Queuing Up

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Interconnecting wind generation into the power system

IN THIS ERA OF OPEN-ACCESS TRANSMISSION, THE INTERCONNECTION QUEUE is the mechanism for grouping and ordering prospective generation projects for evaluating impacts on the bulk system. These days, with record-setting installations of wind generation capacity in the United States, it is difficult to find an interconnection queue that does not contain at least some wind generation projects; in the areas of the country with good or better wind resources, there may be dozens of prospective projects awaiting study. The result has been a much broader exposure within the electric power engineering community to the technical issues and challenges associated with wind generation.

The November 2005 issue of *IEEE Power and Energy Magazine* highlighted some of the initial discussions and activities related to the processes by which wind generation facilities secure approval for interconnection to the transmission grid. Also at that time, awareness of the technical issues and challenges posed by this unique energy source was beginning to grow significantly in the power system engineering community. Just prior to the publication deadline for that issue, the IEEE Power Engineering Society took a major step by establishing the Wind Power Coordinating Committee as the focal point for all wind energy related activities within the PES and for liaison with outside organizations. It is fair to say that those initiatives were just the beginning.

The ensuing two years have seen a broadening of these activities on all fronts with over 5,000 MW of wind generation capacity installed in the United States during that time. Wind turbine manufacturers have advanced technology to make their products more compatible with the bulk transmission network, while at the same time project size and complexity are conspiring to make engineering the grid interface more difficult. Developments on the policy and regulatory fronts are beginning to show the way forward. And, most importantly, experience gained from technical studies of prospective grid impacts from the thousands of megawatts of wind generation capacity installed over the past few years is helping to build the base of knowledge that will be required as the penetration of wind generation continues to grow.

Policy and Regulatory Developments

With restructuring of the electric power industry, rules and regulations tend to impact the wind industry through Federal Energy Regulatory Commission (FERC) actions. It is through FERC orders; for example, that North American Electric Reliability Corporation (NERC) reliability rules and utility interconnection requirements get their authority. FERC orders outline the requirements for wind plant and utility performance. Recent FERC orders impact wind integration in six important areas:

- ✔ voltage ride-through
- ✔ voltage support and dynamic reactive capability
- ✔ new transmission
- ✔ transmission reservation: conditional firm and re-dispatch
- ✔ scheduling and imbalance
- ✔ mandatory NERC reliability rules.

Of these, all but the scheduling and imbalance area have implications for wind plant interconnection.

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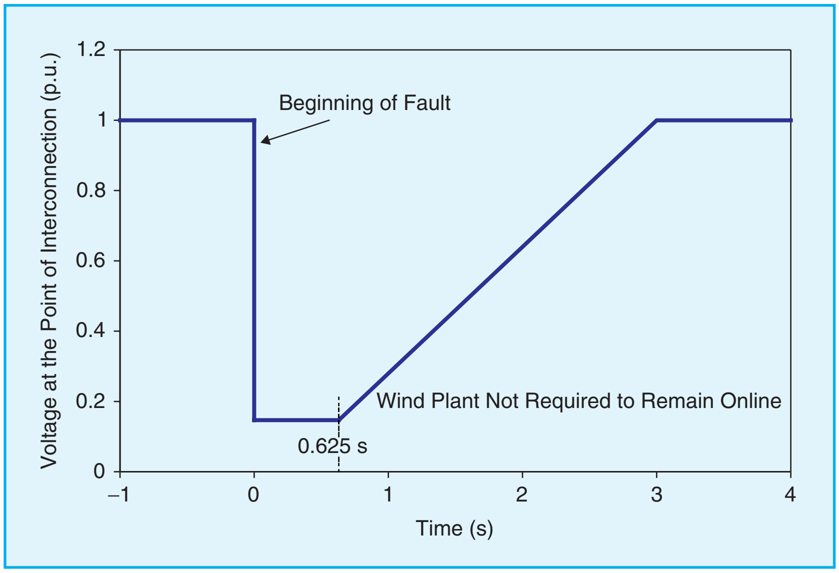

figure 1. FERC Order 661 "Minimum required wind plant response to emergency low voltage."

concerns unique to large wind generation facilities.

From the NERC perspective, certain aspects of Order 661 were inconsistent with good engineering practice for system reliability. For example, the proposed low-voltage ride-through requirements (i.e., the ability to remain online during network short-circuit events, and to resume operation when the fault is cleared) for wind generators (Figure 1) was not as rigorous as what was expected of conventional generators.

The result of the discussions was a new requirement that met reliability needs, was technologically feasible for turbine manufacturers, and was also consistent with requirements for conventional generators. Rather than a voltage versus time curve, the new language stated that wind generating plants are required to remain in service during three phase faults with normal clearing (which is a time period of approximately four to nine cycles) and single line to ground faults with delayed clearing, and subsequent postfault voltage recovery to prefault voltage unless clearing the fault effectively disconnects the generator from the system (Figure 2). The clearing time requirement for a three-phase fault will be specific to the wind generating plant substation location, as determined by and documented by the transmission provider. The maximum clearing time the wind generating plant shall be required to withstand for a three-phase fault shall be nine cycles, after which, if the fault remains following the location-specific normal clearing time for three-phase faults, the wind generating plant may disconnect from the transmission system. A wind generating plant shall remain interconnected during such a fault on the transmission system for a voltage level as low as zero volts, as measured at the high voltage side of the wind generator step-up (GSU) transformer; for wind plants in this context, the transformer at the interconnection substation is considered to be the GSU.

The requirement does not apply to faults that would occur

Wind Plant Behavior During Faults (Low-Voltage Ride-Through)

As the article for the November 2005 issue was being assembled, NERC and the American Wind Energy Association were entering discussions at the behest of FERC to resolve differences over FERC Order 661. This order, issued in June of 2005 and stemming from Order 2003A on Large Generator Interconnection Agreements and Procedures, addressed some

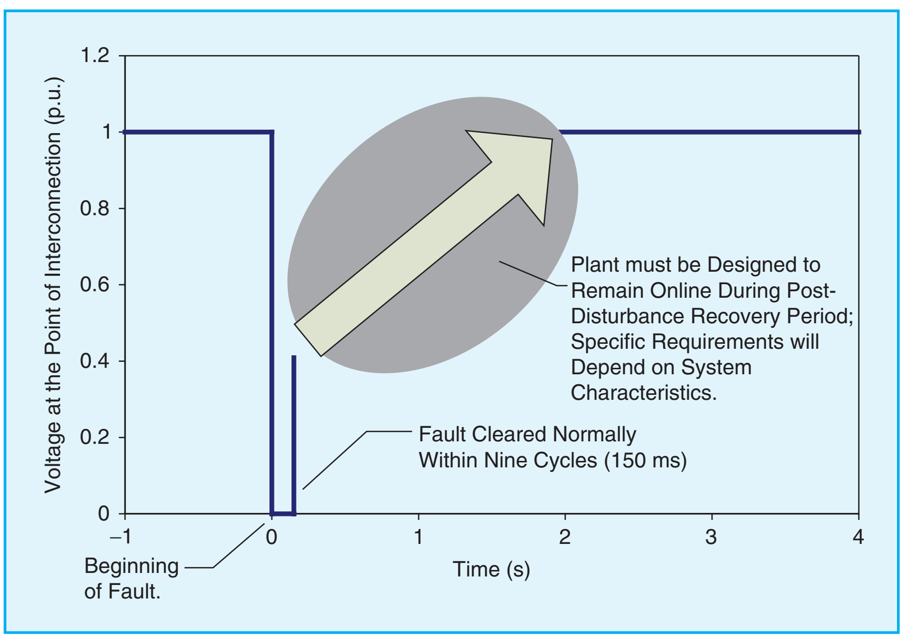

figure 2. FERC Order 661A requires wind generators to remain connected for voltages as low as zero lasting for up to nine cycles.

between the wind generator terminals and the high side of the GSU. Wind plants connected to the transmission network via a radial line would not be required to ride through a fault on that radial line. At the same time, however, the onus is on the plant designers to insure that the facility will remain in operation during the postdisturbance recovery period, which can pose significant challenges in weak parts of the network.

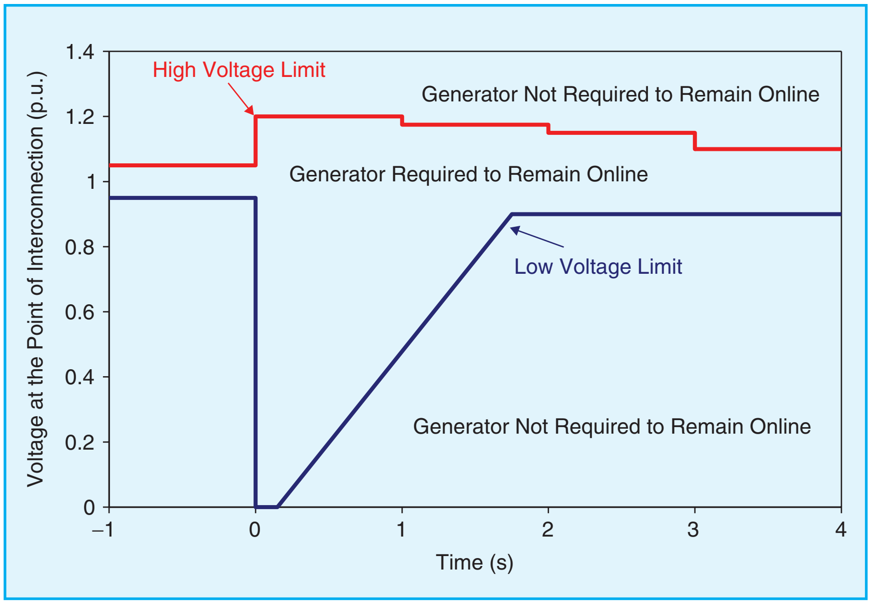

figure 3. Proposed WECC voltage ride-through requirements for all generators.

WECC Assesses its Own Requirements

Transmission providers in the Western Electricity Coordinating Council are experiencing their share of wind generation development and because of their large geographic footprint and low population density have invested in system-specific evaluations of requirements for wind generation technology.

The WECC Wind Generation Task Force (WGTF) has proposed to establish for all generators the technology-neutral standard shown in Figure 3 that will address high and low voltages during the fault itself and the recovery period. A detailed discussion of the WGTF analysis is available in a WECC white paper titled "The Technical Basis for the New WECC Voltage Ride-Through Standard," prepared by WECC in 2007. The proposed WECC standard is a step forward with its more comprehensive coverage of postfault voltage recovery period, the coverage of overvoltage requirements, and the applicability to all (future) generators. This proposed WECC standard may be more appropriately adopted as an NERC continental standard.

Voltage Support and Dynamic Reactive Capability

Older wind generators based on simple induction machines create a reactive power burden for the power system. They often degrade system voltage performance rather than support it. FERC Orders 661 and 661A address the need for wind plants to support power system voltage by requiring new wind generators to have the capability to control their reactive power within the 0.95 leading to 0.95 lagging range. Recognizing that providing this capability can be expensive, FERC only requires it if the interconnection study shows that it is needed. The interconnection study also determines if power electronics are needed for dynamic control or if switched capacitors are sufficient. Many modern wind generators provide this dynamic capability directly from the power electronics that control the real power operation of the machine. These plants can provide excellent voltage control for the power system.

Life Under the ERO: Mandatory NERC Reliability Rules

The U.S. Energy Policy Act of 2005 mandated the creation of an electric reliability organization (ERO) to implement and enforce reliability standards. Where protecting and maintaining the reliability of the electric power grid in North America had once been a voluntary effort of hundreds of organizations, it now becomes federal law, with the FERC charged with oversight responsibility. In the summer of 2006, the NERC was certified by FERC as the ERO for the United States, and it is now known as the North American Electric Reliability Corporation (NERC) **<Author: Please clarify sentence. NERC is now known as NERC?>**. With Order 693, issued in March 2007, FERC approved 83 of NERC's 107 reliability standards. The process to fix and approve the remaining standards and to update the approved ones is ongoing.

The full significance and impact of the ERO and mandatory reliability rules on wind generation interconnection is uncertain at this time but will certainly become apparent over the coming months and years. There are implications not just for bulk wind generation facilities but for all generators. The rules will likely include requirements for development and validation of appropriate plant models for system studies, certification of plant performance through field testing, and documentation of plant performance during actual system disturbances. When and if such requirements are implemented, additional focus on many of the technical issues now associated with wind plant interconnections will be necessary.

Progress with Modeling and Studies

Simulation models are required to conduct interconnection studies for proposed new wind power plants. Models are also required for existing (or committed) wind power plants to conduct periodic assessment of grid reliability and interconnection studies of other proposed projects. Roughly speaking, simulation models fall in two categories: planning models and engineering design models.

Planning models are implemented in positive-sequence simulation programs such as General Electric's PSLF/PSDS and Siemens-PTI PSSE programs and are designed for study of large-scale interconnected systems, where simplifying approximations are acceptable and desirable to balance computational complexity, simulation speed, and data management. The utility industry and other users (consultants, researchers, students, etc.) have grown to expect those models to be nonproprietary, generic, standard, and compatible (or portable) across simulation platforms. Unrestricted sharing of planning models among transmission planers, study consultants, and reliability organizations is needed for the purpose of generator interconnection studies as well as grid planning studies. Planning models for wind power plants exist but generally do not conform to these philosophies. In general, lack of consistency and coordination in the WTG modeling has resulted in proliferation of models that are difficult to manage, validate, and maintain. As the wind industry

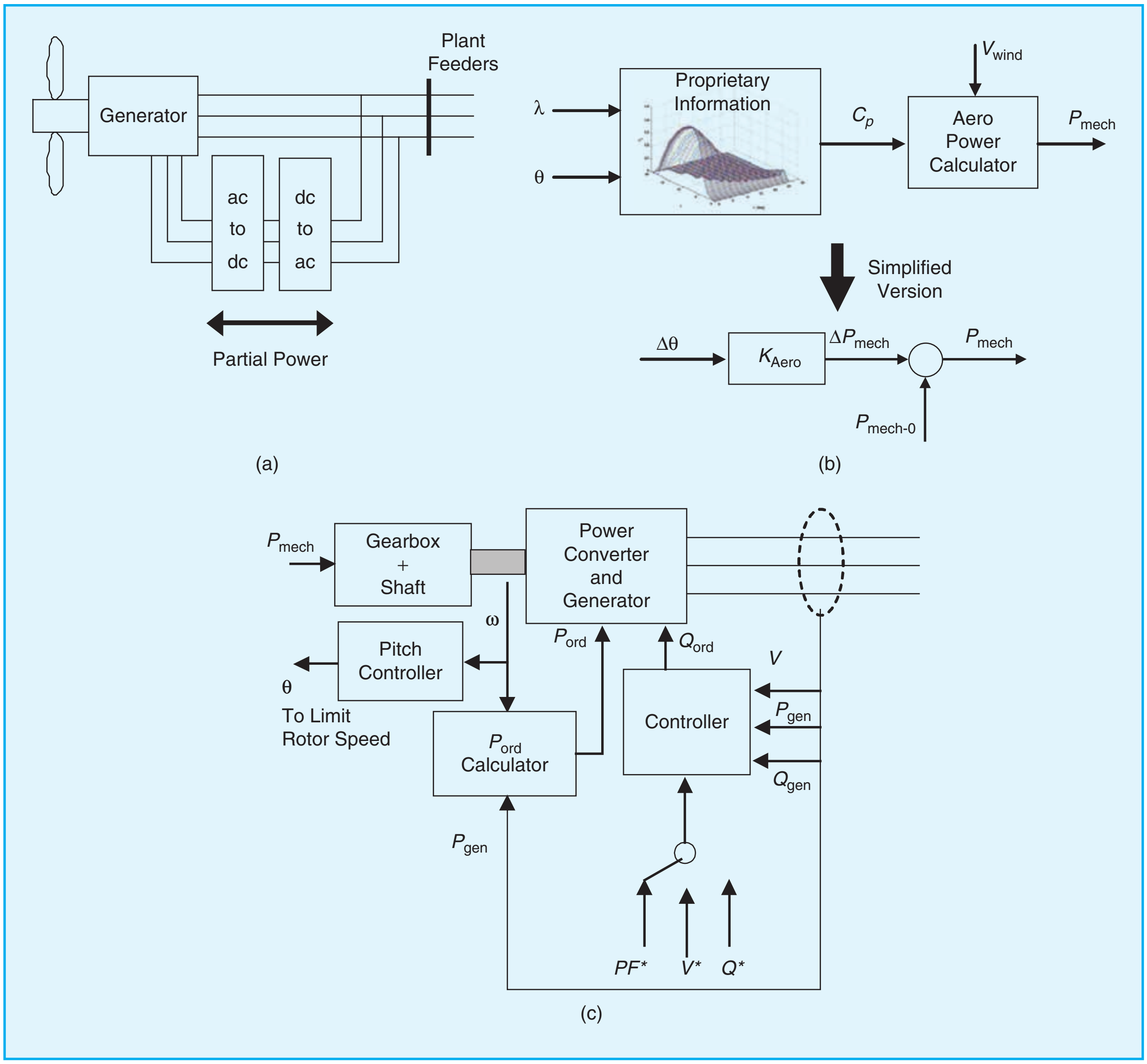

figure 4. Simplification of turbine aerodynamic and mechanical systems for dynamic models.

matures and installed capacity continues to increase, it becomes possible and necessary to address the issues related to planning models.

Engineering design models are implemented in three-phase simulation programs such as PSCAD, EMTP, and Matlab/Simulink. These models are generally much more detailed than planning models and are appropriate for conducting a wider range of electrical studies on a proposed or existing project. The studies may include control interaction studies, harmonic/resonance analysis, as well as equipment/control specification and design.

WECC Wind Generator Modeling Initiative

In 2005, the Wind Generator Modeling Group (WGMG) of the WECC initiated a collaborative project to design and implement standard, generic, nonproprietary wind turbine generator planning models. The desire for generic models was driven primarily by two factors.

- ✔ Many of the existing dynamic models for commercial turbines contain proprietary information and therefore require execution of a confidentiality or nondisclosure agreement between the vendor and the user. Since representations of the plant, when built, must be retained in the interconnection planning models that are available to all qualified users, the confidentiality requirement is problematic.
- ✔ Existing dynamic wind turbine models were found to be relatively complex and more difficult to use by transmission planners because of the unfamiliar technology and topologies. Given that the required scope of application for dynamic simulations in interconnection evaluations could be defined precisely, it was felt that significant simplification of the models was possible, as illustrated in Figure 4.

From the point of view of the grid interface, commercially available wind turbine generators (WTGs) can be grouped according to electrical topology:

- ✔ fixed-speed squirrel-cage induction generators
- ✔ variable slip (wound rotor) induction generators with variable rotor resistance
- ✔ variable speed doubly fed asynchronous generators
- ✔ variable speed generators with full converter interface.

WGMG has developed WECC standard model specifications for each of these types of WTGs, and implementation in PSLF and PSSE is presently underway. When completed, the suite of generic models and corresponding documentation will become part of the standard model libraries for these computer tools. A significant contribution of the WGMG effort has been to demonstrate the technical feasibility of WECC standard WTG planning models and develop consensus and buy-in across a wide cross section of the wind industry.

As WECC and other reliability organizations adopt the WECC standard models, it is expected that manufacturers will begin to populate the parameters for their specific products and produce their own application notes to provide further guidance to users. This will conclude the deployment phase of the WECC standard models.

As part of the WGMG effort, the National Renewable Energy Laboratory (NREL) has initiated a project to validate the generic models and identify areas that need improvement. This project will focus on validation against field measurements of staged tests and naturally occurring disturbances. This effort is sponsored by the California Energy Commission though the Public Interest Energy Research (PIER) program, and will involve WECC, UWIG, ERCOT, manufacturers, wind power plant operators, and other stakeholders.

Collaboration with IEEE's Working Group on Dynamic Performance of Wind Generation Task Force of the PES System Dynamics Committee is also underway, with the goal of further refining the models and using them as a basis for an eventual IEEE WTG modeling standard.

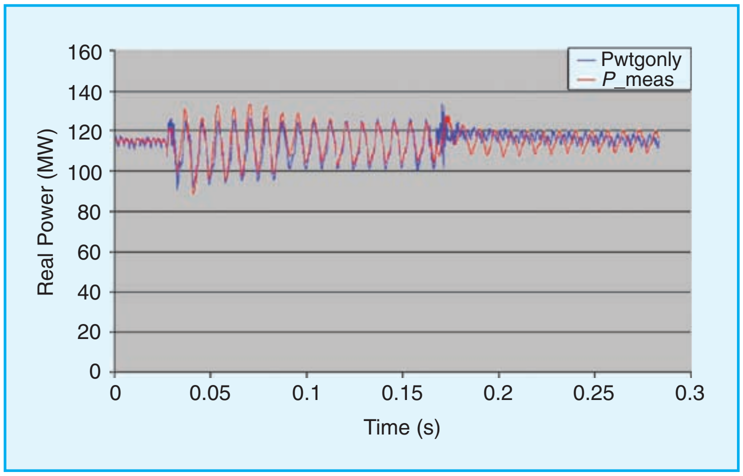

figure 5. Comparison of real power output from simulation model and measurements (from WECC WGMG).

Validating Models

Model validation is a required part of any modeling effort, in order to refine the models and to increase confidence in the model performance. Ideally, model validation should be conducted using field measurements of staged tests or naturally occurring disturbances. Compared with conventional generators, there is very little experience with performance characterization of wind power plants. Data is scarce and considered proprietary in most cases. Model validation against field data is a challenging endeavor.

There are several validation efforts underway or recently completed. As mentioned above, a WECC model validation effort (see Figure 5) is currently underway, focusing specifically on the WGMG standard models. A recent IEA report analyzed several WTG models in different platforms and compared the model performance against a set of field measurements. Manufacturers and other organizations such as Spain's E2Q and Ontario Hydro have conducted field tests to verify or certify equipment dynamic performance and to validate dynamic models. At this time, access to the data generated by such tests is restricted.

Other Modeling Issues

While the general dynamic behavior of wind turbine and wind plants has received much of the recent attention regarding model development, there is also a need for characterization of sources of short-circuit current for design of protective systems. Little guidance currently exists for calculating short-circuit contributions from large wind generation facilities. Analytical approaches are complicated for the following reasons.

- ✔ Most commercial wind turbines employ induction machines for electromechanical energy conversion, which do not strictly conform to the standard procedures and assumptions used in calculation 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.
- ✔ Wind plants are composed of large numbers of relatively small generators, interconnected by an extensive medium-voltage network that itself influences 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 need to be adapted for transmission system fault studies.

With other wind turbine electrical topologies, the response to a short circuit is not intuitive but rather a function of the turbine generator control and protection subsystems. For example, in the doubly fed asynchronous generator topology, the stator current from the machine will be held to around rated if the rotor power converter remains active. For severe (i.e., close-in) faults, however, the rotor power converter may be disabled through operation of a "crowbar" circuit for protection, in which case the generator would behave as an induction machine with a short-circuited rotor and contribute fault currents several times rated for a few cycles. The details of such operation are vendor dependent and therefore difficult to generalize across all turbines of the same topology.

Challenging Interconnections: New Uses for Familiar Equipment

Interconnecting wind generation facilities to the grid poses some new engineering challenges for two primary reasons:

- ✔ wind turbine and plant technology are not as familiar or well-characterized as conventional generating equipment.
- ✔ many wind plants are built in remote areas far from load centers, where the transmission network is weak. This, coupled with the unique time-varying nature of wind generation, puts a premium on reactive power control while at the same time making it more difficult.

Large Plants, More Sophistication

To maximize their return on investment, developers are aggressively pursuing building larger and larger wind plants. In areas where the wind resources support such development, wind plants with total power ratings in excess of 200 MW are becoming the norm. Wind plants recently completed, currently under construction, or recently announced include the Gulf Wind Project in Texas (300 MW Phase I with total of 1,200 MW by the completion of Phase IV), Cedar Creek wind plant in Colorado (300 MW), and the Prince wind plant in Ontario (200 MW).

Larger wind plants with a mixture of wind turbine generator types in the same wind plant and constraints associated with the terrain are leading to more sophisticated plant designs. Plants are often designed for development in several phases, with a mixture of overhead and underground collector circuits consisting of three or four feeder circuits with individual feeder length exceeding 10 mi in some cases. The plant may also include a collector/interconnect substation, and in some cases a transmission line from the collector substation to the interconnect substation, as well as a separate interconnect substation. The distance from the collector substation to the interconnect substation ranges from several miles to tens of miles, depending on the routing of existing transmission lines and the point of interconnect.

In North America, most of the medium-voltage infrastructure is based on 35-kV class equipment. Recent experience is beginning to reveal that while this equipment is very standard and well known to electrical system designers, the arrangement and application in large wind plants is unique.

A number of technical issues have arisen for which there is little guidance based on experience to reference. Over time, the answers to these and other questions will have been determined and will form the practice for electrical design and medium-voltage equipment application in large wind plants. At present however, design decisions may be based on an incomplete understanding of the underlying electrical phenomena.

Some examples include the following areas.

- ✔ **Protection of wind plant collector circuits.** In delta-connected collector systems where grounding transformers are used to eliminate ferroresonance concerns, protection schemes with a forward-looking residual-ground directional overcurrent element supervised by an instantaneous neutral-ground overcurrent element are typically used to trip the faulted feeder circuit breaker when a phase-to-ground fault occurs. By default, the unfaulted feeders will not trip because they either see no residual-ground currents or reverse residual-ground directional currents. For backup protection, if the ground fault condition is not cleared within five cycles, all feeders can be tripped on zero sequence voltage detection. If the ground fault condition persists up to ten cycles, a breaker failure scheme can be employed to trip the lockout relay.

- ✔ **Harmonics.** Although wind turbines, even those employing power converters for generator control, are not significant sources of harmonic distortion, harmonics can be an issue for wind plants due to even small amounts of background distortion on the transmission network. Reactive compensation systems in wind plants often employ shunt capacitor banks at the medium voltage level, which, from the perspective of the transmission network, appear connected in series with the substation transformer. This L-C combination can be tuned to a lower-order odd harmonic frequency, allowing distorted currents to flow from the network. Overloading of capacitor banks and high harmonic voltage distortion on the medium-voltage bus are two of the problems that might arise The situation described above can actually result in the plant not conforming to the IEEE Std. 519 limits, even though the plant equipment is linear and the background distortion on the grid is within the limits provided in the standard.
- ✔ **Insulation coordination.** The configuration of wind turbines and their step-up transformers most times results in the turbine appearing as an ungrounded source to the collector network. If the collector circuit breaker were to open with the turbines still operating,

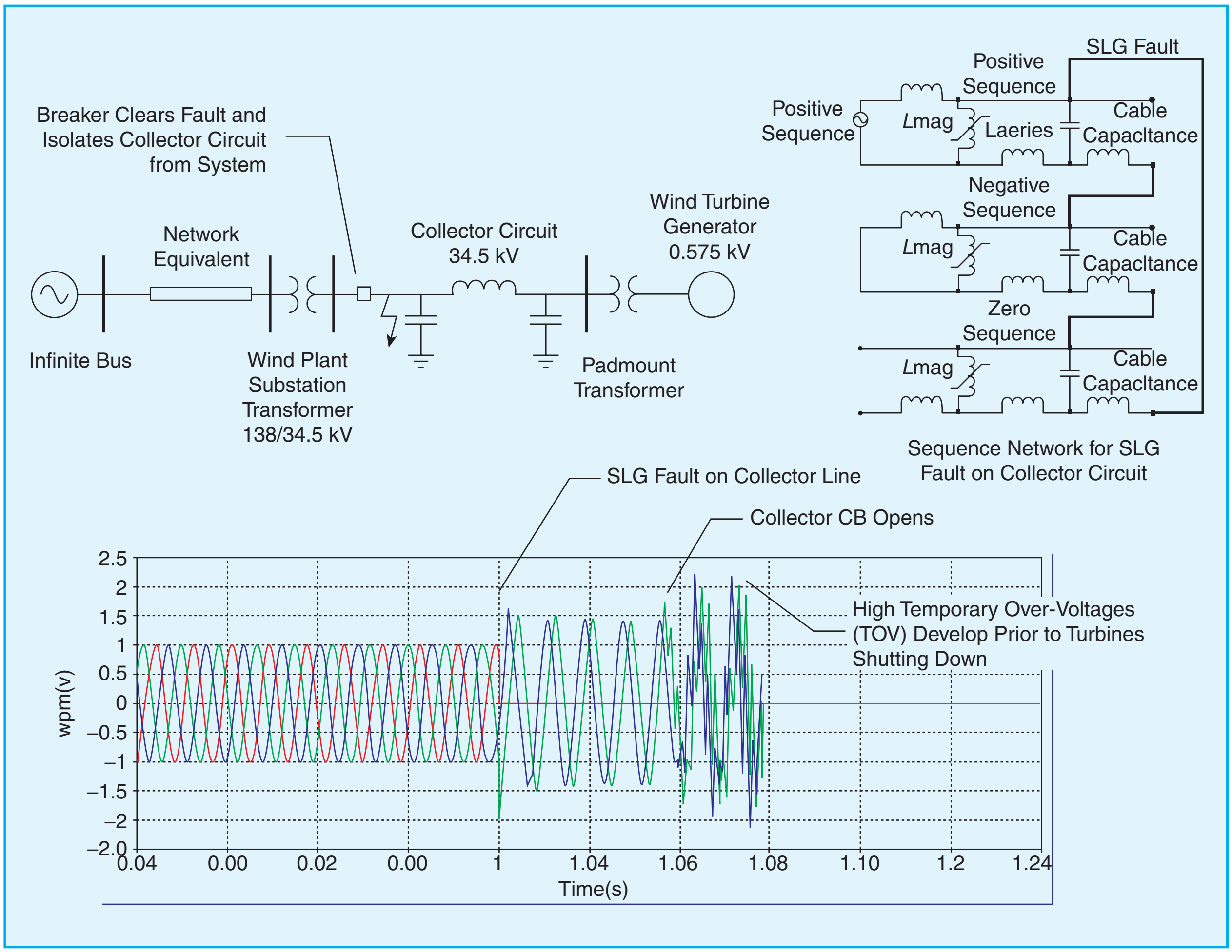

figure 6. Temporary overvoltage on isolated wind plant collector circuit.

the collector line would become ungrounded. In the case where the breaker opens to clear a single-line-to-ground fault on the collector line itself, high temporary overvoltages may occur until all turbines have shut down, as illustrated in Figure 6. The temporary overvoltage may be high enough to exceed surge arrester capability. While grounding transformers are the conventional solution, many plants are being built with a breaker/grounding switch combination. The issue with this device is the one- to several-cycle time delay between breaker opening and ground switch closing, during which time arresters and other collector system equipment would be exposed to high voltages.

The study of the above problem via simulation is complicated by the sophistication of the wind turbine models required and their vendor-specific characteristics. Some important details of turbine operation during this type of dynamic event may actually be considered proprietary.

The IEEE Power Engineering Society has begun to enlist the expertise of its members to work toward answers for these and other technical questions facing wind plant designers and operators. Through the Wind Power Coordinating Committee (WPCC), technical activities are being initiated in the areas of most immediate technical need. At the most recent general meeting in June 2007, in Tampa, Florida, for example, the WPCC worked with the Renewable Energy Subcommittee of the T&D Committee to establish a task force to focus on collector system design and equipment application issues for large wind plants. The goal of the task force will be to engage various subject area experts across the PES and engineers currently involved in wind plant design to assess the issues and provide guidance to the industry. Because of the fast pace of wind development, mechanisms other than standards, such as panel sessions and white papers, will initially be used to disseminate this guidance.

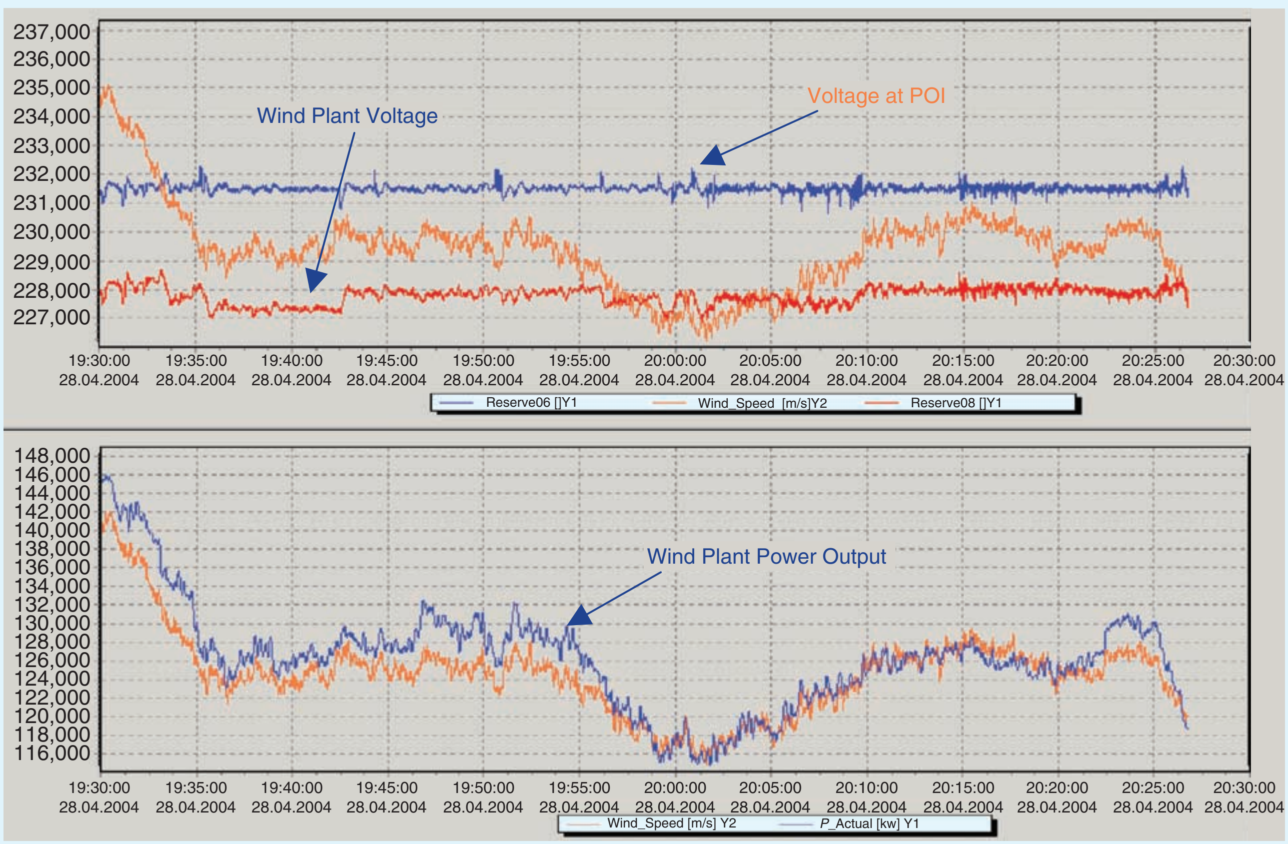

figure 7. Wind plant voltage response and regulation at point of interconnection.

Going Forward: Designing Wind Plants to Look (Sort of) Like Conventional Generators

The grid requirements for the wind industry are rapidly moving toward those applied to other types of generation equip-

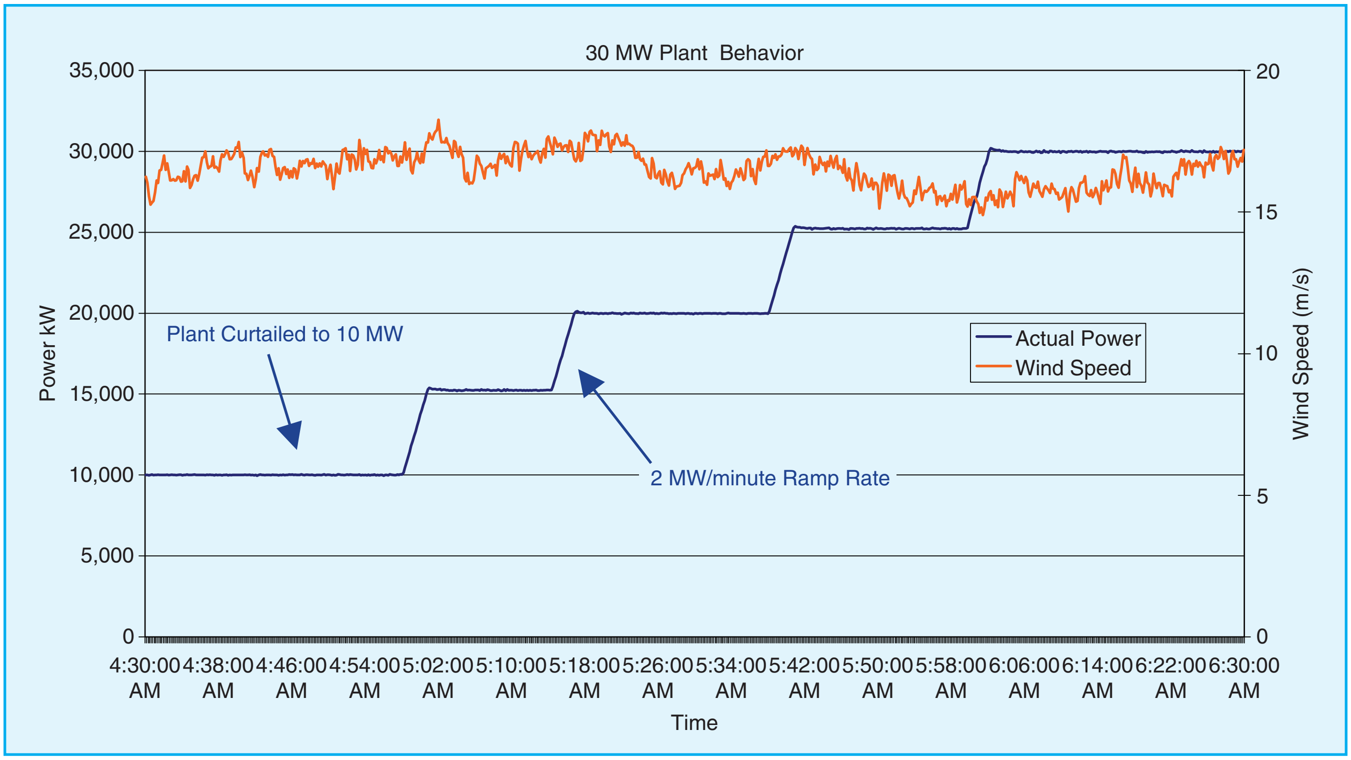

figure 8. Power response of plant to curtailment and ramp rate control.

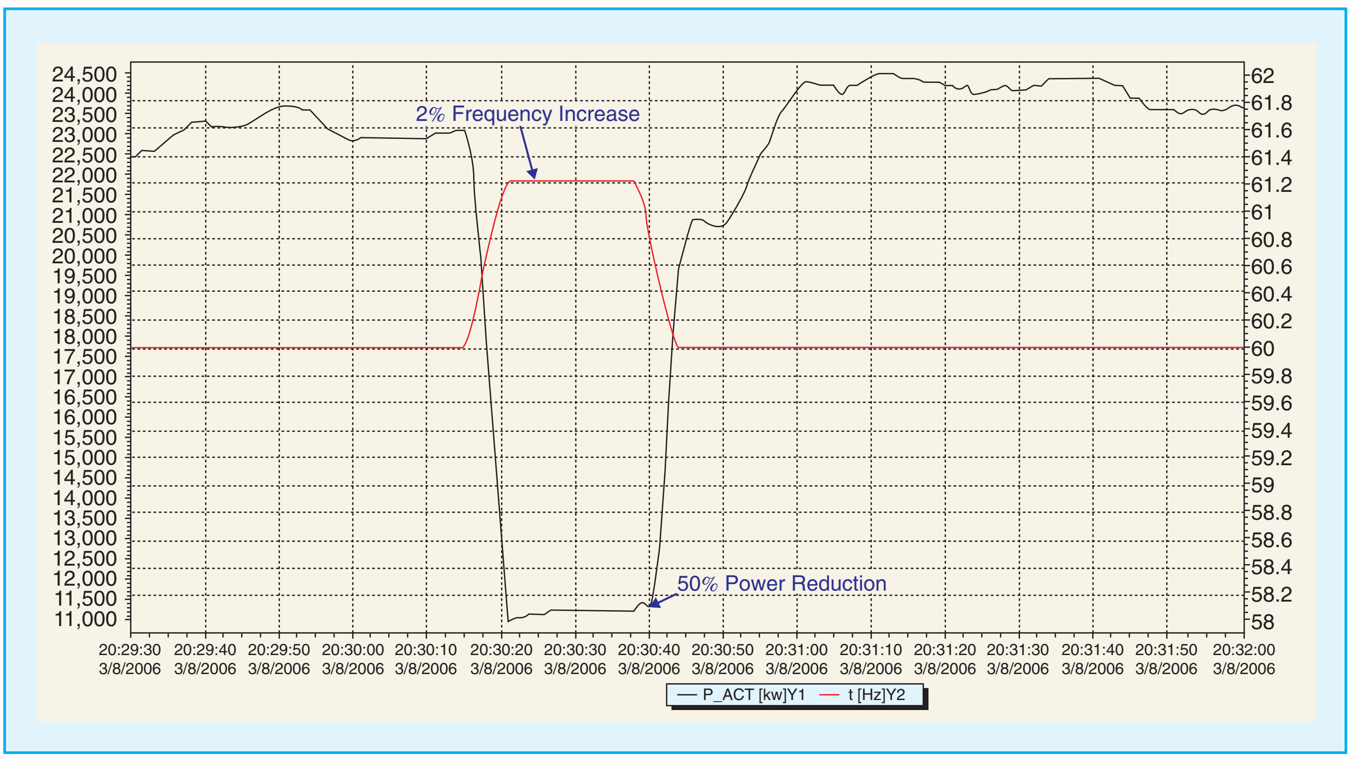

figure 9. Power response of plant to overfrequency condition.

ment, such as gas and steam turbines.

A large wind farm may consist of a hundred or more individual wind turbines, separated by tens or even hundreds of kilometers of electrical collector system. However, the power system needs are dictated at the point of interconnection with the host grid. Most grid codes now require that wind power plants assist the grid in maintaining or regulating the system voltage. Wind power plants are starting to be required to assist the grid in maintaining or regulating the system frequency as well. However, explicit grid code requirements for frequency control are still rare.

Plant-Level/Hierarchical Controls

In order to achieve the higher levels of functionality included in some grid codes, there is a trend toward the use of wind plant supervisory controllers. In general, these controllers, which may utilize wind plant SCADA or other dedicated communications systems, are designed to coordinate the collective reactive power, and sometimes the real power, response of an entire collection of wind turbines to make the plant function as a single power generation source. A wind plant supervisory controller achieves voltage/VAR control by using the inherent reactive power capabilities of some types of wind turbines as well as that of other equipment within a plant, such as shunt capacitors, reactors, and power electronic devices. The controller commands turbine VAR output and shunt device status to maintain proper voltage tolerances as seen at the utility's point of interconnection.

Wind plant supervisory controllers may include multiple closed- or open-loop regulators. The device that measures and controls the aggregate real and reactive power produced by the wind turbines as well as the system voltage and/or power factor usually resides at the power plant's substation. Sometimes a startup/shutdown sequencer is also integrated into the controls.

Reactive Power Supply and Control

For many wind farms, especially large remote and off-shore projects, traditional approaches to managing reactive power are no longer acceptable. In systems with relatively low short-circuit ratios, i.e., where the wind farm is large compared to the electrical stiffness of the host grid, such control strategies can result in unacceptable voltage performance, including flicker.

For plants that use wind turbines without intrinsic independent reactive power production capability, developers and utilities have employed capacitors to correct power factor to near unity during operation but may not have addressed dynamic response to changes in system voltage or frequency. Because these devices are slow and not able to provide fine, continuous control, they are unable to react to the small changes in voltage commonly seen in weak grid or gusty wind conditions. This, in turn, can add stress to the utility grid. To add speed and flexibility, some wind projects have added static VAR compensators or other similar equipment. For example, the Aragonne Mesa wind plant in New Mexico has a distributed static compensator (DSTATCOM), which controls the power factor to unity at the point of interconnect at the Guadalupe 345-kV substation bus. The DSTATCOM, along with four mechanically switched capacitor banks, are located in the collector substation some 22 miles away from the interconnect substation. The collector substation is connected to the interconnect substation via a 138-kV transmission line. The DSTATCOM uses an algorithm that determines the required reactive power output of the compensation system to maintain the power factor at the point of interconnect at unity based on voltage and current measurements at the 34.5-kV collector bus, as well as calculated line drop compensation associated with the collector substation transformer and the 138-kV transmission line. A slow SCADA feedback signal of the actual reactive power at the point of interconnect is used to make any corrections to the reactive power output of the DSTATCOM.

Wind plant supervisory controllers that provide tight closed-loop control of utility system voltages provide two major benefits. First, the impact of active power fluctuations from wind variation on the grid voltage is minimized, and second, fast and precise voltage control effectively strengthens the grid, improving the overall power system's resilience to large disruptions.

An example of this approach is shown in Figure 7. This figure shows the impact of 60 minutes of highly variable wind on a wind plant with 108 GE 1.5-MW wind turbine generators connected to a 230-kV utility transmission line. Line drop compensating algorithms are used to synthesize the voltage at the point of interconnection, which is located approximately 75 km from the wind plant substation. The red and blue traces in the upper chart show the wind plant and the point of interconnection voltages (left scale, volts), respectively. The voltage flicker index, *Pst*, is less than 0.02 for this high stress condition (well within industry expectations). The other variable plotted in the upper chart is the average wind speed of all the turbines plotted over the one-hour interval (orange trace).

The lower chart shows the power (blue trace, left scale, kW) produced by the plant and the same average wind speed (orange trace).

No Wind Reactive Power

A recent advancement in wind turbine generator technology provides control of reactive power output even when the wind turbine is motionless. Currently, all megawatt-class wind turbines stop both watt and VAR production in response to wind speeds either below a minimum threshold or above a high-speed cut-out. While loss of real power production is normally tolerated by the host utility grid, the loss of controlled reactive power production can be locally disruptive.

Some variable-speed wind-turbine generators that rely on a power electronic-based converter can be configured to independently deliver reactive power, regardless of whether the turbine is turning. Wind power plants equipped with this feature will provide effective grid reinforcements by providing continuous voltage regulation—a performance benefit not possible with conventional thermal or hydro generation. From a systemic perspective, the reactive power capability is similar to that provided by various dynamic reactive devices (e.g., synchronous condenser, SVC, STATCOM).

Real/Active Power Regulation

Some wind turbines and wind plant supervisory controllers can now control active power (MW). These controls ensure a grid-friendly response to variations in wind speed and system frequency. They also provide economic options for grid operation under challenging conditions.

Such active power controls include power scheduling, ramp rate limits, and frequency response. Power scheduling is accomplished by curtailing the power output of a wind plant under specific system conditions (e.g., load level, transmission system constraints, equipment outages). Ramp rate limits are designed to reduce the rate of increase in power due to a rapid increase in wind speed. A frequency response control reduces power output when the system frequency is high and increases power output when the system frequency is low. Of necessity, active power controls largely limit power output rather than increase it. However, power output can be increased if a wind plant is already curtailed below the power output available in the wind.

Figure 8 shows field tests of an active power regulator and power ramp rate limiter on an operating 30-MW wind plant with 20 GE turbines. During this test the wind speed (orange trace, right scale, m/s) was sufficient for the plant to produce rated power. Initially, the plant was curtailed to 10 MW. Under these conditions, all 20 turbines are running and synchronized but curtailed in response to commands from the wind plant supervisory controller. During the course of the tests, the active power command is raised in four 5-MW increments. The plant power (blue trace, left scale, kW) follows the change in plant order, with the transition between each step ramp-rate controlled to 2 MW/min.

Power frequency or governor droop functions can be provided to modify the power reference of the regulator to a configurable droop schedule. Figure 9 illustrates the power response of a 60-MW wind plant with GE turbines to a 2% increase in system frequency. During this test, the site was initially producing slightly less than 23 MW. The system overfrequency condition was created using test software that injected a 2% controlled ramp offset into the measured frequency signal. The resulting simulated frequency increased at a 0.25 Hz/s rate from 60 Hz to 61.2 Hz. While the frequency is increasing, the farm power drops at a rate of 2.4 MW/s. After 4.8 s the frequency reaches 61.2 Hz and the power of the farm is reduced by approximately 50%. The overfrequency condition is removed with a controlled ramp back to 60 Hz at the same 0.25 Hz/s rate. The plant power then increases back to an unconstrained power level. This level is slightly higher than the unconstrained level prior to the test due to an increase in the wind speed. These rates of frequency change are representative of relatively severe system disruptions. The plant response is adjustable with control settings. The ramp rate power limiter becomes disabled whenever the system is responding to frequency-related grid conditions and automatically becomes active again once the system frequency is within the droop deadband.

A similar underfrequency response is also possible. However, in order to realize a sustained increase in active power output in response to a frequency drop, the wind plant must initially be curtailed. This has significant economic implications, as energy production will be reduced.

The use of curtailment and underfrequency wind plant response must be balanced with the penalty in energy production. Various system studies have shown that periods of extremely high wind penetration occur rarely. Under these conditions, it may be most economic, and indeed essential, for these functions to be used. These control capabilities enable higher penetration levels of wind power plants in a utility system by allowing for secure operation even in systems with marginal generation resources or low short-circuit ratios. Triggered use of these functions may be the most effective and economic strategy. For example, one way to respond to an unusually rapid increase in wind generation is to implement a temporary cap and ramp rate limit on increasing wind generation. Some studies have shown that the wind energy lost during such curtailment may be quite small.

Summary

The knowledge base of the electric power system engineering community continues to grow with installed capacity of wind generation in North America. While this process has certainly occurred at other times in the industry with other technologies, the relatively explosive growth, the compressed time frames from project conception to commissioning, and the unconventional characteristics of wind generation make this period in the industry somewhat unique.

Large wind generation facilities are necessarily evolving to look more and more like conventional generating plants in terms of their ability to interact with the transmission network in a way that does not compromise performance or system reliability. Such an evolution has only been possible through the cumulative contributions of an ever-growing number of power system engineers who have delved into the unique technologies and technical challenges presented by wind generation.

The industry is still only part of the way up the learning curve, however. Numerous technical challenges remain, and as has been found, each new wind generation facility has the potential to generate some new questions. With the IEEE PES expanding its presence and activities in this increasingly significant commercial arena, the prospects for staying “ahead of the curve” are brightened.

For Further Reading

J.O. Tande, J. Eek, E. Muljadi, O. Carlson, J. Pierik, J. Morren, A. Estanqueiro, P. Sørensen, M. O'Malley, A. Mullane, O. Anaya-Lara, B. Lemstrom, and S. Uski, "Dynamic models of wind farms for power system studies," *IEA RD&D Wind Annex XXI Final Report: International Energy Agency Implementing Agreement for Co-operation in the Research, Development, and Deployment of Wind Energy Systems*, Mar, 2007. **<Author: For this to be "further reading," the reader needs to access it. Is there a URL where it can be accessed?>**

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Biographies

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Older wind generators based on simple induction machines create a reactive power burden for the power system and often degrade system voltage performance rather than support it.

Compared with conventional generators, there is very little experience with performance characterization of wind power plants. Data is scarce and considered proprietary in most cases.

Larger wind plants with a mixture of wind turbine generator types in the same wind plant and constraints associated with the terrain are leading to more sophisticated plant designs.

The grid requirements for the wind industry are rapidly moving toward those applied to other types of generation equipment, such as gas and steam turbines.

For many wind farms, especially large remote and off-shore projects, traditional approaches to managing reactive power are no longer acceptable.

A recent advancement in wind turbine generator technology provides control of reactive power output even when the wind turbine is motionless.

Large wind generation facilities are necessarily evolving to look more and more like conventional generating plants in terms of their ability to interact with the transmission network in a way that does not compromise performance or system reliability.