour, the uncertainty about average wind speed will be smaller, so the variations in wind plant production compared with an average or scheduled value have more to due with the variability of the resource over the expanse of the wind plant and the factors discussed previously. As the forecast moves out into the future, the meteorological details take precedence.

An annex to this document describing the recommended wind generation forecast accuracy assumptions for the NYSERDA assessment will be provided.

6 POWER SYSTEM STUDY MODELS FOR BASELINE AND HORIZON YEAR WIND PLANTS

Recommended assumptions for wind turbine and wind plant characteristics for the NYSERDA system assessment are described in this section. For each category, baseline characteristics to be adopted in the initial year of the study, and the horizon year (2013) of the study are described. The NYSERDA SPC will provide guidance as to the technology mix to be assumed for identified wind generation facilities in the study scenario once defined.

6.1 Turbine and Wind Plant Characteristics

The turbine and wind plant technical characteristics recommended by the SPC for the NYSERDA assessment are described in Table 1.

Table 1: Wind Turbine and Wind Plant Characteristics for NYSERDA Study Baseline and Horizon Years

Attribute/Characteristic	Baseline (CY2006)	Horizon (CY2013)
Turbine Characteristics		
Individual Turbine Size	2 MW	4 MW
Generator Type and Control	Doubly-Fed Induction Generator with Flux-Vector Control of Torque and Stator Reactive Power	Permanent Magnet or other Synchronous Generator coupled to line via full-rated power converter
Operating Speed Range	Limited variable speed range of 0.9 to 1.3 per-unit of rated turbine speed	Wider speed range of 0.5 to 1.5 per unit
Mechanical Power/Torque Control	Blade pitch control	Advanced blade pitch control
Dynamic Characteristics		
Terminal voltage window	Turbine will trip if : v < 30% for more than 100 ms, or v < 70% for more than 300 ms, or v > 110% for more than 1 s v > 113% for more than 300 ms, or v > 120% for more than 100 ms	Turbines meet operating voltage criteria for conventional generators; trip thresholds are programmable within reasonable limits
Frequency window	Turbine will trip if: f > 61 Hz for more than 1 s f < 59 Hz for more than 1 s	Turbine does not trip for frequency excursions which do not lead to load shedding or separation from grid; programmable
Turbine speed/EM torque coupling	Generator torque control uses turbine speed as an input, and therefore will respond to changes or oscillations in generator speed, i.e. mechanical dynamics of turbine couple	Turbine mechanical system is decoupled from grid by power converter. Dynamic response can be programmed to provide system damping or act as part of a remedial action scheme (RAS)

Attribute/Characteristic	Baseline (CY2006)	Horizon (CY2013)
	through to electrical side	or special protective system (SPS)
Inertia constant, H	3 to 5 seconds	3 to 5 seconds of actual inertia in mechanical system; apparent inertia as seen from grid side is programmable
Short-Circuit Behavior	Fault contribution is limited by power converter for remote faults; for terminal voltages below 0.5 per unit, turbine will contribute to fault as an induction machine	Fault current contribution is limited to maximum short-time current rating of line-side power converter. Advanced techniques for detecting and responding to grid faults are employed
Synthetic Governor Behavior (delete synthetic)	None; frequency excursion is reflected as a change in induction generator slip, with corresponding control response	Turbine is able to respond to frequency deviations with a synthesized "droop" control if AGC operation is enabled.
Dynamic damping (grid-side)	N/A	Turbine can be programmed to provide active damping, within ratings, for grid frequency excursions
Steady-State Behavior (Normal Operation)		
Real Power Output	Real power generation follows fluctuations in wind speed for light to moderate winds, modified by turbine inertia and control strategy. At or above rated wind speed, turbine output is held to nominal	Real power output can be throttled to allow "up" room for AGC participation. In light or moderate winds, power is smoothed by mechanical inertia and control strategy designed to take advantage of increased operating speed range and kinetic energy storage
Reactive Power Control	Basic mode is for constant power factor operation, possibly modified by plant SCADA	Dynamically controllable
Zero power (idling) operation	Turbine can provide reactive power support only when generating.	Turbine can provided rated reactive power support at any time while online
Wind Plant Characteristics		
Plant Size (for NY state scenarios)	50 - 200 MW Tughill and offshore plants may be 200+ MW	50 -200 MW offshore plants may be 200+ MW
Interconnect Bus Bar Characteristics		
Reactive power/voltage control	Power factor control; dynamic voltage control with auxiliary equipment (e.g. SVC), available under zero production conditions	Dynamic voltage control available at all times
Blackstart capability	Not available	Possible with limitations according to wind resource availability
Islanded operation	Not desirable or possible. Plant is transferred tripped at interconnect substation to prevent islanded operation with system load	Limited operation with small island is possible with proper consideration of wind resource availability and plant power and regulation set points.

Attribute/Characteristic	Baseline (CY2006)	Horizon (CY2013)
Production Management		
Forced full or partial curtailment	Plant power reduction can be affected via inter-control center communications	Can participate in AGC
Maximum power smoothing	Control of short-term fluctuations in generation is a function of individual turbines only	Plant level controls have capability to minimize short-term power fluctuations by activating certain capabilities of individual turbines
AGC participation	N/A	Possible
Ramp rate control	Power changes can be limited only during plant startup.	Plant ramp rate is programmable for startup and normal operating conditions. Down ramps can be modified to a limited degree
Production Forecasting, Scheduling		
Next-hour forecasting	TBD	TBD
Next-day forecasting	TBD	TBD
Longer-term forecasting (week)	TBD	TBD

6.2 Models for Computer Calculation and Simulation

The scope of work for the NYSERDA study requires an extensive amount of computer modeling and simulation. GE Power Systems Energy Consulting has developed a dynamic model of the GE Wind Energy Systems 1.5/3.6 MW wind turbine for the PSLF package. A similar model is also available from PTI for PSS/E. The SPC recommends that either of these models be used to represent the baseline turbine in the study.

There is no specific model for the turbine characteristics of the horizon year. The SPC believes that a reasonable representation of this turbine could be created by modifying the appropriate parameters of the existing dynamic model for the GE turbine. Note that the technology changes forecast by the SPC improve the characteristics of the turbine as viewed from the grid. Proposed modifications to the existing model to represent the horizon year turbine should be discussed with and reviewed by the SPC.

6.3 Models for System Operations Studies

The SPC recommends that the measurement database compiled by NREL be used as the basis for developing empirical models of the proposed wind plants for assessing the impact on NYISO control area operations.

6.4 Capacity Contributions

Historical wind resource characteristics compiled by the SPC in the Wind Resource Assessment precursor to the project are the primary data source for evaluating wind plant capacity value.

7 REFERENCES

(To be provided)

Thresher, et. al. paper on low wind speed turbines
GE white paper
European papers on dynamic modeling
NREL – Wan – monitoring data summary
NREL - Milligan