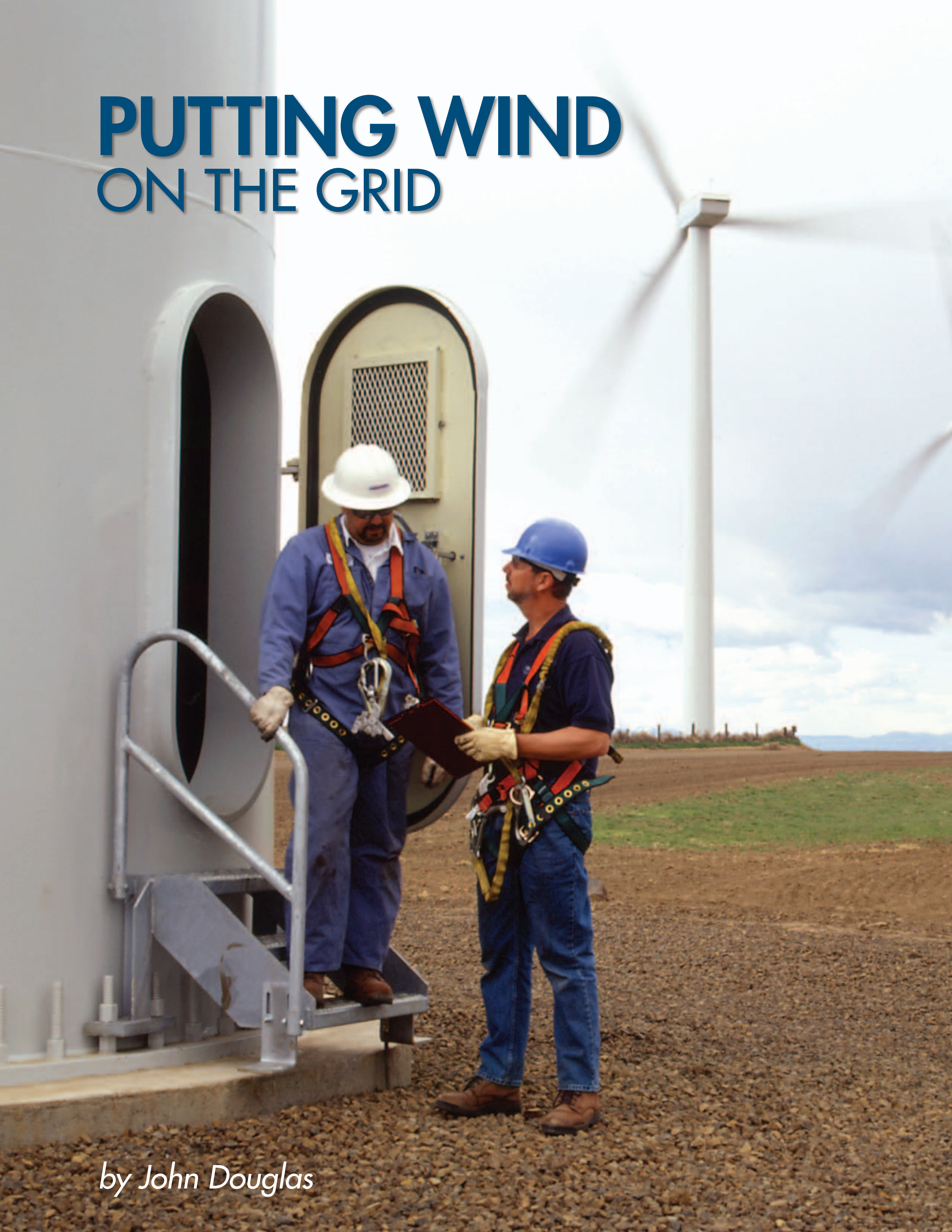


PUTTING WIND
ON THE GRID

by John Douglas

PHOTO COURTESY GE ENERGY

The Story in Brief

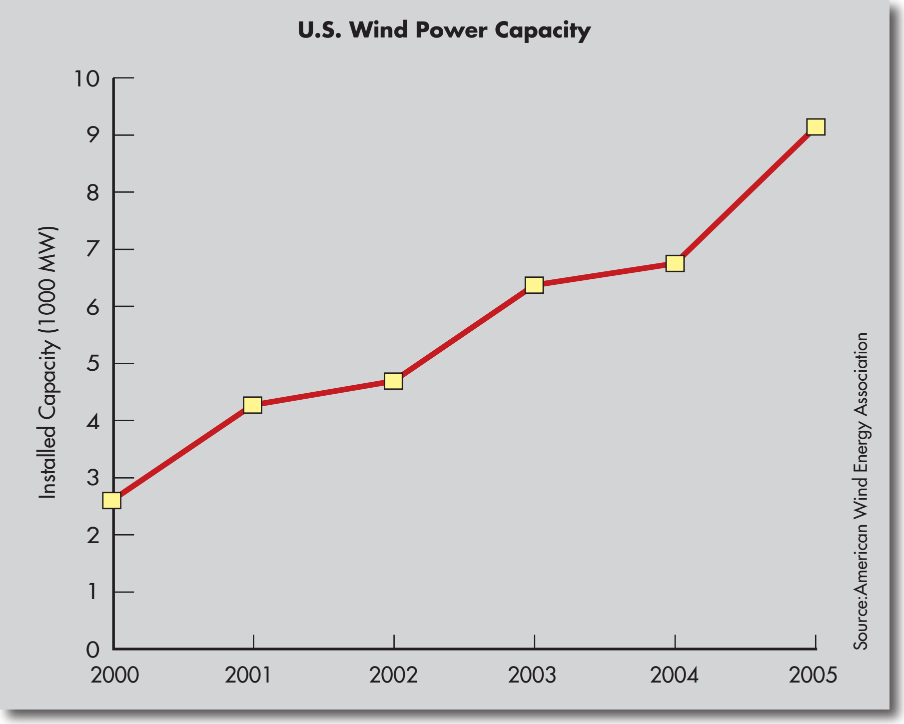
Over the last twenty years, technological advances and manufacturing experience have driven down the cost of electricity from wind by more than 80%—contributing to the 20–30% annual growth of wind capacity worldwide and making wind the fastest-growing large-scale power generation technology in the world. So far, most of the progress is the result of making wind turbine-generators larger, more efficient, and more reliable. Now, as the industry pursues development of even larger wind turbines for offshore applications and further improvements in cost and performance, it is also addressing a second technological thrust: to facilitate the integration of large concentrations of wind generation into electric power grids. If these efforts are successful, utility networks will be able to accept higher levels of wind-based generating capacity, potentially enabling wind power to increase its contribution to U.S. electricity from 0.4%, the figure for 2004, to as much as 5% by 2020.

Today's wind turbines literally tower over those of twenty years ago; they are taller than the Statue of Liberty and have rotor diameters equal to or exceeding the wingspan of a jumbo jet. Capacity ratings of individual turbines have grown even more spectacularly, from dozens of kilowatts in the early 1980s to multiple megawatts today. In addition to increased size, which allows turbines to access the stronger winds aloft and capture their energy more efficiently, today's generators have the ability to operate over a wider range of wind speeds, increasing annual energy output. The bottom line is that electricity from utility-scale wind conversion now costs about 7.5¢/kWh, not including tax credits.

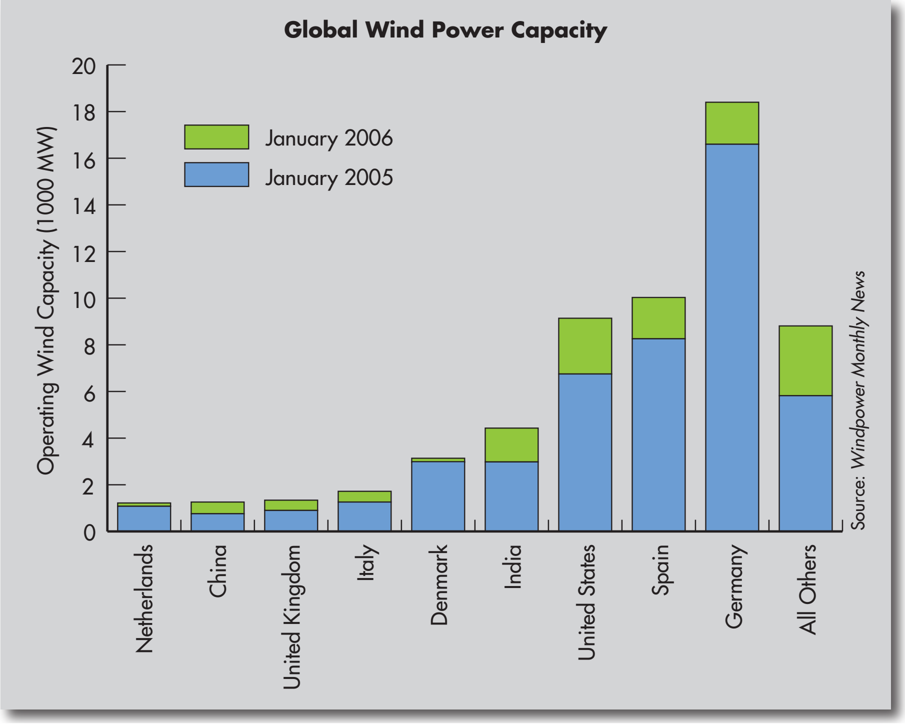
Although such costs make wind power roughly competitive with electricity generated from fossil fuels—particularly in a time of high oil and gas prices—other significant challenges need to be addressed before wind can provide for more than a small percentage of the nation's total electric energy. As installed wind capacity in a region grows and approaches more than about 10% of the system load, the intermittency of wind energy can become a significant issue. Even in areas with relatively favorable wind resources, the annual capacity factor of wind generators (the average actual output as a percentage of the rated output) is typically about 25–35%. This is because wind speed varies with the time of day and the month of the year; for much of the time, it is below the speed needed for a wind turbine to generate power at its rated capacity. In addition, the electrical characteristics of some wind generators affect grid operation and can make grid integration difficult. Fortunately, a number of new technologies and deployment strategies are making wind energy more grid friendly, promising continued growth in its share of total energy. These include improved wind energy forecasting, power electronics, and energy storage.

Better Forecasting Needed

Wind energy forecasting, which relies on numerical weather predictions, meso-scale



The increase in U.S. installed wind capacity has been impressive, with an average annual growth of more than 30% over the last five years. Extension of the production tax credit through the end of 2007 is expected to keep investment high.



Nine countries account for over 85% of the world's wind capacity. While Germany has been the world's largest market for nearly a decade, Spain, the United States, and India have had higher growth rates in recent years. Wind energy currently contributes more than 4% of Germany's electricity supply and nearly 20% of Denmark's.

Advanced designs and use of stronger, lighter-weight materials such as carbon fiber have made wind machines larger and more efficient than ever. Some turbines have blade diameters longer than a football field and sit atop towers as tall as 110 meters. At least one company is testing a 5-MW turbine, while others are working on design concepts in the 5–8-MW range.

wind-flow models, and advanced statistical methods, is already being used to support electricity system operations. Because wind speed and direction can vary over time periods that range from minutes to seasons, integrating electricity from turbines into a utility power system requires the system operator to compensate for these variations by using energy from other, conventional generators. The costs of providing such compensation can vary significantly, depending on the nature of the wind in a region, the characteristics of the control area into which the wind generation is integrated, and the rated wind capacity relative to other generation and system load levels.

One of the largest costs associated with wind operations results when day-ahead and same-day forecasts of hourly wind generation turn out to be inaccurate—that is, when the hourly wind generation is substantially higher or lower than the forecast. Typically, same-day forecasts are issued at least every hour, and next-day, 48-hour forecasts are issued twice daily. If next-day forecasts prove to be significantly off base, the grid operator must either arrange to supplement lower-than-expected wind energy output with other generation, or back off scheduled generation to allow higher-than-expected wind energy output. If same-day forecasts are in error, the operator must ramp other generating units—units usually held in reserve to provide load-following and regulation services—either up or down in response.

The impact of inaccurate forecasts depends on the wind penetration (the fraction of the system peak load supplied by wind), the ramp rate of wind generation (the hourly change in wind generation relative to the previous hour), and the makeup of the electricity system. In most cases, the cost of managing intermittency increases as wind penetration and ramp rates increase. A recent EPRI Technical Update shows that hourly-time-frame integration costs, such as forecast uncertainty and inter-hour load following, range from about 0.18¢/kWh for 3.5% wind penetration, incurred at Xcel Energy, to 0.55¢/kWh for 20% penetration, at PacifiCorp. Such extra unit-commitment costs could be reduced significantly if better wind forecasts were available.

EPRI has been monitoring and evaluating cutting-edge wind forecasting technologies since 1998 in collaboration with both the California Energy Commission and the U.S. Department of Energy. The forecasts are generated through a variety of techniques that include weather prediction, wind-flow modeling, evaluation of plant operating conditions, and statistical analysis. While better day-ahead forecasts will help system operators improve their generation-unit commitment planning, moreaccurate hour-ahead forecasts will provide an opportunity for wind power producers to bid competitively into energy markets.

Developing better forecasts of up-and-down hourly ramp rates is becoming especially important for regions that have large blocks of wind generation. Such forecasts need to be received with sufficient lead time to allow system operators to anticipate the change and increase or decrease other generation to compensate. This capability will become even more important if wind development accelerates, as expected, in the United States and Europe in response to government mandates and other green-energy requirements. EPRI is continuing to work with utilities and regional system operators to develop, test, and implement forecast-technology improvements in collaboration with utilities and system developers. EPRI is also developing and testing a wind energy forecast workstation under an EPRI Technology Innovation grant.

The California Independent System Operator (CAISO) is currently offering a new time-averaging approach, the Participating Intermittent Resources Program (PIRP), to encourage wind power integration. Usually, generators of all types submit a schedule of hourly bids into the day-ahead or hour-ahead market, and penalties for deviation from this schedule are assessed every 10 minutes. The risk of deviation charges could be prohibitive for wind farm operators, who cannot control their power output. To provide a more attractive alternative, PIRP assesses charges on the basis of monthly net deviations—provided that the wind power bids are established using CAISO's own customized wind forecast service. The result has been a very low average monthly charge, and several major wind producers now participate in the rapidly expanding program.

Dealing With Short-Term Fluctuations

While improved forecasting can help with the dispatch problems that wind's intermittency introduces, shorter-term variations in the wind resource can cause other technical problems. Several of these concerns relate to matching the electrical characteristics of the wind turbine's power output to those of the local power network. For example, system energy balance can vary when wind gusts—lasting only minutes or seconds—cause the power output of the turbine to change rapidly. Voltage disturbances can also be a problem; voltage sags, which may result from a grid fault, can trip a group of wind turbines off-line unless the turbines are equipped with low-voltage ride-through capability.

Another technical challenge to the widespread use of wind power is the fact that most wind turbines installed to date have only a limited ability to control reactive power. In addition to providing useful power, measured in watts, generators should also be able to create reactive power, measured in volt-amperes reactive (VARs), which is needed to support the constantly changing magnetic fields in ac circuits. While most conventional utility generators can control both real and reactive power, the induction generators used in most wind turbines absorb reactive power rather than control it, a problem exacerbated by variations in wind speed.

The use of power electronics with wind turbines can largely eliminate such problems, allowing efficient variable-speed operation, controlling reactive power, and providing better low-voltage ride-through capability when a grid disturbance occurs. Fortunately, the advent of larger turbines and massive wind farms is coinciding with the development of lower-cost power electronics technologies to make these solid-state solutions more economically attractive.

An important first step has been to establish a baseline for wind plant performance through high-resolution monitoring of wind intermittency, so that specific needs for power compensation can be better defined. Two recent studies, in particular, have provided important data on the

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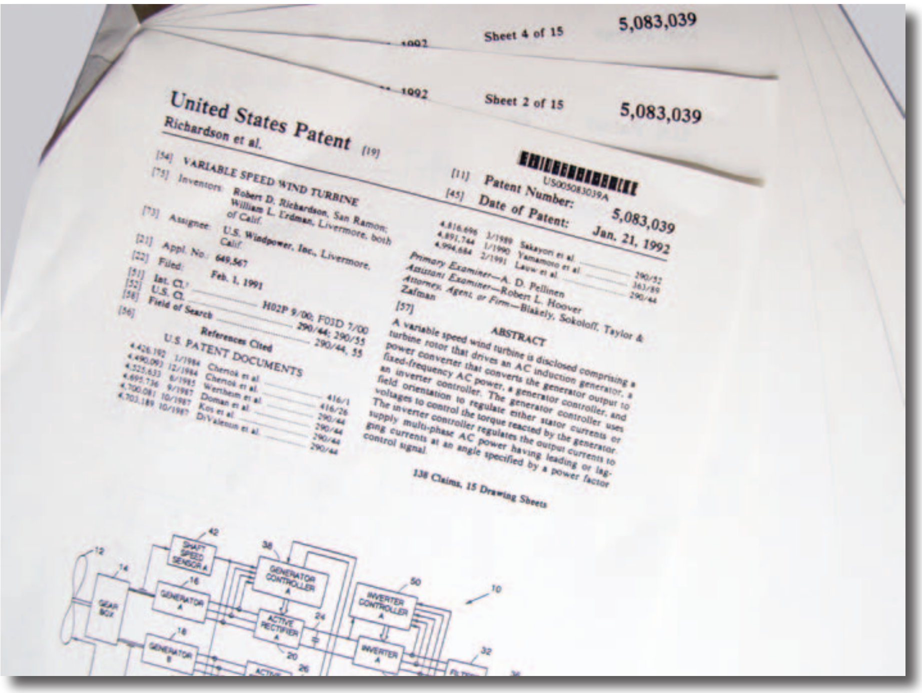
Capturing the kinetic energy of the wind is only the beginning of the challenge for wind farms. The intermittency of the wind resource can cause problems with unit scheduling and dispatch, load following, and contingency reserves, which can potentially add to the cost of operations. Another challenge is the fact that the wind generator's electrical output must match that of the grid that it's tied into, requiring control of reactive power and protection against voltage disturbances. These difficulties are being addressed successfully through improvements in wind forecasting, the use of power-electronic controllers, and additions of small amounts of energy storage.



Sheet 4 of 15 5,083,039

Sheet 2 of 15 5,083,039

United States Patent [19]
Richardson et al.

[11] Patent Number: 5,083,039
[45] Date of Patent: Jan. 21, 1992

US005083039A

[54] VARIABLE SPEED WIND TURBINE
[75] Inventors: Robert D. Richardson, San Ramon; William L. Erdman, Livermore, both of Calif.
[73] Assignee: U.S. Windpower, Inc., Livermore, Calif.
[21] Appl. No.: 649,567
[22] Filed: Feb. 1, 1991
[51] Int. Cl.⁵ H02P 9/00; F03D 7/00
[52] U.S. Cl. 290/44; 290/55
[58] Field of Search 290/44, 55
[56] References Cited

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[57] ABSTRACT

A variable speed wind turbine is disclosed comprising a turbine rotor that drives an AC induction generator, a power converter that converts the generator output to fixed-frequency AC power, a generator controller, and an inverter controller. The generator controller uses field orientation to regulate either stator currents or voltages to control the torque reacted by the generator. The inverter controller regulates the output currents to supply multi-phase AC power having leading or lagging currents at an angle specified by a power factor control signal.

138 Claims, 15 Drawing Sheets

The first variable-speed wind turbine, commercialized in 1993 through a partnership of EPRI, U.S. Windpower, Niagara Mohawk, and Pacific Gas and Electric, revolutionized turbine design. Integrated power-electronic controls allowed the advanced turbine to generate 60-Hz ac power at varying rotor speeds. This innovation not only increased wind capture, reduced power output fluctuations, and prolonged the life of the turbine drivetrain, but also greatly expanded the regions where wind power can compete with other generation sources.

output power variability of large wind farms. The National Renewable Energy Laboratory (NREL) conducted the first monitoring project to collect data at very high resolution at large wind farms. Among other results, these data have provided a new understanding of how electrical disturbances on the grid can cause wind turbines to trip off-line and, conversely, how disturbances at the wind farm can affect the grid. This new information has allowed wind farm operators to design corrective measures and reduce forced outages of individual wind turbine rows, as well as of the entire wind farm.

Another high-resolution study, conducted by the New Energy and Industrial Technology Development Organization (NEDO) of Japan, determined some of the factors that affect power output diversity among individual turbines on a wind farm. For example, wake turbulence from upstream turbines was found to significantly affect downstream turbine output. The main question then was how much such diversity helped smooth out power fluctuations from individual turbines. NEDO researchers concluded that smoothing is significant over time periods of less than 10 minutes, because differences in fluctuations tended to cancel each other out. For periods of more than 100 minutes, however, there was more coherence among the outputs of various turbines and less smoothing, as more-persistent wind changes affected the wind farm as a whole. In both the short-term and long-term cases, there was more smoothing for multiple wind farms that had dozens of turbines dispersed over a wide geographic area.

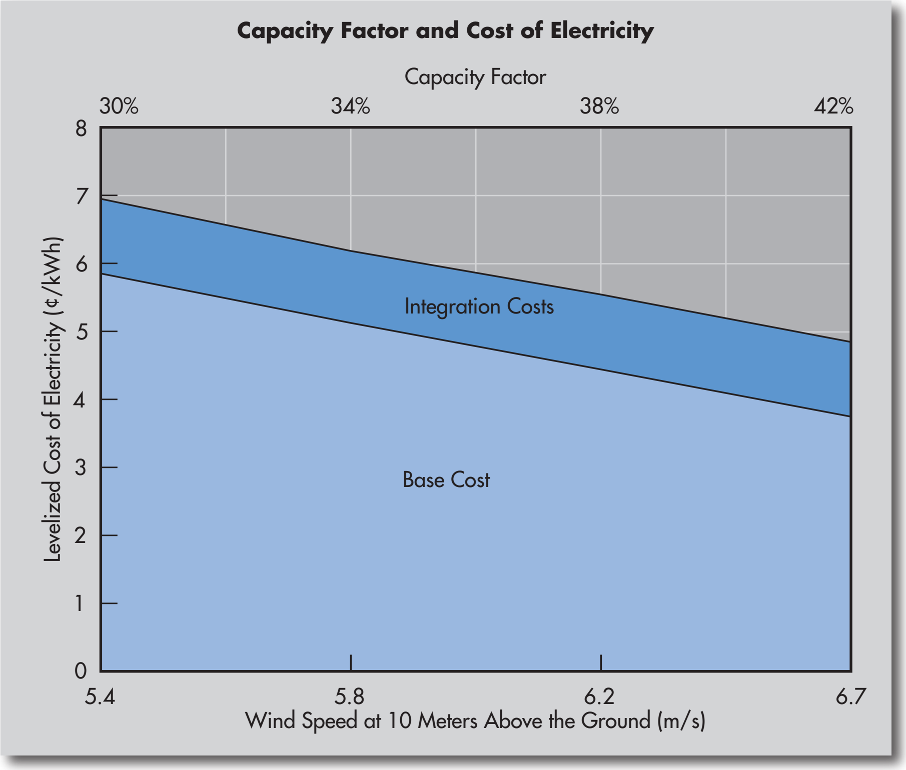
Power-Electronic Solutions

These monitoring data and new technological opportunities have led to considerable recent progress in smoothing short-term power fluctuations. Part of the problem stems from the relatively simple and inexpensive type of turbine generator that has dominated wind energy installations for many years. Now, as wind turbines grow larger and more powerful, they are becoming better able to support more-complex generator designs, including the addition of power-electronic controllers to provide power output smoothing. Although incorporating power electronics is still relatively expensive, the resulting support of variable-speed operation can lead to major savings elsewhere—for example, in lighter-weight mechanical components and lighter foundations for offshore applications.

One popular way of using such controllers is to install a power-electronic converter that feeds the rotor winding of the generator, while the stator windings are still connected to the grid. This doubly fed induction generator not only enables variable-speed operation but also controls the exchange of both useful and reactive power with the grid. Such a design has the economic advantage of combining the low-cost induction generator with power electronics that need be rated at only about 30% of generator rating in order to control variations in output. One drawback of the doubly fed turbine, however, is that the power converters are relatively sensitive to grid disturbances. A low-cost way of keeping this turbine from tripping off-line is to add a set of resistors that the converter can use to divert power to the rotor winding and thus provide ride-through capability.

As the cost of power electronics continues to fall, more-versatile designs that process 100% of the wind power current—technology pioneered through EPRI funding—are becoming more affordable. These designs allow a wider range of variable-speed operation and provide cost savings by eliminating the wear-prone gearbox previously used in most turbines. Perhaps the most important advantage has been excellent low-voltage ride-through capability; as the penetration of wind power grows, the prospect of losing a large part of the generation to a grid disturbance is becoming increasingly unacceptable.

Further advantages can be realized by



Increasing the capacity factor (CF) of wind installations can significantly reduce their levelized cost of electricity. While efficiency gains and other technical improvements to the turbines can improve CF, the biggest increases will come from being able to tap into more-consistent wind regimes, such as those available at high elevations and offshore. A 42% CF could reduce the cost of wind generation to below 5¢/kWh, without tax credits.

physically splitting the rectifier and inverter stages of the power converter and connecting them with a high-voltage dc (HVDC) link. A short HVDC link between the stages of the electronic controls provides a convenient way to synchronize output power with the grid without concern about frequency shifts created by variable-speed operation. In addition, the HVDC link could potentially be extended to carry large amounts of power over long distances.

While individual turbines can be modified for output smoothing, a more adaptable (though more expensive) option is to control the interface between a wind farm and a grid by using power electronics in stand-alone auxiliary equipment. A number of custom power devices are being tried for such applications, particularly in situations where fast reactive power control is essential. The DSTATCOM, for example, is a device that uses power-electronic switches to insert an appropriate number of multistage power capacitors into the circuit so quickly it can help solve the problem of voltage flicker caused by certain types of large loads elsewhere on the system.

Energy Storage for Smoothing Output

Energy storage is an often-discussed option for dealing with wind's intermittency. (See the accompanying article "Energy Storage: Big Opportunities on a Smaller Scale" for more information on storage technologies and their application.) EPRI research indicates that although installing energy storage capacity at a wind farm is not essential, it practically eliminates wind integration issues and can add several value streams for overall grid operations. Unfortunately, the high cost of storage systems limits the situations in which they are useful. A pre-existing energy storage facility, if available, can ease the solution of wind integration issues, but the business case for constructing high-capacity, long-duration energy storage solely to solve wind integration issues has been limited to very remote or island systems.

Nevertheless, for some applications, a relatively small amount of storage capability packaged for short-term and fast response can be quite beneficial. For example, adding storage to an electronically controlled interface between a wind farm and the grid can further enhance the dynamic response, providing reactive power for voltage control and real power for damping energy oscillations. More than a dozen large wind farms in North America currently use some form of static or dynamic reactive power compensation.

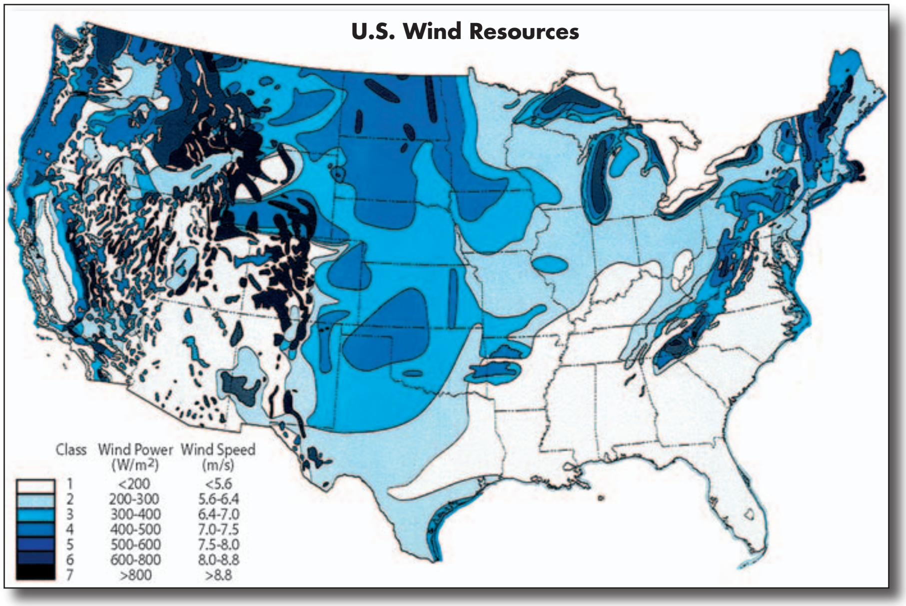
In applications where dynamics are more critical and where other compensation resources are limited, ultracapacitors and flywheels have also been considered. Hawaiian Electric Company, for example, recently patented and installed a prototype of its Electronic Shock Absorber (ESA) at a wind farm on the island of Hawaii. The installation is specifically designed to store energy during wind gusts and then return the energy to the grid during a lull or to compensate for sudden loss of one of the turbines. This function is most critical when other island generation is at a minimum, such as at night, when the wind power fluctuations could significantly affect the stability of the island's relatively small grid. The ESA can also add or absorb reactive power as needed to help compensate for voltage changes originating on the grid. Energy storage in the ESA is provided by ultracapacitors, which are compact enough to make the device potentially mountable on a truck trailer.

Other applications require adding enough storage to substantially shift the timing of wind farm output. Particularly during periods of minimum load, power output may exceed system requirements, resulting in curtailment of wind generation and lost revenues. A relatively large energy storage system could capture the extra energy produced at these times and deliver it later, when curtailment is not necessary. Similarly, output shifting could enable a wind farm operator to effectively arbitrage between times of peak generation and peak pricing. Even a few minutes' worth of storage capacity would enable a combined wind/storage facility to replace some conventional generation in performing ramping functions.

Bulk Storage Technologies

The most mature technology for handling bulk power over longer time periods is pumped-hydro storage, which uses electricity generated during off-peak hours to pump water from a reservoir at low elevation into a reservoir at a higher elevation. The energy is recovered when the water flows back to the lower reservoir through hydroelectric turbine generators. In principle, wind energy generated during off-peak hours can be stored in pumped-hydro facilities for regeneration at a later time. This approach has sometimes been optimistically called the "wind and water" scenario for expanding the use of wind energy. The main obstacle to this scenario lies in the difficulty of siting new pumped-hydro storage facilities, which requires finding suitable terrain with sufficient water, purchasing the large amounts of land required, and obtaining the necessary environmental and building permits. In addition, since the remaining appropriate sites tend to be remote, construction costs would be high and new transmission lines would be required. As a result, the extensive construction of new pumped-hydro storage facilities for storage of wind energy is unlikely.

Existing hydroelectric facilities can be used as a sort of "virtual storage" to compensate for wind intermittency as needed, while allowing available wind energy to save water supply reserves for hydro generation. In one example, the Bonneville Power Administration (BPA) recently introduced its Network Wind Integration Service, charging wind farms a flat integration fee of 0.6¢/kWh to provide the necessary compensation for intermittency. In turn, the wind energy offers BPA a way to conserve its hydro resources, which tend to fluctuate seasonally and which provide more revenue if saved for use during peak hours.



The highest wind speeds in the country are typically found on mountain peaks and offshore, but good wind resources are available in large expanses of the Great Plains, the upper Midwest, and the Southwest. Unfortunately, many of the best of these sites lie far from population centers, requiring additional transmission capacity to get the power to where it is needed.

Besides pumped hydro, the only other mature commercial technology that can store and regenerate energy in bulk for utility-scale power generation is compressed-air energy storage (CAES). Air is stored at high pressure in underground salt caverns, mined hard rock, or the porous rock of a depleted gas field. The system is charged by an electrically driven compressor during off-peak hours; the compressed air is later fed into the combustion chamber of a gas turbine to generate on-peak power. This scheme reduces by 40% the amount of natural gas required to generate a megawatt of electricity, because gas turbines generally consume more than this amount just compressing air for use in combustion. Two CAES systems have recently been proposed for use with wind generation. One, with a generating capacity of 100–200 MW, is scheduled to begin operation in Iowa by 2009. The other, with a generating capacity of 270 MW, was evaluated for application to a wind farm in West Texas, but subsequent transmission line upgrades displaced part of the potential value of the storage facility.

Electrochemical storage batteries have often been proposed for storing energy from wind. Lead-acid batteries have been investigated for both stabilization and time shifting, but research to date indicates that such batteries would not be a cost-effective choice for deep-discharge applications. The limited storage capacity and short service life of lead-acid batteries make it difficult to make an economic case for them in wind support activities at present.

A relatively new battery technology that is already being installed to provide storage at the megawatt level for wind farm output stabilization and time shifting is the vanadium redox battery (VRB). The VRB is one of a class of devices known as flow batteries, in which the active materials are contained in two liquid electrolytes rather than in the solid electrodes. VRBs have already been installed for use with wind. On King Island, Australia, for example, a 200-kW unit provides stabilization and time-shifting services for a 2450-kW wind farm. A similar installation at a larger scale has been built in Japan at the Tomamae Wind Villa facility in Hokkaido. This VRB is sized to provide a 4-MW discharge for 1.5 hours or 6 MW for 20 minutes.

Another battery technology that has potential in wind applications is the sodium-sulfur battery, often known by its commercial name, NAS. The NAS technology is based on high-temperature electrochemical reactions between sodium and sulfur, mediated by a beta alumina ceramic electrolyte. In Japan, NAS technology has been used several times specifically for wind power stabilization and time shifting. In 2001, for example, a 400-kW NAS battery was used to provide stabilization as well as 7 hours of storage for time shifting for a small wind installation on the island of Hachijojima.

Prospects for the Future

Although most of the recent wind energy development has been focused on land-based installations, a recent EPRI report concludes that "the longer-term future appears to be offshore wind. . . . In fact, over the next five years, more than 2300 offshore wind turbines are predicted to be installed worldwide at a cost of $13 billion." Generally, the motivation for offshore development is access to higher wind speeds and, in some cases, fewer logistical obstacles. More than 600 MW of offshore wind capacity is currently operating in Europe, with major projects already commissioned off the coasts of Denmark and Ireland, another under construction off Scotland, and ambitious offshore programs being pursued elsewhere.

A major driver for offshore wind development in the United States is customer location: the best wind resources on the East and West Coasts are offshore, close to population centers; most land-based wind farms are situated in the middle of the country, far away from large populations. U.S. wind power developers have been hindered by local opposition to offshore installations and the lack of a clearly defined federal permitting process. NREL is focusing on a long-term solution of putting offshore wind turbines farther offshore—in deeper water and over the horizon—but this approach will require the development of affordable floating platforms similar to those used in the oil and gas industry.

In the United States, only two major commercial offshore wind projects have been proposed so far: the 130-turbine, 454-MW Cape Wind project off Cape Cod, Massachusetts, and the 40-turbine, 140-MW Long Island Wind Power Initiative off the coast of Long Island, New York. Although the Long Island project has generally enjoyed local public support and is expected to be operational in 2008, Cape Wind has become embroiled in bitter political battles at both state and federal levels. In addition to these commercial projects, Southern Company and Georgia Tech are evaluating the feasibility of a small-scale pilot project off the Georgia coast.

Further in the future, tying together wind farms on a regional basis would bring several advantages, including inherently

PHOTO COURTESY GE ENERGY

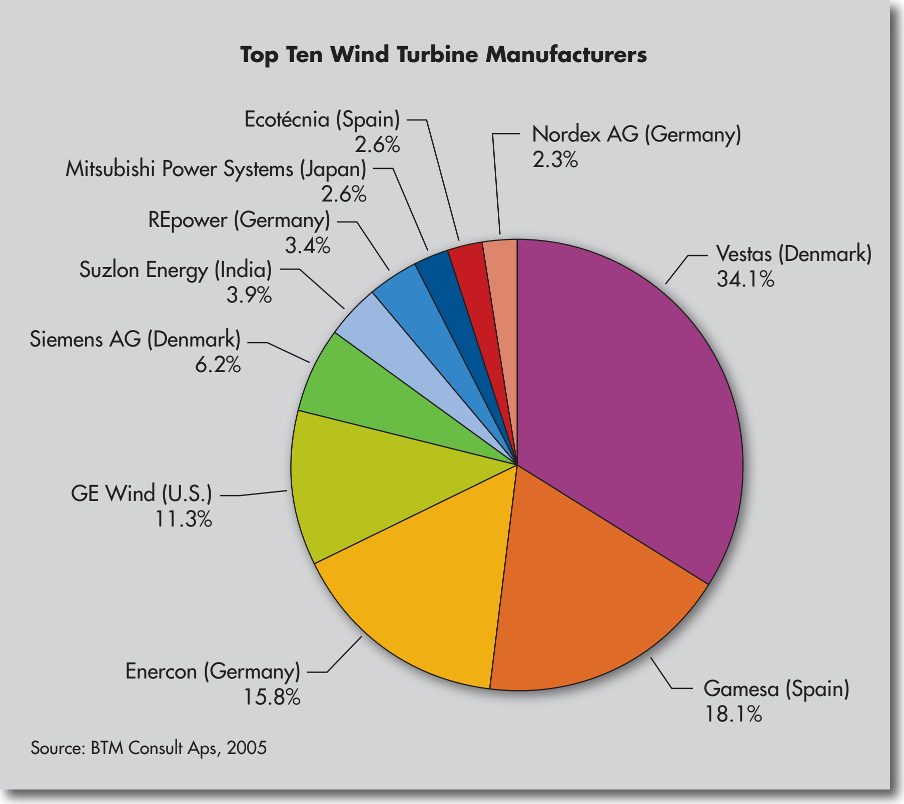
Ireland's Arklow Bank Wind Park exemplifies Europe's success in exploiting superior coastal and deep-water offshore wind environments. Two offshore projects are currently being pursued in the United States—a 130-turbine, 454-MW project near Cape Cod and a 40-turbine, 140-MW project off the coast of Long Island—and other offshore projects are being considered near Savannah, Georgia, and Galveston, Texas. However, the threat of local opposition and the lack of a clearly defined federal permitting process are tending to hinder offshore development in this country.

smoothing out intermittency problems by balancing strong winds in one area against lulls in another. It would also facilitate the delivery of power to load centers from abundant wind resources in remote areas, which might otherwise remain stranded. Bringing about such regional integration, however, will require changes in both transmission system planning and pricing. Today, few individual wind projects can afford to pay for transmission expansion on their own, and most transmission tariffs include penalties for differences between scheduled generation and actual production, which can significantly impact the cost of wind integration.

Several efforts are under way to overcome obstacles to bulk wind power integration on a regional basis. The Midwest ISO (MISO), for example, has considered the implications of introducing a 10% renewable energy objective throughout its region; this would require integrating about 19,000 MW of wind generation—a huge increase over the current 860 MW of network-connected wind capacity. As a guide to potential developers as they make their investment decisions, MISO recently conducted a study of the transmission expansion that would be needed for 10,000 MW of new wind generation. A companion study looked at the capital expenditures required to increase renewable energy penetration by the year 2020. The 10% renewable energy objective for Minnesota is modeled in these studies.

The Federal Energy Regulatory Commission is considering rule changes that would reduce transmission tariff penalties for intermittent generators. One proposed change would be to offer wind farms "flexible firm" transmission service when long-term firm service is unavailable. Under this proposal, wind facilities would be provided the equivalent of firm service most of the time, but not during hours of peak electricity demand or if the transmission system became unexpectedly constrained. Combined with other technological advances and deployment trends already under way, regulatory changes of this sort could help make wind energy a major contributor to America's electric power future.

Background information for this article was provided by Chuck McGowin (cmcgowin@epri.com), Tom Key (tkey@epri.com), Daniel Brooks (dbrooks@eprisolutions.com), and Haresh Kamath (hkamath@eprisolutions.com).



Vestas Wind Systems has dominated the world wind turbine market—accounting for roughly a third of the installed megawatts in 2004—but Gamesa, Enercon, GE Wind, and Siemens are all aggressively expanding production and closing in on the market leader. GE Wind is the leading supplier of turbines installed in the United States.

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