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CHALLENGES OF INTEGRATING LARGE AMOUNTS OF WIND POWER

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Abstract – Wind energy has experienced remarkable growth over the last decade, due in part to renewed public support and maturing turbine technologies. But often hidden from public view are the difficulties and challenges associated with introducing a new technology into an older electrical system of established infrastructure. Many early wind turbines utilized a *squirrel-cage* or *wound-rotor* induction generator to produce electricity. These generators allowed small variations in rotor speed thus improving energy capture and reducing torque shocks caused by wind gusts. However, they absorbed large amounts of reactive power and sometimes caused severe voltage stability problems on the grid. This paper explores some of the solutions that have resulted over the years, including the introduction of two new variable-speed generator types, *doubly-fed induction* and *synchronous machines.* It also considers the evolution of new grid codes and turbine improvements that make wind energy more grid-compatible to ensure further growth of this promising renewable source of energy.

WIND: A NEW PLAYER

The wind industry has seen explosive growth in the last eight years, due to favorable tax conditions, renewed public interest, and maturing turbine technologies (Fig. 1). It is common for wind turbines to be collected into groups, called *wind farms*. The largest wind farm in the world is the Horse Hollow wind ranch in northwest Texas, boasting 421 wind turbines that are rated between 1.5 and 2.3 megawatts (MW) each. The farm stretches over 47,000 acres, and totals 736.5 MW of installed capacity[1] [1]. For comparison, many traditional thermal power plants are on the order of 200-300 MW, with the largest coal and nuclear power plants rated at 2,000 to 3,000 MW.

Although wind energy only supplies 0.6% [3] of the total U.S. electricity consumption, the concentration of wind energy into discrete large farms implies that it can have very significant effects on the local electric grid. This paper explores some of these effects: how wind energy differs from traditional sources of electrical energy, and how experts are working together to ensure reliable delivery of electricity as the number of wind farms continues to increase.

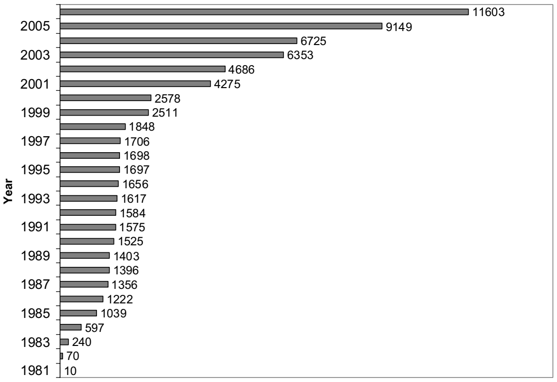

Fig. 1. U.S. total installed wind capacity (MW) 1981-2006 [4].

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[1] Installed capacity refers to the maximum amount of energy produced by the farm if winds are strong enough to run all turbines at full output. When averaged throughout the year, most wind farms produce 25-35% of their installed capacity [2].

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A GRID WITH LIMITED CAPACITY

Most electric grids are meshed networks of transmission lines connecting together cities, towns, and power plants. Interconnection improves reliability and opens electricity trading opportunities between energy companies. Because electricity cannot be stored on a large scale, power plants must constantly adjust their output to match the energy being consumed and maintain the grid frequency at 60 Hz.

In recent years, grid expansion has lagged behind growth in electricity consumption [5]. Consequently, the electric grid is becoming congested. During times of heavy load (heavy electricity usage), power lines approach their operating limits, and the grid operator must take action to prevent overloads. Wind energy is entering a world of increased competition for a finite grid capacity.

Fortunately, timing works in favor of wind energy: on land, wind tends to blow the strongest at night and during winter, while the grid tends to be more congested during the daytime in summer when electricity consumption is highest [6]. Although this makes wind energy less desirable in serving peak demand, it does allow wind to utilize the grid at times when it is less congested.

Ultimately, as wind farms and population centers continue to grow, new transmission lines will need to be built. Unfortunately, there are usually several obstacles [7]:

- Costs can easily exceed $1M/mile, and deciding how to distribute costs fairly among electricity producers and consumers often results in disagreements.
- Land must be purchased, numerous public hearings must be held, electrical-impact studies and even environmental-impact studies must all be run. This can take several years and significant cooperation.

Since wind farms can be built in under a year, developers sometimes build a farm, hoping that new transmission lines will soon arrive. On one occasion in Texas, the McCamey-area farms totaled 760 MW while the electric grid could only export 330 MW [8]. There were several times a year when the farm risked overloading transmission lines, and the Texas electric reliability operator was forced to curtail the wind farm output via computer control. Texas has since been working to solve this problem with ambitious transmission construction goals.

A WEAK GRID AND DIFFERENT TYPES OF GENERATION TECHNOLOGY

The windiest locations in the US tend to be isolated and remote [9]. These areas often have weak transmission infrastructure, meaning that the transmission lines operate at lower voltages and with higher impedances than stronger parts of the grid. Such lines are poorly suited to accommodating wind power. According to ohm’s law, higher impedance lines will incur higher voltage drops from one end of the line to the other for the same amount of current flow.

If this voltage drop is not accounted for, load centers (regions with many electricity consumers but few generators) would experience low voltages. To combat this effect, transmission companies usually install capacitor banks. Capacitors are electrical energy storage devices, which when connected to an AC system, inject reactive power[2] into the grid. This injected current compensates the load current, causing load voltages to rise. Depending on the severity of the voltage problem, utilities may choose to install fixed capacitor banks, which inject near-constant reactive power regardless of variations in load power, or they may use more expensive switched capacitor banks, where different amounts of capacitance are mechanically switched in and out to regulate the local system voltages to set values.

Wind turbines tend to create voltage problems on weak power systems. As a result of wind variability, weak grids with high wind penetration may experience significant voltage swings. Most grid codes require that the grid voltage remain

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[2] Reactive power is always associated with energy storage devices, such as capacitors and inductors. When connected to a steady-state AC voltage source, these devices charge and discharge with each cycle of the voltage source. The result is that no useful work is performed; rather energy moves back and forth between the energy storage device and the voltage source. The phase (timing) at which energy is stored and released is opposite for inductors and capacitors, and as a matter of convention, inductors are said to consume reactive power while capacitors are said to produce it. Reactive power corresponds to current flow that is phase-shifted 90 degrees from voltage.

within 10% of nominal for proper operation. A traditional switched capacitor bank cannot easily follow voltage swings caused by a wind farm, since these devices are only designed to correct slowly-changing voltages that naturally occur as load cycles over 24 hours. A *static var compensator* (SVC) is a much better solution [10]. This device is similar to a switched capacitor bank, but instead of mechanical switches, power electronic semiconductors are used thus achieving fast and continuously-variable reactive power output.

Another reason why wind turbines can sometimes cause unexpected problems on the grid is due to the electrical generator technology. Traditional power plants (fossil fuel, nuclear, and hydro) use synchronous generators, which rotate in synchronism with grid frequency. Grid frequency is 60 Hz in North America, so these generators commonly turn at 1200 or 1800 rpm, with the exact ratio depending on the construction of the machine. Wind turbines, on the other hand, use variable speed generation technologies to increase energy capture at different wind speeds. Virtually all wind turbines fall within one of the four main categories that follow [11], [12].

Type A: Many early commercial-scale wind turbines used a simple induction generator. Induction generators are almost identical to induction motors in construction (Fig. 2): the stator is wound with magnetic coils energized by the grid, while the rotor consists of a simple, solid metallic shaft, called a squirrel cage. The changing magnetic field from the stator induces currents in the rotor, which then again interact with the stator magnetic fields and cause the machine to absorb torque and generate electricity. Induction generators are simple, durable machines that allow only small variations in rotor speed, called *slip*, on the order of 1-3%. Higher values of slip correspond to faster rotor speeds and more power generated. But because this speed range is so small, windmills using these machines are typically called fixed speed turbines.

Type B: Sometime later, turbine manufacturers developed another generation technology with a higher speed range for increased energy yields. Starting with an induction generator, the solid rotor was replaced by a rotor with wound coils, which are then connected through slip rings[3] to a control box. The control box uses power electronics and power resistors to vary the effective rotor resistance and thus control rotor current flow (Fig. 3). This allowed the control system to change the generator slip-torque characteristic, enabling wider speed variations (slip over 0-10%). One turbine manufacturer, Vestas, is commonly associated with this semi-variable speed method, and so it is often referred to by the brand name “OptiSlip.”

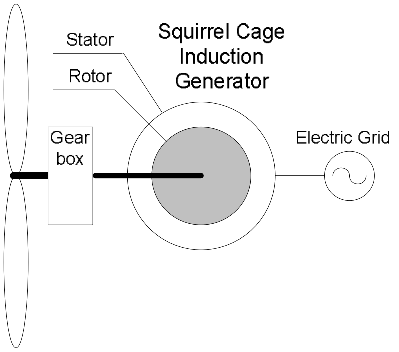

Fig. 2. Type A generator configuration.

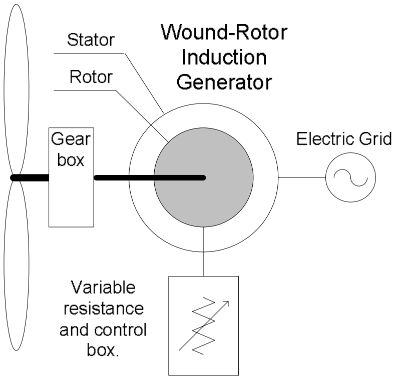

Fig. 3. Type B generator configuration.

Type C: An unfortunate characteristic of the induction generators used in Type A and B turbines is that the machines consume large amounts of reactive power. Since reactive power consumption lowers local grid voltages [13], wind farm developers using Type A and B turbines were often required to install large numbers of additional capacitors and SVC units at a high cost. To help overcome this problem, the wind industry turned to another type of generator, the *doubly-fed induction generator* (DFIG) [14]. This generator is much like the Type B generator, except instead of attaching a variable resistance

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[3] Slip rings allow electrical connections between stationary and moving parts of the machine.

to the rotor circuit, an inverter[4] is connected for active control of the rotor current magnitude, frequency, and phase (Fig. 4). By controlling the current magnitude, the inverter controls machine torque and thus real power generated. Controlling real power allows the inverter to control the blade speed: if the generator requires more torque than the blades produce, the blades begin to slow down. The inverter current phase offset translates into reactive power control of the entire wind turbine. Finally, the frequency of the injected rotor current cannot be set independently but must match the frequency difference between the rotor angular speed and the frequency of the changing magnetic waves within the stator (which is 60 Hz in North America, since the stator coils are connected to the grid). Thus, the inverter has full control over the active and reactive power output of the turbine.

Type D: Synchronous machines are another type of generator employed to solve the dilemmas of fixed speed and uncontrollable reactive power. This is the same type of machine used in a traditional power plant, and as implied by the name, the machine generates electrical power at a frequency directly related to the shaft speed by some fixed ratio. In order to achieve variable speeds, the output of the synchronous generator is electronically converted to grid frequency via an inverter (Fig. 5). Because the current output of the inverter is fully controllable, the inverter can control the real and reactive power transferred to the grid. If permanent magnets are used on the synchronous machine rotor to generate flux, then this type of machine is also referred to as a permanent magnet machine.

In the case of the Type D configuration, the inverter must be sized to carry the full generator output power, since it sits between the generator and the grid. The inverter in the Type C configuration is connected to the rotor, allowing a much lower rating. Typically about one third of the generator power passes through the inverter, with the remaining two thirds flowing through the stator terminals [15].

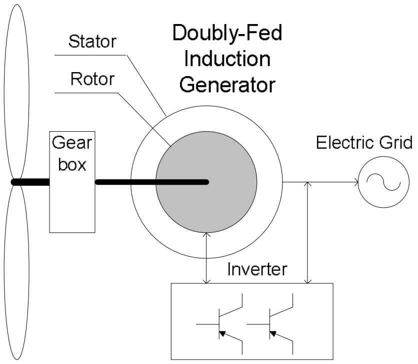

Fig. 4. Type C generator configuration.

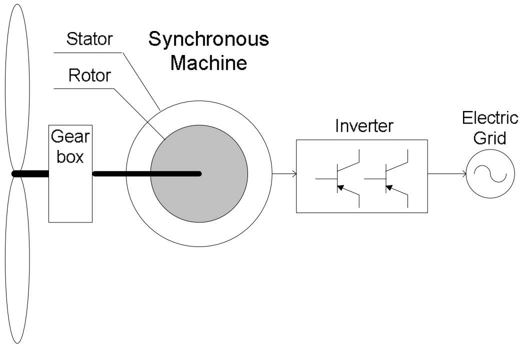

Fig. 5. Type D generator configuration.

The doubly-fed induction-machine turbine has grown to become the most popular type of wind turbine, judging by numbers installed. Better than the semi-variable speed and fixed speed turbines (Type A and B), this machine allows full reactive power control and reduces or eliminates the need for additional reactive power support devices at the substation. When compared with the Type D turbine generator, this machine has historically been less expensive due to the lower cost of the associated power electronics.

WIND TURBINE RESPONSE DURING FAULTS AND ABNORMAL GRID EVENTS

Faults are unexpected energy transfers between conductors and/or ground. Lightning strikes are the most common cause, with the lightning ionizing the air surrounding a transmission line and creating a temporary path to ground [16]. Fault protection is carefully engineered into all parts of the electric grid, and most lightning strikes never cause more than a brief service interruption to the customer. Faults usually cause a decrease in the surrounding system voltages due to the high currents involved. After a short delay, most traditional power plants in the region will

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[4] An inverter has power electronic switches to convert currents and voltages from DC to AC and vise-versa. A two-inverter back-to-back configuration is often used in wind turbines to convert from AC to DC and back to AC at a different frequency.

automatically increase their reactive power output to help raise the voltage. It is crucial to keep post-fault voltages close to nominal to ensure that protection systems operate properly and to prevent blackouts.

Original wind turbines (and even many wind turbines installed today) do not operate like traditional power plants during a fault. Manufacturers wanted to protect their equipment, so they often programmed the turbines to simply disconnect from the grid during any electrical disturbance. However, as the number of large wind farms continues to grow, many transmission operators no longer view this practice as acceptable. They worry that, if a fault suddenly sent offline all turbines in a wind farm, the combined effect of the fault and a sudden loss of generation might cause severely decreased voltages, and lead to voltage instability.

In response to this concern, transmission operators and regulatory agencies such as the Federal Energy Regulatory Commission (FERC) are drafting proposals that new wind turbines be equipped with *low voltage ride through* (LVRT) [2]. LVRT dictates that a turbine is to remain connected during a period of depressed voltage, and continue to deliver power to the grid. Graphs, such as the one shown in Fig. 6, outline the minimum voltage swing over which the turbine must stay connected. This new regulation has presented a challenge for many turbine manufacturers, especially manufacturers of DFIG (Type C) turbines. Due to the nature of the generator, a sudden drop in voltage at the machine stator terminals causes large currents to flow in the rotor. These currents can easily exceed the inverter ratings and damage the rotor inverter. To protect against this, most DFIG turbine manufacturers include a mechanism where upon over-current, the inverter is disconnected from the rotor, and a short circuit or a group of resistors is connected to the rotor instead [17]. This effectively turns the DFIG into a Type A or Type B generator. Although this scheme makes the generator very robust against grid events, the change causes the turbine to suddenly start consuming reactive power, which could decrease voltages and cause the LVRT scheme to do more harm than if the wind turbine had simply disconnected from the grid [18].

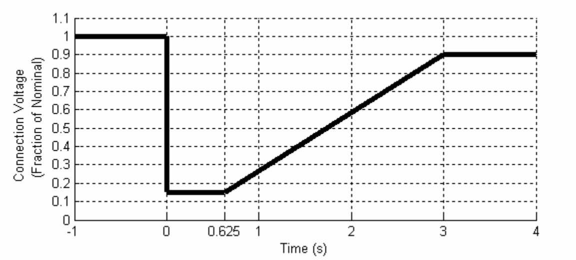

Fig. 6. LVRT scheme as proposed in FERC Order 661-A [19].

WIND VARIABILITY AND POWER SYSTEM OPERATION

Many people wonder, “What happens when the wind stops blowing?” Currently, wind accounts for a small percentage of total generation on the grid, so the variability of wind is negligible compared to natural variations in load. Load follows well-established patterns, according to the time of day, week, and month of the year, and according to the weather: people tend to consume the most amount of electricity during a hot afternoon workday, for example. Although the load pattern of a large population is very well understood, there still exists some random variability, and so power system operators must be prepared to adjust generation.

Operators maintain extra generation capability, called *reserves*, in the event that the load should suddenly increase, or a large power plant have mechanical problems and suddenly shut down. Spinning reserves are a category of reserves that can be made available in less than five minutes [13].[5] Many other types of reserves are slower-responding reserves, designed to meet slowly-developing unexpected swings in load. These can sometimes take the form of quick-start[6] generation units. Many reserves, especially spinning reserves, cost money to have available, thus the operator will maintain the least amount needed to satisfy standard reliability criteria: loss of load probability (LOLP) should be no more than one day in ten years [20]. Because load deviations are currently much larger than wind deviations, the addition of wind requires an almost negligible increase in system reserves.

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[5] Ten or fifteen minutes, by some definitions.

[6] Different power plants require different amounts of time and money to start up. Many large coal and nuclear plants require over a day to start up, and thus are often run around the clock. Smaller coal plants can start within a few hours and natural gas turbines can often start within minutes to meet the peak afternoon loads.

Wind penetration will continue to grow over the coming years, and at some point the renewable resource is expected to incur significant regulation costs. A recent study addressed some of these concerns. Interested in the prospect of renewable energy, the Minnesota state legislature requested a study "of the impacts on reliability and costs associated with increasing wind capacity to 20% of Minnesota retail electric energy sales by the year 2020 [21]." The results of the study were very promising: No increases in spinning reserves were found to be required. This is largely due to the geographic expanse over which the wind farms are usually placed, which turned out to be very effective in reducing power variability over short (10 minute) periods of time. Weather patterns at different sites only became correlated for longer time frames (approaching an hour), allowing long term reserves to meet changes in production. Concluding, the report suggested an increase in long-term reserves in order to maintain the LOLP standard. At a 30% penetration, the additional reserves needed would only cost $2.11 to $4.41 per mega-watt hour (MWh) of wind energy produced. Since electric energy is usually sold wholesale at prices around $30/MWh at times of moderate demand, and since wind energy can be produced at costs significantly lower than $30/MWh, this would seem to indicate that wind energy would still be affordable even if penalized for incurring these additional operating costs. Other studies have shown similar results [22], [23], [24]. Feasibility of high wind penetrations has also been proven in Europe, where Denmark has enough installed wind capacity to meet 25% of its average annual electricity consumption [25].

FUTURE TRENDS

It is hard to predict what will happen next in an industry that is changing so quickly. Turbines will likely develop many more features that enable behavior much more like traditional power plants, providing additional services that maintain the quality and reliability of the electric grid. Reactive power control is one service that has been introduced, and many predict that turbines will soon provide voltage regulation services even when the wind is not blowing [26].

Many innovations will likely bring lower costs and higher reliability. For example, turbine gearboxes have presented numerous reliability problems over the years. In an effort to prevent such problems and reduce costs, one Type D turbine manufacturer has been able to eliminate the gearbox from its turbine design.

CONCLUSIONS

Many people see the new turbines popping up, but do not realize the immense challenges involved with introducing wind energy into the electric grid. Wind farms are often located in remote regions where grid access is relatively weak and unfavorable for new generation. Many older types of electrical generator technologies (Type A and B) could not interface successfully without the additional expense of external reactive power compensation. Newer turbine designs have largely solved this problem. Type C and D generators now provide many of the same services as traditional power plants, and some studies have even indicated that these generators are faster to react and do a better job of maintaining voltage stability than traditional power plants [24]. Wind energy has come a long way in the last ten years, and it will probably continue to advance over the next ten years. Costs will come down, and turbines will become more capable and more reliable.

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