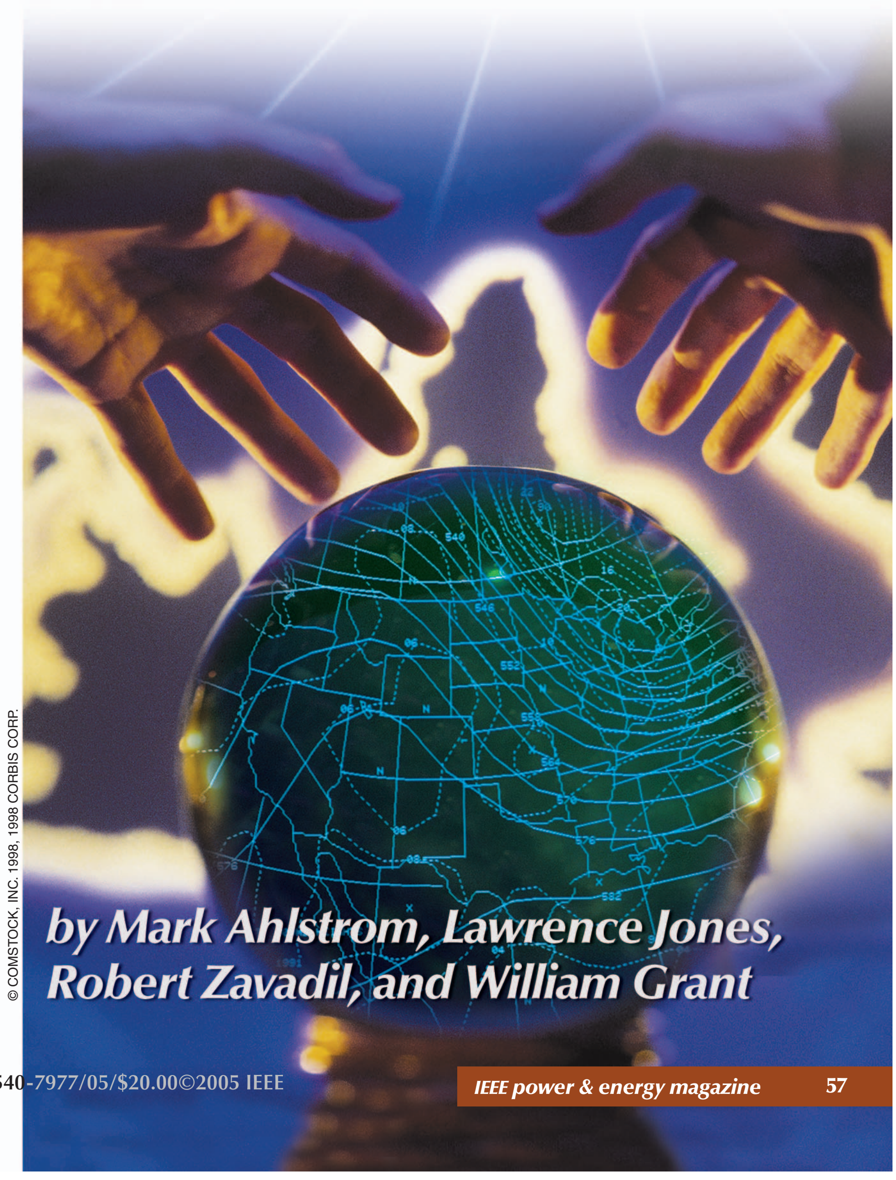
The Future of Wind Forecasting and Utility Operations

Planning for Improved System Operations



by Mark Ahlstrom, Lawrence Jones, Robert Zavadil, and William Grant

AS MORE WIND ENERGY IS CONNECTED to utility systems, it becomes important to understand and manage the impact of wind generation on system operations. Recent studies and simulations provide a better understanding of these impacts, and with this knowledge, progress is now being made in developing the tools and methods to minimize costs and operate reliably with higher levels of wind generation. Advances in wind forecasting, and especially developments to integrate these forecasts into the control room, are important for real-time operations. Knowledge of wind characteristics and impacts can be used to our advantage as we plan the future generation mix.

There are very good reasons for using more wind energy on electricity systems, but we must understand how the wind energy interacts with the systems and how grid operators can cope with this new type of resource during planning and real-time operations. Understanding and quantifying the actual impact of wind energy on specific systems is the first critical issue. The term *impact* is generic, but generally includes any additional costs borne by the operators of the power system resulting from the variability and predictability of wind generation.

Once we understand the impacts, we can then design the rules, tools, and systems to

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minimize cost impacts and maximize the value of wind energy on the system. While wind energy may not be dispatchable, the cost impacts of wind can be substantially reduced if the wind energy can be scheduled using wind forecasting. We cannot fully realize the value of wind energy on the system, however, until we integrate wind forecasts and related information directly into the control room, market operations, and planning systems.

Utility Impacts of Wind

The nature of its fuel supply distinguishes wind generation from more traditional means of producing electric energy. The electric power output of a wind turbine depends on the speed of the wind passing over its blades. This moving airstream varies on a wide range of time scales—from seconds to hours, days, and seasons. Local and regional weather patterns, seasonal variations, terrain, and other nearby turbines are just a few of the factors that can influence the electrical output variability of a wind turbine generator.

At the power system level, the aggregate performance of a large number of turbines is generally more important than the details of an individual wind turbine. Wind turbines are usually spread out over a significant geographical area within the wind plant, and multiple wind plants are distributed over a much larger area within the balancing area. This spatial diversity has the beneficial effect of smoothing some variations in electrical output.

Another aspect of wind generation, which applies to conventional generation but to a much smaller degree, is the ability to predict with reasonable confidence what the output level will be at some time in the future. Conventional plants cannot be counted on with 100% confidence since mechanical failures or other circumstances may limit their output. The probability that this will occur, however, is low enough that such an occurrence is often ignored in short-term planning activities.

Because wind generation is driven by the same physical phenomena that control the weather, the uncertainty associated with a prediction of future generation is more significant. The combination of production variability and higher uncertainty of prediction can make it more difficult to fit wind generation into established procedures for power system operations, planning, and scheduling.

On most large power systems, multiple individual balancing areas coordinate their activities to maintain reliability and conduct transactions of electric energy. A balancing area consists of generators, loads, and transmission ties to neighboring areas. Each balancing area assists the larger interconnection with maintaining frequency and balances load, generation, and out-of-area purchases and sales on a nearly continuous basis. In addition, a prescribed amount of reserve capacity must be maintained at all times as protection against unplanned failure or outage of equipment.

To minimize costs while ensuring system performance and reliability, each balancing area is continuously developing plans and schedules for meeting the forecast load while honoring all technical constraints and contractual obligations. The operators of the balancing area monitor the operation of the area in real time and make adjustments when the actual conditions deviate from those that were forecast. These adjustments and deviations from the optimal plans and schedules may add incremental operating costs. These ancillary services cost money to provide, and there may be no direct mechanism for recovering these costs.

Strategies for operating the power system are based on forecasts of conditions to come, whether it is seasons, days, or minutes ahead. Even without any wind generation on the system, there are many uncertainties involved in developing the operating strategies, and uncertainty regarding the aggregate load to be served at each instant over the planning horizon is a major factor. Sophisticated algorithms are used to forecast the load, and an optimal plan is created for meeting that load. If the actual load deviates significantly from the forecast used to develop the plan, there is a high likelihood that the cost to serve that load will be higher than with an optimized plan.

For wind generation, the questions are: How do the variability and forecasting accuracy affect the deployment and operation of other generating resources in a balancing area? and how does the cost of those operational modifications affect the overall cost to serve the load? One does not have to look too far back to recall claims that wind plants need 100% backup because they are not reliable. While the wind and power industries have moved beyond such claims, the presence of significant amounts of wind generation in a balancing area may often require some prudent adjustments to operating strategy. The objective today has turned to identifying methods for quantifying the economic impacts of these changes, assessing the technical impacts of wind generation on system performance and reliability, and engineering solutions to minimize these impacts.

Cost Impact Example— The Xcel Wind Integration Studies

The Xcel studies provide a good example of the cost impacts of wind energy and how they are determined. Xcel Energy is the fourth-largest combination electricity and natural gas energy company in the United States. Its northern balancing area, the former Northern States Power (NSP) system, serves more than 1.4 million electric customers in the states of Minnesota, Wisconsin, North Dakota, South Dakota, and Michigan. Peak demand in the balancing area was approximately 9,000 MW in 2003 and is projected to rise to approximately 10,000 MW by 2010.

Partially as a result of Minnesota legislation, it is expected that this system will have 1,500 MW of wind power by 2010 and as much as 2,250 MW by 2015. This could represent one of the highest wind penetrations of any North American power system.

In 2004, the Minnesota Department of Commerce and Xcel Energy commissioned a study to assess how larger amounts of wind generation would affect Xcel operating costs in the NSP balancing area. Unlike an earlier study, the scenario included wind plants not yet in operation and dispersed over a considerable geographic region. Determining how the aggregate wind generation would appear to the Xcel balancing area operators was a critical aspect of the analysis.

To create a detailed and realistic chronological representation of the projected wind generation facilities, the study used sophisticated meteorological simulations to recreate the weather for recent historical years. This was done using large archives of the hour-by-hour historical weather data to initialize and continuously adjust a numerical simulation model of the atmosphere in the region of interest. While the base model is very similar to those used for weather

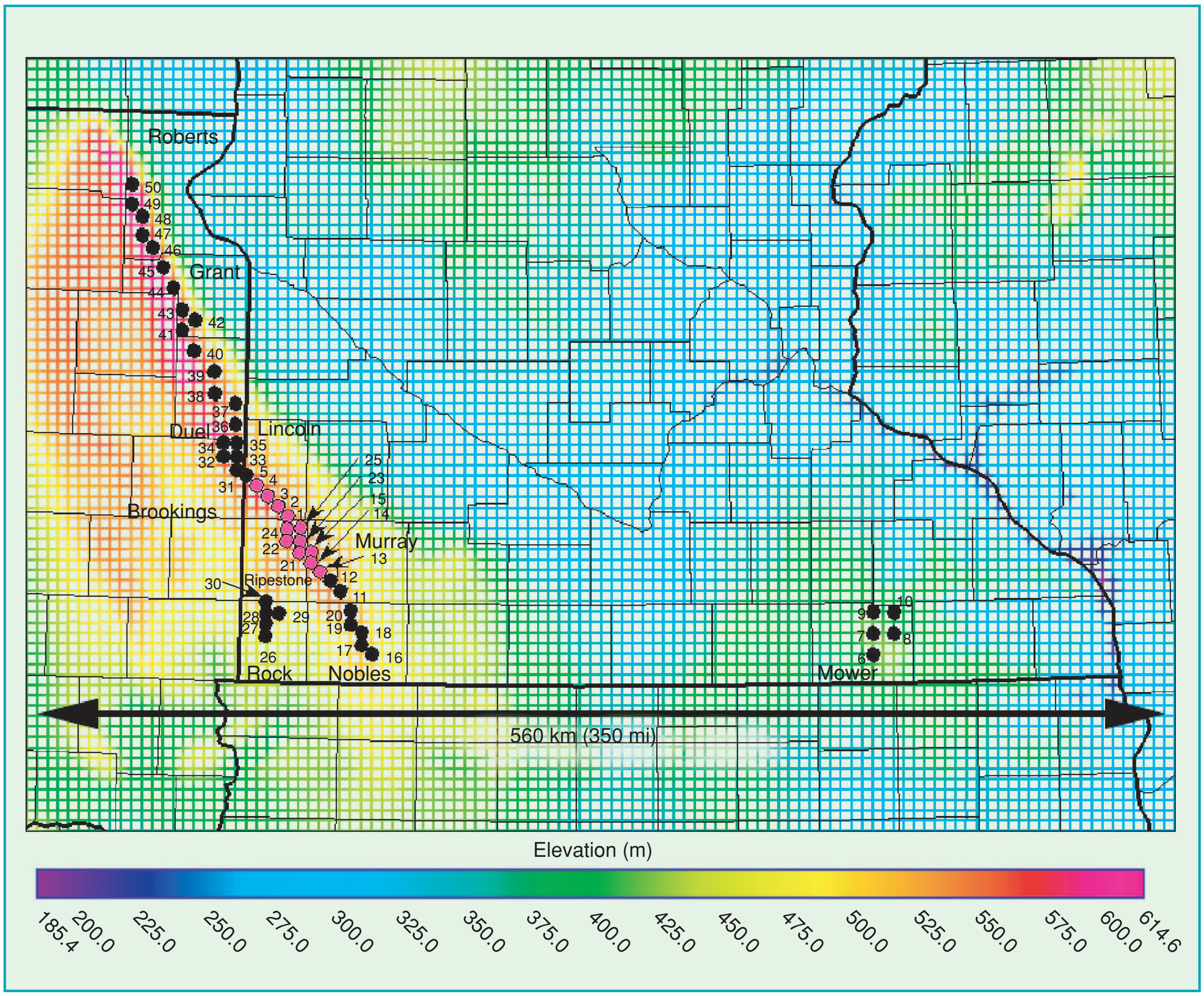

figure 1. The wind plant locations (in the states of Minnesota and South Dakota, mostly on the area known as the Buffalo Ridge). The detailed weather and wind plant energy production were derived from years of hourly data in three-dimensional gridded weather archives. Using physics-based weather modeling methods and racks of computers running for many weeks, three years of hub-height wind data was generated at 10-min time steps.

> The accuracy of forecast results depends on the specific challenges of the wind plant location, the surrounding terrain, and the local climatology.

forecasting, special techniques allow the spatial resolution of the model to be increased in and around the locations of the prospective wind generation facilities.

On the innermost modeling grid, specific points that were either colocated with existing wind plants or likely prospects for future development were identified. Wind speed data, along with other key atmospheric variables from these selected locations (Figure 1), were saved at 10-min intervals as the simulation progressed through three years of weather.

The high-resolution time series of wind speed data was converted to wind generation data by applying power curves for existing and prospective commercial wind turbines. As a check on the accuracy of this approach, to validate the models, the calculated wind generation data was compared to actual measurements collected by the National Renewable Energy Laboratory (NREL) from groups of turbines at an existing wind plant in the area for the entire year of 2003.

Because this approach is directly based on real weather data, it does an outstanding job of representing key items critical to the analysis.

- ✔ Wind plant energy is properly time synchronized with other utility operating data, which is important since correlations exist between weather events and system data (including load).
- ✔ This physics-based modeling approach captures the effects of geographic dispersion of wind plants and other relationships between the individual plants.

Three years of day-ahead wind forecasting data for all 50 wind plant locations were also developed from the model. This was used to study unit commitment issues and costs for wind energy using a wind forecast. Additional forecast experiments showed the value of more sophisticated forecasting methods using computational learning systems with numerical weather models. These methods significantly improved the accuracy of forecasts spanning a range from hours to days ahead. With subsequent funding, we are now working on the development and demonstration of these advanced systemwide forecasting methods.

Xcel Study Results

The high-fidelity data from the meteorological simulations provided a very solid basis for analyzing how the proposed wind generation would affect the operation of the Xcel balancing area in Minnesota. Specific impacts that were analyzed included:

- ✔ how much additional regulation capability to deal with system fluctuations over the next few minutes would be required due to the addition of wind generation
- ✔ how fluctuating wind generation affects the amount of controllable generation required in the load following time frame, the changes over the next few hours
- ✔ how the uncertainty associated with wind generation forecasts affect the commitment and scheduling of generation for the next day or days, and what the economic consequences are.

By matching the wind generation data from the meteorological simulation model with the historic load and generation data, we were able to use straightforward approaches to the major study questions. Balancing area regulation requirements were assessed by analyzing the statistics of the fast fluctuations in existing load and comparing them to similar fluctuations in high-resolution measurement data from wind generation facilities in Minnesota. Since fast changes in wind and load are uncorrelated, simple algebra can calculate the regulation requirement of the projected balancing area load combined with wind generation. The addition of 1,500 MW of wind generation to the Xcel balancing area increases the system regulation requirement by only 8 MW, from 60 to 68 MW.

Because the synthesized wind generation and historical load data were time synchronized, the effect of wind generation on longer-term (tens of minutes to hours) changes in balancing area demand was analyzed by comparing the changes in the load alone to those in the load combined with wind generation. It was found that wind generation has only a small effect. Further mathematical analysis of these distributions reveals that only a small increase in generation ramping capability would be necessary to prevent degradation of control performance.

Finally, because most electrical generating systems cannot be stopped or started at will, balancing area operators must develop an optimized plan for the coming days. This plan must have the lowest cost while still honoring the constraints of individual generating units (permissible stops/starts and ramp rates) and the balancing area itself (e.g., spinning reserve and operating reserve). While system operators are quite familiar with the patterns of load in their balancing area, wind generation introduces some significant unknowns into this process. Using the synthesized wind generation and historical load data, the effect of wind generation on the hour-by-hour balancing area demand pattern can be assessed—with some surprising results.

While the cost impact on many systems may be primarily in the next-day time frame, operators clearly want to know what is expected to happen in the next few hours.

To quantify the cost impact, we mimicked the activities of the system schedulers and then calculated the costs of the resulting plans. The input data for the analysis was hourly load data, wind generation data, and wind generation forecast data for a two-year period. For each day, a reference case was developed that assumed that the daily energy from wind generation was known precisely, and that it was delivered in equal amounts over the 24 hours of the day. This conservative reference case was selected since it represents wind as a resource that would have the least impact on the operation of other resources.

Next, we represented the actions of the system schedulers. The projected load and hour-by-hour wind generation forecast were input to the unit commitment and scheduling program. The program determined the lowest cost way to accommodate the forecast wind generation while meeting the load. The forecast wind generation was then replaced by actual wind generation and a simulation of the same day was conducted. However, instead of allowing the program to change the planned deployment of generating resources, only the resources available in the original plan could be used to meet the actual load.

Applying this method to over 700 days of wind generation and system load data, it was determined that Xcel Energy was effectively paying an additional US$4.37 for each MWh of wind energy. These costs were incurred in the form of additional production costs to Xcel (the cost to serve the load not served by wind generation).

These results assumed the conservative use of current operating practices and a modest effort wind energy forecast. It is very likely that these costs would be reduced significantly through modifications to operating practices, use of energy markets, and improved forecasting methods. That is the next logical step: engineering ways to reduce these cost impacts.

Technology and Expectations of Wind Forecasting

Wind forecasting is increasingly showing value for the improved scheduling of wind energy, and as shown above, such forecasts can have substantial value even if they are not perfectly accurate. Using physics-based forecasting models, real-time wind and energy data from the wind plants, and computational learning systems such as artificial neural nets or support vector machines, it is possible to provide forecasts of wind energy delivery that are significantly better than simplistic forecasts based on climatology (historic values) or persistence (assuming that what is currently happening will continue without change).

The accuracy of forecast results depends on the specific challenges of the wind plant location, the surrounding terrain, and the local climatology. Because wind plants are intentionally located at sites that tend to amplify wind effects when compared with the surrounding space, it is often worthwhile to run customized fine-scale forecasting models and local wind flow models to simulate the enhanced local effects. These results may be combined with other regional forecasts, using computational learning systems to detect complex relationships and optimize the wind energy forecast.

Typically, the operator will want to receive forecasts that run hour-by-hour for the next few days to reduce the unit commitment costs that were described above. While results are site specific, a reasonable expectation at most locations is that the accuracy of next day hour-by-hour power forecasts using current state-of-the-art methods will have a mean absolute error (MAE) of perhaps 10–15% of the rated (nameplate) capacity of the wind plant.

For the purposes of supporting reliability and providing information to real-time operators of the grid, it is also important to provide forecasts of the coming hours with high temporal resolution. While the cost impact on many systems may be primarily in the next-day time frame, operators clearly want to know what is expected to happen in the next few hours, especially with regard to more dramatic (but infrequent) events, such as rapid shifts in wind energy production from storm events. It is quite possible to update the forecast every hour to provide additional detail for the next few hours at a resolution of every 10 or 15 min. When they provide value, special "rapid update cycle" forecasting methods may also be used that run every hour to provide updated results for the next few hours. The accuracy of power forecasts for the next few hours can typically have MAEs on the order of 5% of rated wind plant capacity.

Notably, the accuracy of energy forecasts (for example, total wind energy for tomorrow) can be significantly better than the accuracy of power forecasts. The exact timing of the passage of weather fronts can be difficult to predict, and because the winds can change with the passage of such fronts, errors in timing can result is large power errors. These errors tend to balance out over longer periods of time (several hours or a full day, for example) so the accuracy of energy forecasting can be quite good. This may be useful on systems with substantial gas or hydro generation that have flexibility to reschedule energy delivery over the day.

In addition, as already mentioned, forecasting errors are significantly reduced when aggregated on a systemwide basis. Due to the smoothing effects of geographic dispersion, systemwide forecasting errors for multiple dispersed wind plants may be reduced by perhaps 30–50% when compared with the errors of individual wind plants.

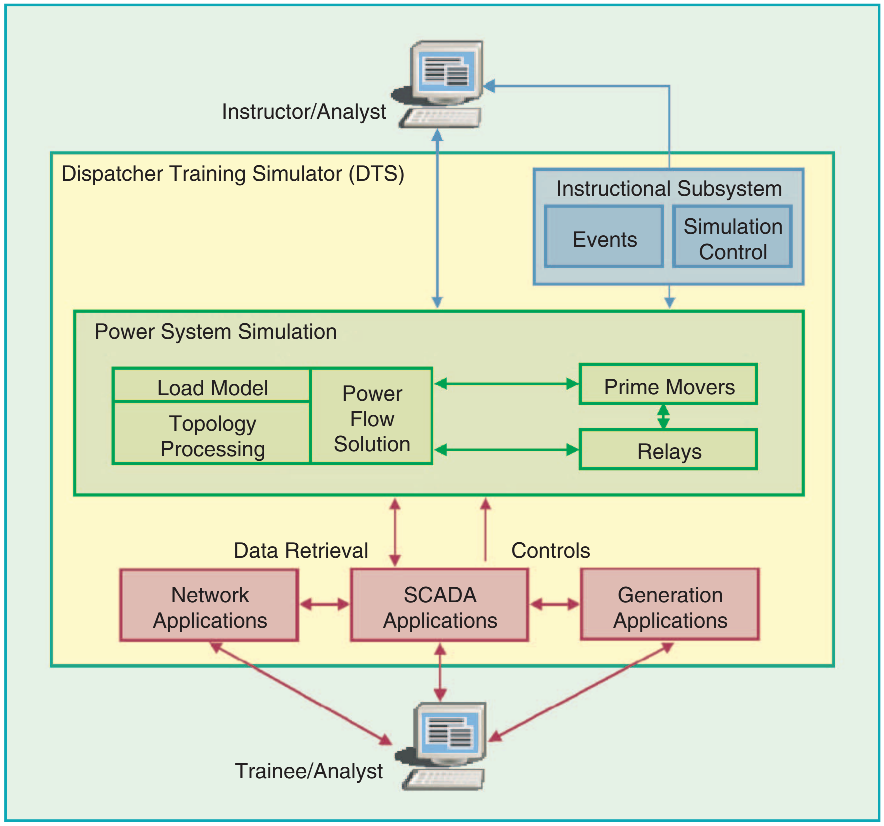

figure 2. DTS functional overview.

Control Room Integration of Wind Forecasting

When discussing impacts associated with wind energy, it is important to realize that wind is not totally unique. All elements of the bulk power network—generators, transmission lines, and substations—influence or increase the aggregate demand for ancillary services. The challenge is to understand what is different about wind energy (and what is not really much different) so that wind energy can be integrated as a mainstream component of the energy system.

The wind power forecast is obviously a critical element when it comes to integrating large amounts of wind energy, but the way that the forecast is used is just as important. The forecast is wasted if it is not integrated into utility operations and markets in a way that makes the information useful and actionable. If the operators are not confident in the forecasts, or if the forecast information is not presented in a way that is useful to them, they are likely to operate the system in a more conservative manner that will increase cost impacts.

Integration of wind forecasting information directly in the utility control center energy management systems (EMSs) is needed to:

- ✔ mitigate risks and consequences of inadequate situational awareness in control centers
- ✔ increase the confidence of system operators and dispatchers to manage wind variability
- ✔ reduce costs through improved operational planning and utilization of generation and transmission resources for the system as a whole
- ✔ increase the benefits of wind forecast and extract its full value to the system.

A current area of investigation is how to use simulation methods all the way down to the detailed control room environment. This simulation can be done using a dispatcher training simulator (DTS) that closely mimics the operation of the EMS and the power system. The DTS provides a realistic simulation of real-time power system operation and EMS functions.

As shown in Figure 2, the DTS is made up of three major components:

- ✔ the power system model, which provides the power system dynamic simulation functions
- ✔ the control center model, which is a replication of the EMS functions
- ✔ the instructor control component, which is used for setting up and controlling the simulation scenarios, reviewing the dispatcher's performance, and teaching the dispatcher.

A dispatcher using the simulator will work with a supervisory control procedure that exactly matches the procedure used on the real system. Often used for operator training purposes, this high-quality DTS simulates the entire power system and EMS system. The simulator can also be a powerful tool for analysis purposes.

We believe there are several promising areas for integrating wind forecasting information more tightly into power systems operations for both analysis and operator training scenarios.

Modeling of Wind Plant Characteristics for Operational Planning

As we move to higher penetrations of wind energy on power systems, modeling the dynamic characteristics for different timescales is becoming an important issue. Most of the recent attention has been focused on the dynamic modeling of large wind plants to study the impact on power system transient stability. For the purpose of operational planning, which involves unit commitment in the day-ahead time frame, as well as for real-time operational impacts, it is not necessary to have such detailed dynamic models. A generalized prime mover model is sufficient to capture the long-term dynamic interaction of the power plant with the power system, but currently there is no standard methodology for developing prime mover models for wind plants. Research is ongoing and results are promising. So what can we do right now?

Building on the methods that were discussed above for wind impact studies, one approach is to model the characteristics of a wind plant as a time series response that can be derived from actual measured power output (or, more powerfully, wind plant data that is modeled from historical weather data as done for the Xcel study). Until reliable analytical prime mover models are developed, such models provide a realistic approach for use in operational planning.

Using such time series data in the DTS, grid operators can improve operational planning for day-ahead and real-time system conditions. By studying the movement of other generators in response to wind plant power output fluctuation, ancillary service and other operational costs can be analyzed more accurately. An example of a time response model of a wind plant and the response of other generators within the simulation is shown in Figure 3.

Integration of EMS with Wind Forecasting

To integrate wind forecasting, a logical first step is to directly integrate real-time wind forecasts into the DTS (and eventually, into the EMS) much as we already do with load forecasts. The DTS should accept the wind plant forecasts calculated by a utility-wide wind forecasting system. The DTS uses the wind plants generation output (measured or forecasted) and drives the corresponding prime movers toward the forecasted targets. In the meantime, all the components of the DTS simulate the behavior of the power system and of the EMS in response to the wind farm behavior.

While the simulation is taking place, critical data such as operating cost deviations, system security, and reliability indices are gathered and consolidated as part of the wind penetration impact analysis.

Integration of Power System and Power Market Simulators

In the deregulated environment, the power industry restructuring has given birth to new business entities (i.e., independent system operators, transmission companies, and generating companies) using highly integrated and increasingly complex operational systems. This demands a high level of expertise and an increasing emphasis on quality control.

To meet these objectives, the simulation environments become key elements to conduct operation staff training, systems testing, and analysis. This goes beyond just the DTS. A testing and training simulation environment (TTSE) is needed that includes the DTS along with replicas of all the key elements of the real-time system (e.g., market management system, load forecast, and wind forecast).

Real-Time Power System Prediction with Look-Ahead Simulation

These concepts can be extended to address real-time operator needs by including the simulation environment in the control room. By being able to look ahead and perform operational system prediction, we can offer operators the situation awareness that is required to optimize the real-time actions that may concern them with higher wind penetrations.

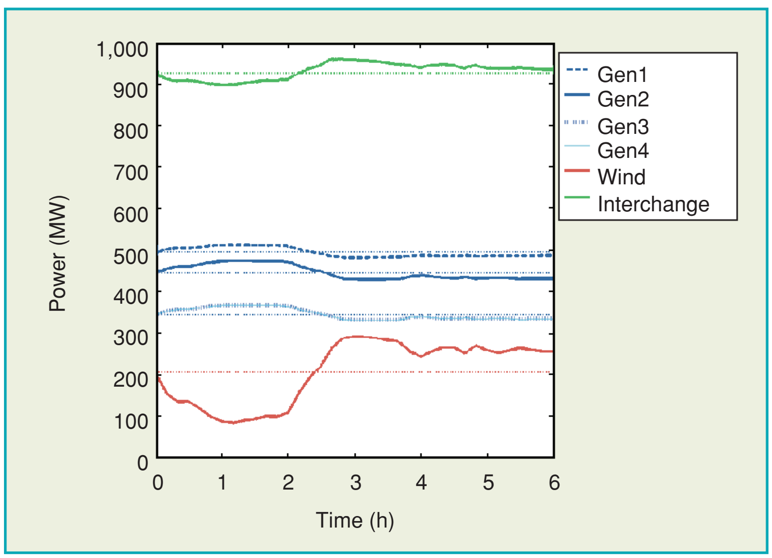

figure 3. Movement of system generators in response to varying wind plant output.

The simulation environment described above can be used in the operational environment, where it can be automatically initialized from the real-time conditions and then perform an ultrafast look ahead simulation, leveraging the wind forecast information. The ultimate objective is to provide displays that allow the operators and dispatchers to understand at a glance what is coming up in the next 10–40 min. This will involve a variety of indexes and decision-making support tools.

Using such a framework in the real-time operation environment, the operators will perform their duties while being aware not only of the wind forecast over the next few hours, but also about the forecasted wind's impact on the operation of the power system. With such visibility, the operator will be able to take the most appropriate decisions to leverage and control the wind power benefits.

An important topic for future research is analytical methods in the simulation environment to study the interactions between the stochastic output of a wind plant, the probabilistic loading of transmission lines and other equipment that connect the wind farm and the load, and the probabilistic nature of real-time energy prices. More work is needed to improve the accuracy of look-ahead simulation techniques before operators can have confidence in power system prediction with wind forecast. An important subject in this regard is the ability to forecast and provide warning of high wind events that can lead to more extreme fluctuation in the wind plant output. Such an early warning system will give operators continuous situational awareness about the health of the system.

Utilizing ultrafast simulations, operators and dispatchers can mitigate the risk of system failures. They would be able to take preventive actions based on forecasted system conditions that provide improved situational awareness and optimal real-time decision making.

Advances in Unit Commitment Methods

Unit commitment focuses on developing a low-cost generation plan that can meet expected load while maintaining reliability. Recent advances in unit commitment solutions include using mixed integer programming (MIP) methods for solving large system unit commitment problems. The successful use of MIP now makes it possible to solve this previously intractable problem without the use of complex decomposition methods. The MIP approach also allows for more sophisticated modeling of many resources such as combined cycle plants. With improved modeling of such resources, the operational impacts of wind plants on grid and market operations can be more accurately analyzed.

Conclusions

To run the power system most efficiently and effectively, we must focus our attention on the system as a whole rather than on individual components—and this is true regardless of whether or not the system includes wind generation. As larger amounts of wind energy are added to our power systems, we must certainly be aware of the impacts of its variability on the system, but we must also keep in mind that our power systems are already designed to deal with substantial amounts of uncertainty and variability. By making proper use of wind forecasting and integrating it into our control rooms and our systems, we can facilitate the cost-effective use of wind energy as a mainstream component of the energy system.

For Further Reading

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Biographies

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William Grant is the director of power operations in the commercial enterprises business unit of Xcel Energy. He is responsible for the economic dispatch and real-time merchant and the short-term analytical functions for Xcel Energy. He has been employed in the electric utility industry for 27 years and has experience in power plant operations as well as bulk power operations.