# ELECTRICAL GENERATION AND GRID SYSTEM INTEGRATION

4/29/2017

> "Those who cannot remember the past are condemned to repeat it."
> George Santayana, The life of Reason, 1905.

## INTRODUCTION

Wind turbines convert the rotational mechanical energy of their rotors into electrical energy in their electrical generators. All types of electrical generators produce an electrical current through Faraday's law of electromagnetic induction, whereas when the magnetic field lines are cut with a conducting wire with a relative velocity, an electric potential is induced in the wire. If the wire is part of a closed circuit, an electrical current flows through it. The magnitude of the current increases in proportion to the strength of the field, the length of the wire cut by the magnetic field and the relative velocity.

A critical issue in wind farm construction is that installed capacity in some regions is outstripping the producers' ability to move the wind power from relatively remote areas to load centers in other areas. This affects market prices in a significant way; because the cost of installing and upgrading the transmission lines to deliver the generation must be factored into the final consumer price.

Under the 1992 Energy Policy Act, a consolidation process has happened in the USA utility business, and many operations were merged. Some far-sighted power producers purchased power plants from utilities, which prefer to become power distributors rather than power producers, at quite advantageous prices. In fact, a fragmentation process has occurred, where the electrical utilities have been polarized into power producers and power distributors. Electricity being a service as well as a commodity, many power experts question the long term viability and sustainability of those short-sighted utilities that have morphed themselves into power purchasers and lost control of their electrical supply seeking unsustainable temporary higher profits under the pressure of the deregulation process.

Table 1. USA electrical production by source, 2009. Data: Energy Information Administration, EIA.

| Source | Percent |
|---|---|
| Coal | 44.7 |
| Natural Gas | 23.3 |
| Nuclear power | 20.2 |
| Hydroelectric | 6.9 |
| Renewable sources | 3.6 |
| Other sources | 1.4 |
| Total | 100.1 |

## SMART GRID ARCHITECTURE FOR RENEWABLE AND CONVENTIONAL RESOURCES

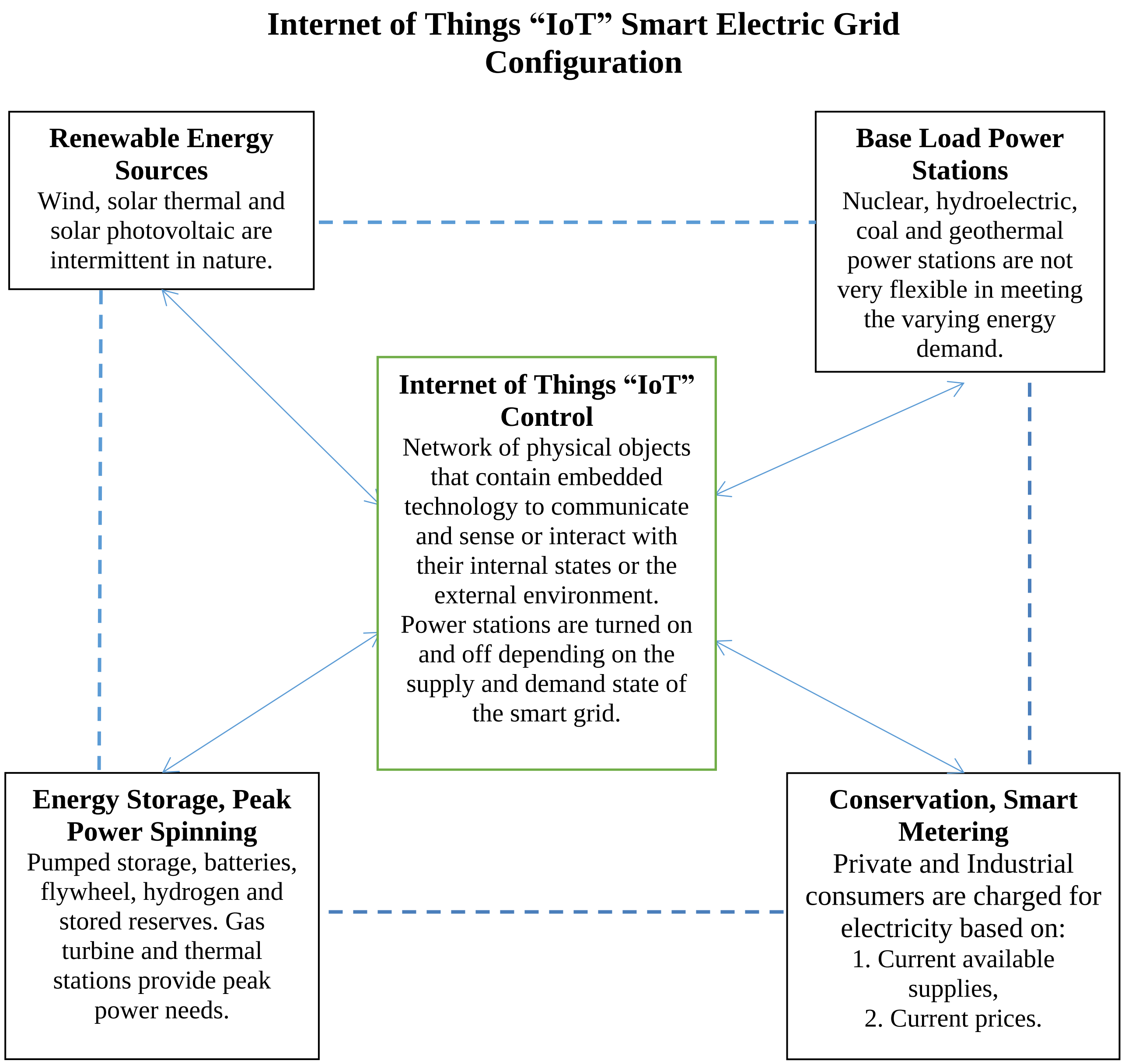

Figure 1. Smart grid configuration using Internet of Things "IoT", connecting renewables and conventional energy sources to electricity consumers through decentralized control of the power grid.

On a macroscopic scale, the electrical grids in the industrialized nations must grow larger as well as flexible and smarter using modern information technology to perfectly coordinate energy distribution, making them more efficient and reliable.

The global electricity industry is spending billions on building new, transnational power lines to harness electricity from renewable energy sources. The Smart Grid system is meant to make the distribution of electricity more reliable and efficient. As an example, the European power grid is 6,875 miles or 11,000 kilometers in length. Only when the electrical consumption and supply are perfectly balanced does the grid remain stable.

## SMART GRID PLANS

Electrical grid lines carry high-voltage electricity for long distances to deliver energy from power plants to homes or businesses. Common transmission line voltages include 138,000 volts, 161,000 volts, 230,000 volts and 345,000 volts.

Transmission constraints in West Texas have negatively impacted operations of numerous wind farms in that area. Wind power generation in that region has been routinely curtailed to prevent overloading the local transmission system. This has resulted in losses of many millions of dollars per year of electric power sales. The State of Texas generators and regulators addressed the situation by upgrading existing facilities and constructing additional transmission facilities for high-voltage power.

The State of New Mexico had similar problems and adopted its own solution. It enacted legislation that will create the New Mexico Renewable Energy Transmission Authority, a quasi-governmental agency that will plan, finance, acquire and build power lines and energy storage projects. The Authority will have power to designate transmission corridors and to negotiate with other entities on the establishment of interstate corridors. It will be able to use eminent domain authority to help get projects built. The State of Wyoming, also has a transmission authority that likewise is intended to help transmit and export electricity produced by the state's energy resources.

A major investment plan in the USA national grid system is contemplated using smart metering, distributed storage and other advanced technologies. This includes the establishment of a Grid Modernization Commission to facilitate the adoption of Smart Grid Practices. These would instruct the Secretary of Energy to:

1. Establish a Smart Grid Investment Matching Grant Program to provide reimbursement of ¼ of qualifying Smart Grid investments.
2. Conduct programs to deploy advanced techniques for managing peak load reductions and energy efficiency savings on customer premises from smart metering, demand response, distributed generation and electricity storage systems.
3. Establish demonstration projects specifically focused on advanced technologies for power grid sensing, communications, analysis and power flow control, including the integration of demand-side resources into grid management.

## OVERCOMONG THE INTERMITTENCE PROBLEM

The storage option that is competitive for grid-to-grid storage is pumped hydroelectric. Carbon-lead-acid batteries come in second, then hydrogen fuel cells, Compressed Air Storage System (CAES) and Flywheels.

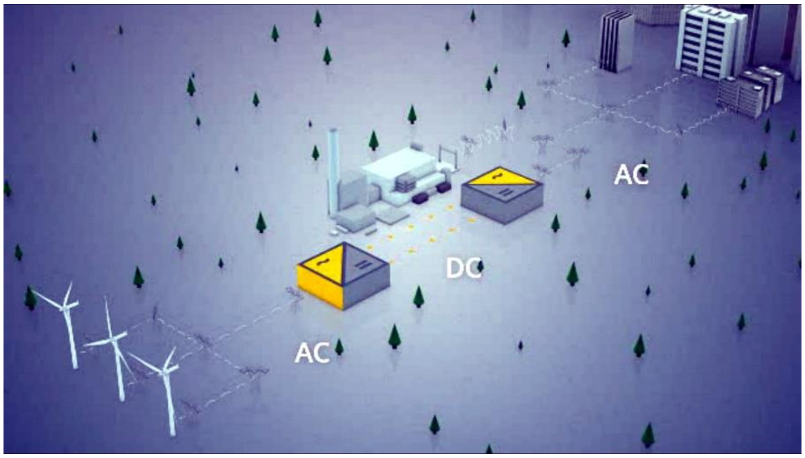

Figure 2. The wind intermittence problem and the ensuing power fluctuations can be remedied by vertical integration by pairing wind turbines with Combined Cycle Gas Turbines (OCGTs) or Open Cycle Gas Turbines (OCGTs). Source: Siemens.

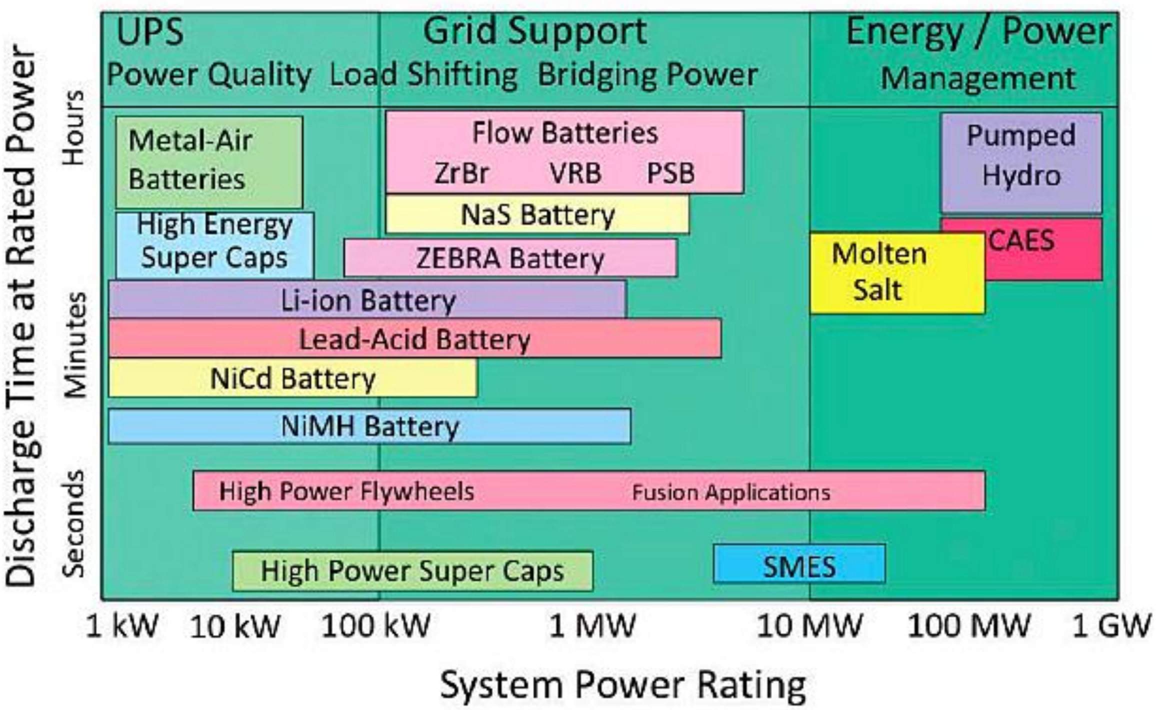

Figure 3. Energy Storage Options with discharge time at rated power as a function of the power system rating. CAES: Compressed Air Energy Storage. Caps: Capacitors. SMES: Superconductiong Magnetic Energy Storage.

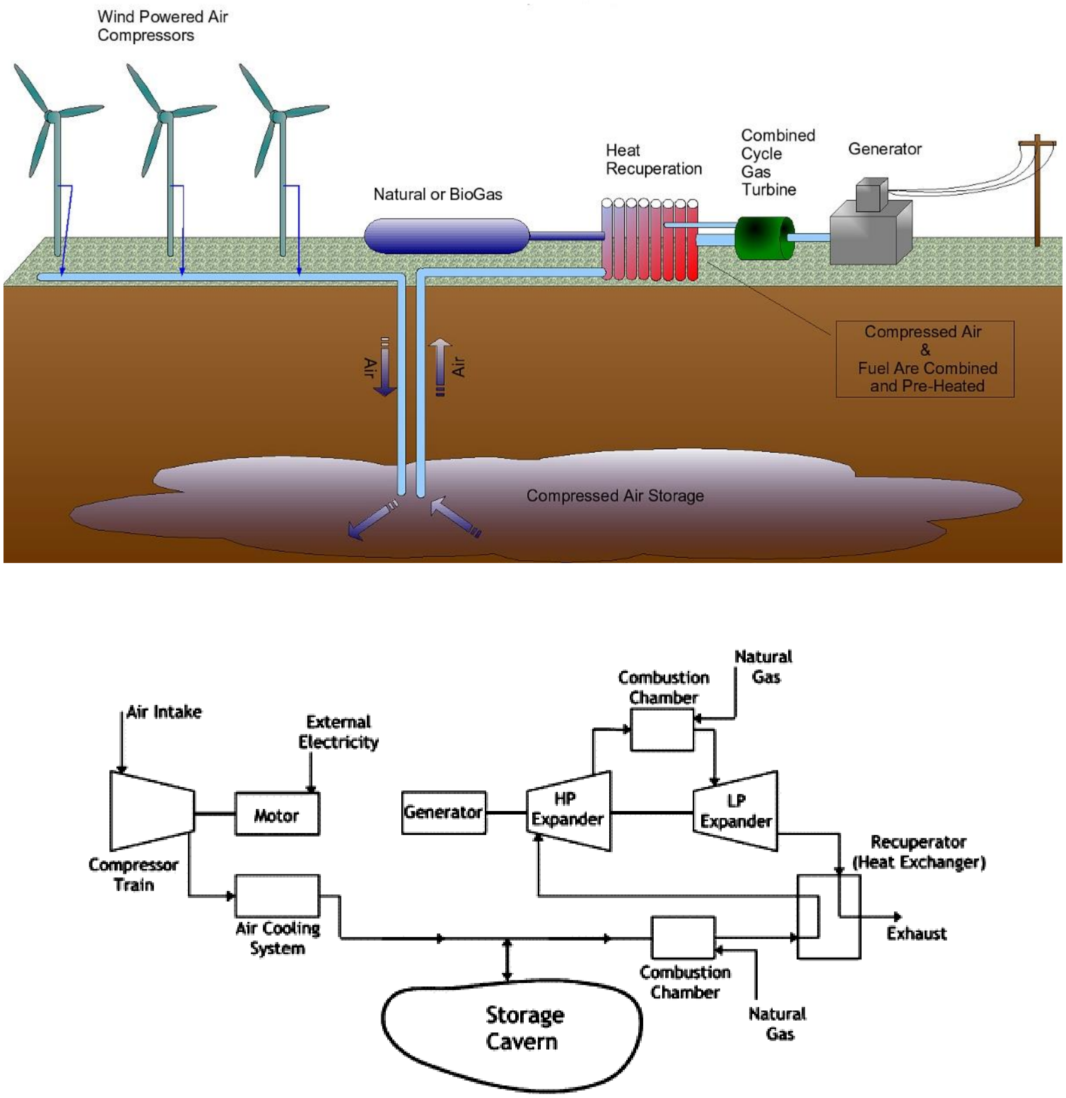

Figure 4. Schematic of Compressed Air Energy Storage (CAES) system. Source: Sciam.

Figure 5. A 290 MW Compressed Air Energy Storage (CAES) in conjunction with wind power at Huntorf, Germany [9].

A new variable affects the equation: everything can be planned, except for the wind availability. It fluctuates between gentle breezes and powerful gusts of wind during storms.

In Europe, the grid operators are required by law to give priority to the renewable forms of energy when feeding electricity into the grid. The problem is that the sun and the wind are very unpredictable. The fluctuations complicate their work with the grids reaching their maximum loads more frequently.

According to Decher [6]:

> "The grid is not an electricity storage device. Some advertisements make the analogy to the grid being like a bathtub filling up with water from different types of faucets. This analogy is completely false, because electricity basically cannot be stored, but needs to be used as it is generated. Except for a small amount of pumped hydropower on some grids, there is virtually no storage capacity."

A study by the USA National Renewable Energy Laboratory (NREL) looked at scenarios for integrating up to 35 percent renewables into the electricity network of the western USA. About 30 percent wind and 5 percent solar penetration was technically feasible and economic without the use of storage, provided other measures are put in place, including improvements to the transmission system. On the hand, a study prepared for the California Energy Commission points to the very immediate advantages of storing renewable energy, for example from its potential to cut reliance on conventional assets for balancing the system, contributing to an overall lower emissions power economy.

Basic CAES technology uses the energy to be stored to drive air compressors. The air is stored underground until required and then released to drive a turbine that operates on less than 40% of the gas normally required due to its pre-compressed air input. A commercial 290 MW CAES plant began operating in Huntorf, Germany, in 1978. First Energy in the USA acquired the rights to the Norton Energy Storage Project in Ohio, based on a former limestone mine, and said the first phase could involve around 270 MW of generation capacity. With 9.6 million $sm^2$ of storage available, the company claimed the site has the potential to expand up to 2.7 GW.

Pacific Gas and Electric received government match funding for a US$50 million demonstration CAES project in Kern County, California. The facility would be designed to store enough energy to deliver 300 MW for 10 hours. New York State Electric and Gas is also looking at a 150 MW demonstrator based in a salt cavern. The Iowa Stored Energy Park, plans up to 150 MW of wind capacity with an underground storage facility.

The scale and siting issues of CAES projects make them slow burners, and the involvement of conventional generation in the process has led some to question their status in the renewables equation.

Pumped storage hydropower boasts around 127 GW of capacity worldwide and is growing at a rate that puts other storage technologies in the shade. China's state grid operator, for example, plans to raise its pumped storage capacity from 14 GW at the end of 2009 to 21 GW by 2015 and 41 GW by 2020, with the need to complement wind and solar generation given as the reason. Among a host of other developments so far in 2010, a 1.5 GW project has been announced in Vietnam, while Slovenia's first pumped storage facility started operation, and the first unit of the Dnister plant in Ukraine, one of the largest pumped storage plants in the world, came on stream.

Japan has been the global pacesetter in large-scale battery storage for two decades, predominantly through the Sodium Sulphur (NaS) systems developed by NGK in conjunction with Tokyo Electric Power. With more than 200 MW of installed capacity in the country, NaS is well-established in Japan, where it is used at substations and major industrial sites. Tokyo Electric Power believes NaS storage has a major part to play in the country's future renewables infrastructure, and has established a hybrid wind/NaS installation at Rokkasho in the north of Japan consisting of a 51 MW turbine array and a 34 MW NaS system. NaS is also spreading its wings, notably through the recent installation of a 4 MW system at Presidio, Texas, the state's first utility-scale battery.

Observers expect Lithium Ion (Li-ion) to quickly emerge as another serious contender. A study by Pike Research in late 2009 forecast that Li-ion batteries will be the fastest-growing category for utility-scale applications representing a 26 percent share of a $4.1 billion stationary energy storage market by 2018.

Flow battery technologies, where an electrolyte flows through an electrochemical cell is viewed as one of the most promising options thanks to its promise of fast response and long life. The development of commercial flow battery products has been relatively slow. A vanadium redox flow battery, employing vanadium salts in its electrolyte results in a virtually unlimited number of charge/discharge cycles and a 20-year lifespan.

Frequency regulation is foreseen using flywheel storage systems 'kinetic batteries' that store energy in a high-speed rotating matrix and then discharge it as electricity when required. Flywheels are hailed by their supporters as the 'greenest' storage solution as they do not consume fuel or produce emissions. Already used for applications such as UPS, the flywheel now has bigger ambitions at utility level. Beacon Power Corporation closed the financing on its flagship 20 MW flywheel energy storage plant in Stephentown, New York, thanks to a $43 million loan guarantee from the US Department of Energy (USDOE). The Stephentown project, billed as the first utility-scale plant of its kind in the world, is designed to aid regulation of the power grid, enabling greater use of renewable resources and reducing dependence on conventional assets. It will eventually provide around 10 percent of New York's daily frequency regulation capacity.

The Beacon Coapany has installed a system at a wind farm in Tehachapi, California, as part of a demonstrator project for the California Energy Commission. The company is now developing the next generation of its flywheel technology, aimed at storing four times the energy at one-eighth the cost of its current flagship Smart Energy 25 system.

## NORTH AMERICAN GRID SYSTEM

The North American Power Grid System that covers the USA, Canada and a northern part of Mexico is considered to be the largest machine ever built by the human race. It has to meet an increased demand from today’s information and digital world. It consists of a network of power plants, transmission lines, substations and distribution lines covering the entire USA and parts of Canada and Mexico. It is divided into regional grids that are interconnected at transmission substations through which power utilities can trade electricity from each other.

This single network is physically and administratively subdivided into three “interconnects”: the Eastern, covering the eastern two-thirds of the USA and Canada; the Western, encompassing most of the rest of the two countries; and the Electric Reliability Council of Texas (ERCOT), covering most of Texas. Within each interconnect, power flows through AC lines, so all generators are tightly synchronized to the same 60-Hz cycle.

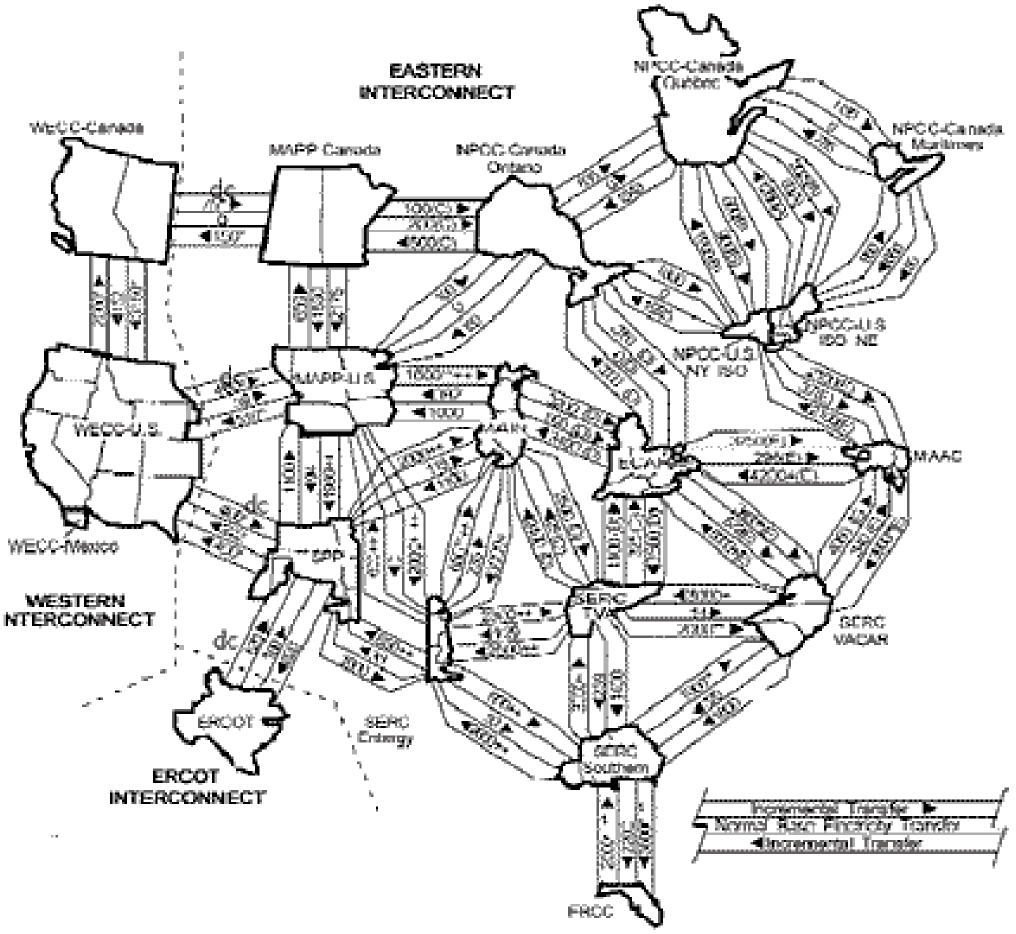

Figure 6. The North American Grid System. Normal USA base electricity transfers and first-contingency incremental transfer capabilities [MW]. Shown are the Western, Eastern, and the Electric Reliability Council of Texas (ERCOT) Interconnects. Source: North American Electrical Reliability Council.

The interconnects are joined to each other by DC links, so the coupling is much looser among the interconnects than within them. The capacity of the transmission lines between the interconnects is also far less than the capacity of the links within them.

Electrical energy comes from a multitude of sources such as wind, solar, coal, natural gas, oil, hydroelectric, methane from landfills, animal waste, geothermal and nuclear energy. A power plant sends its electricity to a transmission substation where it is boosted to high voltages in the range of 69-765 kilovolts (kV) to minimize the losses when traveling over long distances through transmission lines held above ground on transmission towers.

When the electricity reaches a distribution substation, it is stepped down by transformers to lower voltages in the range of 7.2-12.47 kV, and then sent throughout the distribution system.

Electricity leaves the substations on distribution lines attached to power poles. These are mostly wooden and could support telephone wires and street lights. The distribution lines carry the electricity to distribution transformers mostly placed at the top of the power poles. These step the voltage further down to the range of 120-240 Volts for ordinary residential use passing through a meter for usage determination.

## GRID STABILITY IN THE PRE-DEREGULATION NORTH AMERICAN POWER SYSTEM

Prior to the 1992 Energy Policy Act, the regional and local electric utilities were regulated, vertical monopolies. Each company controlled its own electricity generation, transmission lines, and distribution different geographical areas. Each electrical utility maintained sufficient generation capacity to meet the needs of its customers. Long-distance energy shipments were reserved for emergency situations, such as storm-related unexpected generation outages. The long distance connections served as insurance against sudden loss of power. An exception was the net flows of power out of the large hydropower generators in Québec and Ontario in Canada.

The limited use of long-distance connections enhanced the system's reliability. This is so because the physical complexities of power transmission rise rapidly as distance and the complexity of interconnections grow. Power in an electric network does not travel along a set path. When a utility agrees to sell electricity to another utility, the sender utility increases the amount of power it generates while the receiving utility decreases production or has an increased demand. The power flows from the source to the sink along all the paths that connect them. Changes in generation and transmission at any point in the system will change loads on generators and transmission lines at every other point effectively in ways not anticipated or easily controlled.

To avoid system failures, the amount of power flowing over each transmission line must remain below the line's capacity. If the line capacity is exceeded, this generates too much heat in a line, which can cause the line to sag into trees or break or can create power-supply instability such as phase angle, frequency and voltage fluctuations. The line capacities vary, depending on the length of the line and the transmission voltage. In general, longer lines have less capacity than shorter ones.

Table 2. Electrical transmission lines capacity.

| Voltage [kV] | Maximum Capacity [GW] | Length [miles] |
|---|---|---|
| 765 | 3.8 | 100 |
| | 2.0 | 400 |
| 500 | 1.3 | 100 |
| | 0.6 | 400 |
| 230 | 0.2 | 100 |
| | 0.1 | 400 |

For an AC power grid to remain stable, the frequency and phase of all power generation units must remain synchronized within narrow limits. A generator that drops 2 Hz below 60 Hz will rapidly build up enough heat in its bearings to disintegrate. Circuit breakers are incorporated with the purpose of tripping a generator out of the system when the frequency varies too much. Much smaller frequency changes would indicate instability in the grid. In the Eastern Interconnect system, a 30 mHz drop in frequency reduces the power delivered by a 1 GW magnitude.

If parts of the grid are carrying electricity at near capacity, a small shift of power flow can trip the circuit breakers, which sends larger flows into neighboring lines to start a chain-reaction domino-effect cascading failure. Such an event occurred on November 10, 1965, when an incorrectly set circuit breaker tripped and set off a blackout.

After the 1965 blackout, the USA electrical utility industry set up regional reliability councils, coordinated by the North American Electric Reliability Council, to set standards to improve planning and cooperation among the utilities. A single-contingency-loss standard was set up to keep the system functioning if a single unit, such as a generator or transition line, went off. Utilities built up spare generation and transmission capacity to maintain a reasonable safety margin [1].

## ENERGY POLICY ACT OF 1992, FRAGMENTATION OF THE ELECTRICAL UTILITY SYSTEM

In 1992, the economic rules governing the electrical grid system were changed with passage of the Energy Policy Act. This law empowered the Federal Energy Regulatory Commission (FERC) to separate electric power generation from transmission and distribution. Under this unwarranted politically-induced and not technically-induced change in regulations, by 1998 utilities in California were compelled to sell off their generating capacity to independent power producers, such as Enron and Dynergy. Enron later went bankrupt under the burden of a financial scandal.

The politically-oriented new regulations envisioned trading electricity like a commodity. Generating companies would sell their power for the best price they could get, and utilities would buy at the lowest price possible. For this concept to work, it was imperative to compel utilities that owned transmission lines to carry power from other companies' generators in the same way as they carried their own, even if the power went to a third party. FERC's Order 888 mandated the wheeling of electric power across utility lines in 1996. That technically-unsound order remained in litigation until March 4, 2000, when the USA Supreme Court validated it and it went into force.

The power engineers warned that the new rules ignored the physics of the grid. The new policies do not recognize the single-machine characteristics of the electric-power network. According to Casazza [2, 3]:

> "The new rule balkanized control over the single machine. It is like having every player in an orchestra use their own tunes."

In the view of Casazza and many other power experts, the key error in the new rules was to view electricity as a commodity rather than as an essential service. Commodities can be shipped from one chosen point to another predetermined one. On the other hand, power shifts affect the entire single machine system. As a result, increased long distance trading of electric power created dangerous levels of congestion on transmission lines where controllers did not expect them and could not deal with them.

The power engineers warned that the problems would be compounded as independent power producers added new generating units at essentially random locations determined by low labor costs, lax local regulations, or local tax incentives. If generators were added far from the main consuming areas, the total quantity of power flows would rapidly increase, overloading the transmission lines. The system was never designed to handle long-distance wheeling.

The data needed to predict and react to system stress, such as basic information on the quantity of energy flows, began disappearing, treated by the utilities as competitive proprietary information and kept secret. Starting in 1998, the utilities hid from the public the reporting on blackout statistics, so the system reliability could no longer be accurately assessed.

The polarization into generation and transmission companies resulted in an inadequate amount of reactive power, which is current that is 90 degrees out of phase with the voltage. Reactive power is needed to maintain voltage, and longer-distance transmission increases the need for it. However, only generating companies can produce reactive power, and with the new rules, they do not benefit from it since reactive-power production reduces the amount of the deliverable power produced. So transmission companies, under the new rules, cannot require generating companies to produce enough reactive power to stabilize voltages and increase the system's stability.

A net result of the new rules was to more tightly couple the system physically and stress it closer to capacity, and at the same time, make its control more diffuse and less coordinated, a definite prescription for brownouts and blackouts.

As described by Eric J. Lerner [1]:

> "In March 2000, the warnings began to come true. Within a month of the Supreme Court decision implementing Order 888, electricity trading skyrocketed, as did stresses on the grid. One measure of stress is the number of transmission loading relief procedures (TLRs)—events that include relieving line loads by shifting power to other lines. In May 2000, TLRs on the Eastern Interconnect jumped to 6 times the level of May 1999. Equally important, the frequency stability of the grid rapidly deteriorated, with average hourly frequency deviations from 60 Hz leaping from 1.3 mHz in May 1999, to 4.9 mHz in May 2000, to 7.6 mHz by January 2001. As predicted, the new trading had the effect of overstressing and destabilizing the grid.
>
> "Under the new system, the financial incentive was to run things up to the limit of capacity," explains Carreras. In fact, energy companies did more: they gamed the system. Federal investigations later showed that employees of Enron and other energy traders "knowingly and intentionally" filed transmission schedules designed to block competitors' access to the grid and to drive up prices by creating artificial shortages. In California, this behavior resulted in widespread blackouts, the doubling and tripling of retail rates, and eventual costs to ratepayers and taxpayers of more than $30 billion. In the more tightly regulated Eastern Interconnect, retail prices rose less dramatically.
>
> After a pause following Enron's collapse in 2001 and a fall in electricity demand (partly due to recession and partly to weather), energy trading resumed its frenzy in 2002 and 2003. Although power generation in

> 2003 has increased only 3% above that in 2000, generation by independent power producers, a rough measure of wholesale trading, has doubled. System stress, as measured by TLRs and frequency instability, has soared, and with it, warnings by FERC and other groups.
>
> Major bank and investment institutions such as Morgan Stanley and Citigroup stepped into the place of fallen traders such as Enron and began buying up power plants. But as more players have entered and trading margins have narrowed, more trades are needed to pay off the huge debts incurred in buying and building generators. Revenues also have shrunk, because after the California debacle, states have refused to substantially increase the rates consumers pay. As their credit ratings and stock prices fell, utility companies began to cut personnel, training, maintenance, and research. Nationwide, 150,000 utility jobs evaporated. “We have a lot of utilities in deep financial trouble,” says Richard Bush, editor of Transmission and Distribution, a trade magazine.
>
> The August 14 blackout, although set off by specific chance events, became the logical outcome of these trends. Controllers in Ohio, where the blackout started, were overextended, lacked vital data, and failed to act appropriately on outages that occurred more than an hour before the blackout. When energy shifted from one transmission line to another, overheating caused lines to sag into a tree. The snowballing cascade of shunted power that rippled across the Northeast in seconds would not have happened had the grid not been operating so near to its transmission capacity.”

## ANATOMY OF THE AUGUST 14, 2003 BLACKOUT

In 2003 one of the largest power outages in history occurred. 508 large power generators were knocked out, leaving 55 million people in North America without power for upward of 24 hours. The cause was a software defect in an alarm system in an Ohio control center.

1:58 pm
The Eastlake, Ohio, generating plant shuts down.
The plant is owned by First Energy, a utility that had experienced extensive recent maintenance difficulties, including a major nuclear-plant incident.

3:06 pm
A First Energy 345 kV transmission line fails south of Cleveland, Ohio.

3:17 pm
Voltage dips temporarily on the Ohio portion of the grid.
Controllers take no action, but power shifted by the first failure onto another power line, heated the line, caused expansion in the conductors, causing it to sag into a tree at 3:32 pm, bringing it offline as well.
While Mid-West ISO and First Energy controllers try to understand the failures, they fail

to inform system controllers in nearby states.

3:41 and 3:46 pm
Two circuit breakers connecting First Energy's grid with American Electric Power are tripped.

4:05 pm
A sustained power surge on some Ohio lines signals more trouble building.

4:09:02 pm
Voltage sags deeply as Ohio draws 2 GW of power from Michigan.

4:10:34 pm
Many transmission lines trip out, first in Michigan and then in Ohio, blocking the eastward flow of power.
Generators go down, creating a large power deficit.
Within seconds, power surges out of the East, tripping East coast generators to protect them, and the blackout is now full-fledged.

## REGIONAL TRANSMISSION ORGANIZATIONS (RTOs) AND INDEPENDENT SYSTEM OPERATORS (ISOs)

Regional Transmission Organizations (RTOs) such as PJM and MISO coordinate the movement of wholesale electricity in the USA. PJM controls electricity in all or parts of 13 states and the District of Columbia.

An Independent System Operator (ISO) is a non-profit organization that combines the transmission facilities of several transmission owners into a single transmission system to move energy over long distances at a single lower price than the combined charges of each utility that may be located between the buyer and seller. The ISO provides non-discriminatory service, and must be independent of the transmission owners and the customers who use its system.

The ISOs and RTOs coordinate electrical generation and transmission across a wide geographic area, matching generation instantaneously to the demand for electricity. They forecast load and schedule generation to assure that sufficient generation and back-up power is available if demand rises or a power plant or power line is lost.

The ISOs and RTOs provide non-discriminatory transmission access, facilitate competition among wholesale electricity suppliers, and conduct regional planning to ensure a reliable grid for the future.

They are involved in improving grid reliability and driving innovation in grid management technology and effectiveness, including data visualization for system operations, faster contingency analysis and data interpretation, and cyber-security protection measures.

Both ISOs and RTOs are organizations formed with the approval of the Federal Energy Regulatory Commission (FERC) to coordinate, control and monitor the use of the electric transmission system by utilities, generators and marketers. In North America, there are nine ISOs, five of which are RTOs. They manage the systems that serve two thirds of the customers in the USA, and over half the population of Canada.

The distinction between ISOs and RTOs in the USA has become insignificant. Both organizations provide similar transmission services under a single tariff at a single rate, and they operate energy markets within their footprints.

## PJM (PENNSYLVANIA-NEW JERSEY-MARYLAND) REGIONAL TRANSMISSION ORGANIZATION (RTO)

PJM was established in 1927 when the three utilities: Public Service and Gas Company, Philadelphia Electric Company, and Pennsylvania Power and Light Company, realizing the benefits and efficiencies possible by interconnecting to share their generating resources, formed the world's first continuing power pool that was called the Pennsylvania-New Jersey Interconnection.

Additional utilities such as Baltimore Gas and Electric Company and General Public Utilities joined in 1956, 1965 and 1981. The pool was renamed the Pennsylvania-New Jersey-Maryland interconnection or JPM.

From 2002 through 2005, PJM integrated a number of utility transmission systems into its operations. They included Allegheny Power in 2002, Commonwealth Edison, American Electric Power and Dayton Power and Light in 2004 and Duquesne Light and Dominion in 2005.

In 2011, American Transmission Systems, Inc. (ATSI), the transmission affiliate of First Energy, and Cleveland Public Power (CPP) were integrated into PJM. These integrations expanded the number and diversity of resources available to meet consumer demand for electricity and increased the benefits of PJM's wholesale electricity market.

PJM began the transition to an independent organization in 1993 when the PJM Interconnection Association was formed to administer the power pool. In 1997, PJM became a fully independent organization. At that time, membership was opened to non-utilities and an independent Board of Managers was elected.

On April 1, 1997, PJM opened its first bid-based energy market. Later that year the Federal Energy Regulatory Commission (FERC) approved PJM as the nation's first fully functioning Independent System Operator (ISO). ISOs operate, but do not own, transmission systems in order to provide open access to the grid for non-utility users.

Later, the FERC encouraged the formation of regional transmission organizations (RTOs) to operate the transmission system in multi-state areas and to advance the development of competitive wholesale power markets. PJM became the nation's first fully functioning RTO in 2001.

PJM as a Regional Transmission Organization (RTO) is part of the Eastern Interconnection part of the North American grid operating the electric transmission system serving all or parts of Delaware, Illinois, Indiana, Kentucky, Maryland, Michigan, New Jersey, North Carolina, Ohio, Pennsylvania, Tennessee, Virginia, West Virginia and the District of Columbia. It is headquartered at Valley Forge, Pennsylvania.

PJM includes more than 650 member companies serving 60 million customers with 167 GWs of installed generating capacity from 1,325 generation sources, 59,750 miles or 96,158.304 kilometers of transmission lines and 6,038 transmission substations.

## MISO (MIDWEST INDEPENDENT SYSTEM OPERATOR)

MISO is an Independent System Operator (ISO) and a Regional Transmission Organization (RTO) that provides electrical transmission service throughout the Midwest USA and Manitoba, Canada. MISO operates 93,600 miles of transmission lines.

MISO was established in 1998 as an ISO and was approved as the nation's first RTO by FERC in 2001. The organization is headquartered in Carmel, Indiana with operation control centers in Carmel and St. Paul, Minnesota.

MISO members include 35 transmission owners with more than $17 billion in transmission assets. Members include investor-owned utilities, public power utilities, and cooperatives, such as: Duke Energy, Indianapolis Power & Light, International Transmission Company, Great River Energy, Xcel Energy, Wabash Valley Power Association and City Water Light and Power.

It serves all or part of: Illinois, Indiana, Iowa, Kentucky, Michigan, Minnesota, Missouri, Montana, North Dakota, Ohio, South Dakota, Wisconsin, and the Canadian province of Manitoba with an installed generation capacity of 146.497 GWs, 53,203 miles of transmission lines: 53,203, serving a population of 40 million people.

## THE ISO-RTO COUNCIL (IRC)

The ISO/RTO Council (IRC) is an industry organization consisting of representatives of North American ISOs and RTOs. The IRC works collaboratively to develop effective processes, tools, and standard methods for improving competitive electricity markets across North America. The IRC’s goal is to balance reliability considerations with market practices, resulting in efficient and robust markets that provide competitive and reliable service to the electricity users.

In the 1990s states and regions within the USA established wholesale competition for electricity. In response, the utilities rearranged themselves into independent transmission operators.

Currently, 10 Independent System Operators (ISOs) and Regional Transmission Organizations (RTOs) in North America serve two-thirds of the electricity consumers in the USA and more than 50 percent of Canada's population.

The IRC meets quarterly and is funded by members of the organization. Chartered on April 24, 2003, it includes standing and ad hoc committees to coordinate activities and information related to markets, regulatory and legislative policy, planning, standards review, information technology and communications. Committees are composed of staff members of the ISO/RTOs.

Table 3: Independent System Operators (ISOs) and Regional Transmission Organizations (RTOs), 2009. Source: IRC.

| RTO/ISO Name | Operates in All or Parts of the Following USA States and/or Canadian Provinces and Mexico | Population [Millions] | Capacity [MW] | Miles of Transmission Lines | | | | | Total Miles of Line |
|---|---|---|---|---|---|---|---|---|---|
| | | | | < 230 KV | 230 KV | 345 KV | 500 KV | 765 KV | |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Alberta Electric System Operator, AESO | Alberta, Canada | 4 | 12,163 | 8,976 | 4,714 | | 198 | | 13,888 |
| California ISO, CAISO | California and Northern Mexico | 30 | 57,124 | 13,668 | 8,627 | | 3103 | | 25,398 |
| Electric Reliability Council of Texas (ERCOT) | Texas | 22 | 88,227 | 31,410 | | 8,917 | | | 40,327 |
| ISO New England (ISO-NE) | Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, Vermont | 14 | 33,700 | 5,603 | 443 | 2,084 | | | 8,130 |
| Midwest System Operator (MISO) | Illinois, Indiana, Iowa, Kentucky, Michigan, Minnesota, Missouri, Montana, North Dakota, Ohio, South Dakota, Pennsylvania, Wisconsin, and Manitoba | 40 | 159,900 | 35,557 | 3,541 | 10,695 | 442 | | 50,235 |
| New Brunswick System Operator (NBSO) | New Brunswick, Nova Scotia, Prince Edward Island, and Maine | 2 | 7,000 | 5,800 | 1,100 | 1,100 | | | 8,000 |
| New York ISO (NYISO) | New York | 19 | 40,685 | 6,772 | 1,080 | 2,815 | 71 | 155 | 10,893 |
| Pennsylvania- New Jersey-Maryland RTO (PJM) | Delaware, Illinois, Indiana, Kentucky, Maryland, Michigan, New Jersey, North Carolina, Ohio, Pennsylvania, Tennessee, Virginia, West Virginia and the District of Columbia | 51 | 164,895 | 36,789 | 7,228 | 2,901 | 7,366 | 2,215 | 56,499 |
| Ontario's Indpendent Electric System Operator (IESO) | Ontario, Canada | 13 | 35,338 | 6,959 | 8,836 | 4 | 2,361 | | 18,160 |
| Southwest Power Pool (SPP) | Arkansas, Kansas, Louisiana, Missouri, Nebraska, New Mexico, Oklahoma, and Texas | 5 | 63,000 | 36,664 | 3,531 | 6,620 | 106 | | 46,921 |
| TotalsS | 3 Countries: USA, Canada, Mexico<br>36 USA States<br>6 Canadian Provinces | 200 | 662,032 | 188,198 | 39,100 | 35,136 | 13,647 | 2,370 | 278,451 |

## POWER LINE COSTS

The costs of construction of overhead power lines is affected by the following factors:

1. Siting, permitting and/or environmental mitigation requirements,
2. Land use, population density and right-of-way land value,
3. Terrain and geophysical conditions and their effects on line design and construction.

Table 4. Installation costs for overhead transmission lines. 2008 dollars rural terrain with rolling hills. Excludes station costs but includes siting and Right Of Way (ROW) cost.

| Voltage class [kV] single circuit | Cost [$million/mile] |
|---|---|
| 765 | 2.6-4.0 |
| 500 | 2.3-2.5 |
| 345 | 1.1-2.0 |

Table 5. Cost breakdown for a typical 765 kV overhead line with truss towers.

| Component | Percent |
|---|---|
| Siting | 3 |
| Right Of Way (ROW) | 10 |
| Engineering and management | 5 |
| Materials (Structures/conductors/other : 60/30/10) | 41 |
| Construction | 41 |

Table 6. Right of Way (ROW) width and tower height for single circuit power lines.

| Voltage class [kV] | ROW width [feet] | Hilly terrain Tower height [feet] | Flat terrain Tower height [feet] |
|---|---|---|---|
| 765 | 200 | 135 | 150 |
| 500 | 175-200 | 120 | 135 |
| 345 | 150 | 110 | 125 |

## WIND TURBINES EFFICIENCY

When generating electricity from fuel sources in thermal processes, the efficiency of conversion is described by the second law of thermodynamics and is low in magnitude in the range of 30-40 percent.

The direct conversion of mechanical to electrical energy in a wind turbine generator should in principle yield 100 percent efficiency. Practically it is much lower due to some factors that must be considered in the process of supplying an Alternating Current (AC) suitable for connection to an electrical grid network:

The efficiency of a wind turbine is greatest if its rotational frequency varies with the wind velocity in order to maintain a constant tip speed ratio. However, for most wind turbines, the generator must operate at a constant or nearly constant frequency in order to supply grid-compatible electricity.

The control of turbine speed by flaps and other methods is costly and inefficient, thus the rotational frequency is best controlled by varying the electrical load on the turbine.

The optimal rotational frequencies of all but the smallest wind turbine rotors are much lower than those of the existing generators since the rotor speed decreases with rotor radius for a constant wind speed. This necessitates the use of gearboxes to increase the shaft speed from the low rotational speed of the rotor to the higher rotational speed of the generator. These gearboxes are bulky mechanical components which absorb energy, can be noisy, are subject to mechanical failures and require frequent maintenance.

## HIGH TEMPERATURE LOW SAG (HTLS) CONDUCTORS

A general class of conductors termed High Temperature Low Sag (HTLS) conductors include composite core conductors. HTLS conductors exhibit less sag between tower spans at elevated operating temperatures than traditional conductors.

Composite core conductors carry a cost premium and are most cost effective when installed on existing transmission structures as a quick, effective means to increase the thermal capacity of an established transmission corridor. They are stronger and, when built with trapezoidal strands, are more compact and have lower resistance than conventional round-strand conductors with the same diameter..

## GRID CONNECTION AND REINFORCEMENT

### INTRODUCTION

Large wind turbines must have a connection to the electrical grid. It is essential for small wind installations to be close to a 10-30 kV power line to minimize the cost of extending the power line to the nearest connection.

The generators in large wind turbines produce electricity at 0.69 kV. A transformer located on the ground next to the turbine, or inside the turbine tower, converts the electricity to a higher voltage of 10-30 kV.

The electrical grid near the wind turbine should be able to accommodate the electricity generated from the transformer.

If many turbines are connected to the grid, the grid may need reinforcement in the form of a larger cable connected to a higher voltage transformer station.

### SITE CONSIDERATIONS

Wind farm locations and the associated weather conditions pose engineers with challenges in meeting wind farm design requirements and installing systems. Poor site access can hinder the delivery of large and heavy components, bare rock can make excavation impossible and rain and mist can result in water ingress in the cable terminations and joints causing corrosion.

The transformer location and generator voltage have acquired more importance as wind turbines size has increased. An issue for electrical systems of wind farms is the choice of the site distribution system voltage. Optimization of wind farm electrical systems is constantly being sought in the effort to reduce component costs and site losses and at the same time increase the flexibility and reliability of the system.

Alternatives to the common 11 kV site distribution voltages have been investigated including 20kV and 33kV systems. Such systems may offer both a reduction in site electrical losses and saving in the capital cost.

## INTEGRATION INTO THE GRID

The electrical power P is the product of voltage V and current I:

$$P = VI \tag{1}$$

If the power can be transmitted at high voltage V, then the current I is correspondingly small.

This is significant for power grids transmitting electricity over large distances for two reasons:

1. The voltage drop in the transmission lines is proportional to the current in the lines.
2. The power loss in the lines is proportional to the square of the current I and is caused by ohmic heating:

$$P_{ohmic} = VI = IR.I = I^2R \tag{2}$$

where R is the resistance of the power line.

This suggests that the adoption of futuristic superconducting transmission lines with negligible resistive losses is a desirable development. The superconductor could be cooled to cryogenic temperatures with hydrogen produced through water electrolysis with wind electricity produced along lakes, rivers or sea shore lines. The transmission line can then also support a transport system using high speed Magnetically Levitated (Maglev) trains.

It is necessary to transmit electrical power at the lowest possible current I and consequently highest possible voltage V. As alternating voltages may be easily transformed from one value to another via transformers, local and national grid distribution systems use AC power transmission.

Typical voltage levels in a grid transmission system are shown in Table 7.

Table 7. Typical grid connections voltages, EU.

| Grid Component | Voltage [kV] | Phase mode |
|---|---|---|
| Wind turbine | 0.48 | 3 phase |
| Wind farm ring main | 11 | 3 phase |
| Local grid | 33 or 132 | 3 phase |
| Main grid distribution system | 132, 275 or 400 | 3 phase |
| Secondary transmission system | 33, 66 or 132 | 3 phase |
| Primary distribution system | 3.3, 6,6, 11 or 33 | 3 phase |

| | | |
|---|---|---|
| Local distribution system | 0.415<br>0.240<br>0.120 | 3 phase<br>single phase<br>single phase |

## RURAL NETWORK INTEGRATION

To achieve lower prices for wind generated electricity wind farm developments tend to concentrate at high wind speed sites, which, in turn are areas with low population densities, remote from a strong electrical connection point.

The necessary capital costs of reinforcing the network, together with the difficulty of obtaining zoning allowances for new overhead lines, encourage maximum use of the existing network infrastructure.

Rural electricity networks are characterized by long medium voltage lines to distributed loads, which are predominantly single phase. This leads to a low fault level and a low X/R ratio at the point of connection. Combined with the high wind turbulence intensity which is often associated with upland terrain, these conditions provide the least favorable circumstances for the quality of output power from wind turbines.

One can identify the following problems encountered in the implementation of wind generated power in a rural network:

1. Surges in reactive power as each wind turbine comes on-line until the turbine is synchronized with the grid. This can lead to a voltage drop of up to 5 percent on a 33kV line at each start up when the wind conditions become favorable.
2. Voltage flicker, which can be significant due to synchronizations, wind gusting and the effect of the tower shadow.
3. Harmonic factors, which can approach 3 percent for a 33 kV grid line.

The allowable peak output, harmonics, flicker, power factor and switching operations must be clearly stated in any technical specifications of a wind farm project..

Very low fault levels and low X/R ratios typical of wind farm grid connections increase the need for predicting any potential disturbances to the network. Methods need to be developed and implemented to prevent the possible disturbances to the grid system. These may include programming the turbine start ups in a staggered manner and the use of fast acting voltage control equipment.

Figure 7. High Voltage DC (HVDC) Converter station. Source: Siemens.

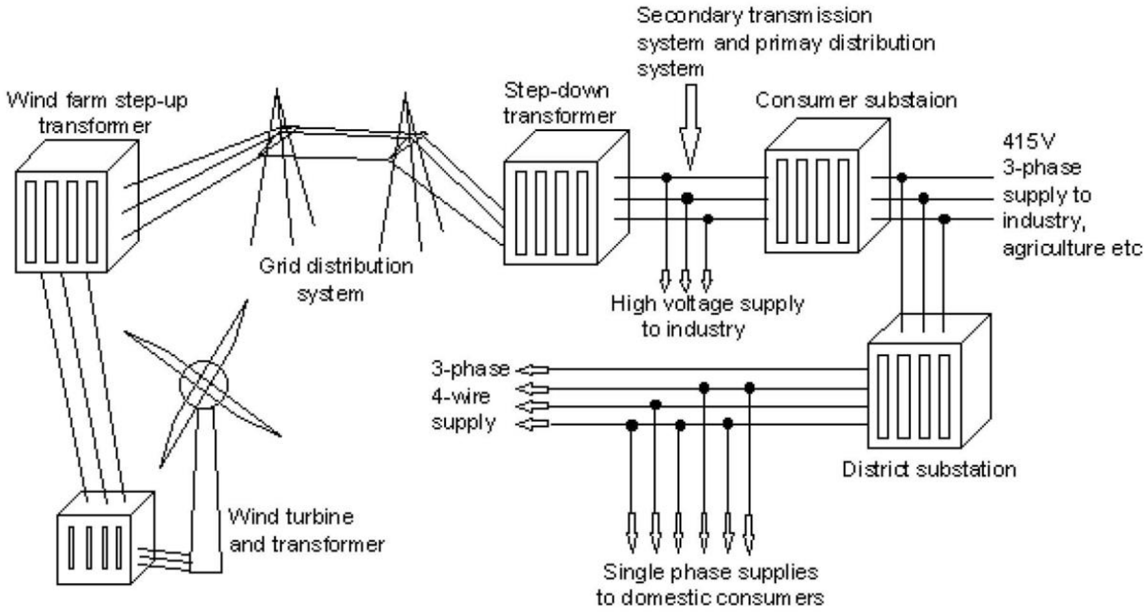

Figure 8. Grid connections for wind energy.

# POWER GENERATION THEORY

## ACTIVE AND REACTIVE POWER

In a DC circuit, the power consumed by the circuit is given by the product of the volts and the current. For an AC circuit, the situation is different. If the voltage and current waveforms are in phase with one another, the circuit is said to be purely resistive. When an instantaneous current *i(t)* flows through a circuit across which an in phase instantaneous voltage *v(t)* exists, then the instantaneous power associated with the circuit is given by:

$$p = i(t).v(t) \tag{3}$$

For a purely resistive circuit with an impressed sinusoidal voltage, the active power P is more easily expressed by an average, rather than an instantaneous value:

$$p = i_{rms} v_{rms} = I.V \tag{4}$$

where *I* and *V* are the Root Mean Square (RMS) values of current and voltage respectively.

If the voltage and current are out of phase, the circuit is said to have an inductive component.

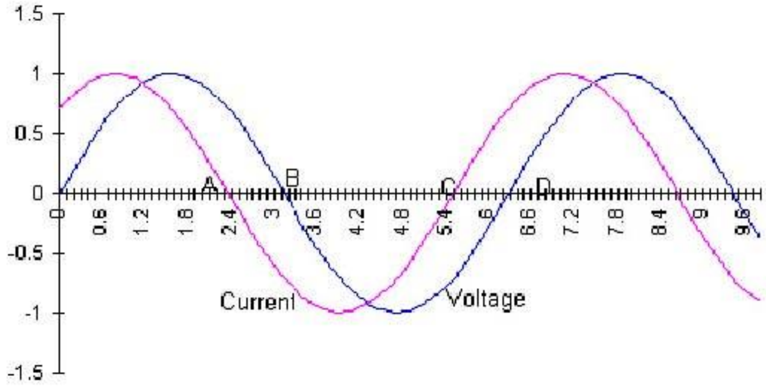

Figure 9. Voltage and current lag in a circuit with an inductive component.

In a circuit with an inductive component, the voltage lags the current by an angle given by the distance A-B. In this interval, the current is negative, whilst the voltage is positive. The Volt Ampere (VA) product V.I is therefore also negative. Also, in the interval C-D, the volt ampere V.I product is negative. Between B and C the V.I product is positive since V and I are both negative. Similarly, the V.I product before point A and after point D is also positive.

When the VA product is positive, power is consumed by the load. On the other hand, when the VA product is negative, the load consumes a negative power. This means that power is being returned to the supply. This is caused by energy being released from the magnetic field when the field collapses.

In the case of the shown figure, more energy is consumed by the load than is returned, and so the average power consumption over a cycle is positive. However, if the voltage and current are out of phase by 90 degrees, the VA product graph would have equal positive and negative areas, so that the load returns as much power to the supply as it consumes implying that the average power consumed is zero. In this case, the energy flow oscillates between the generator and inductor and back again at twice the frequency of the voltage.

It is useful to define the peak of this wattless power generation as the reactive power of the circuit *Q*, where:

$$Reactive\,Power\ \ Q = V.I \qquad (5)$$

To estimate the power consumed by an AC circuit, we need to know not just the V.I product, but also the phase angle between the current and voltage.

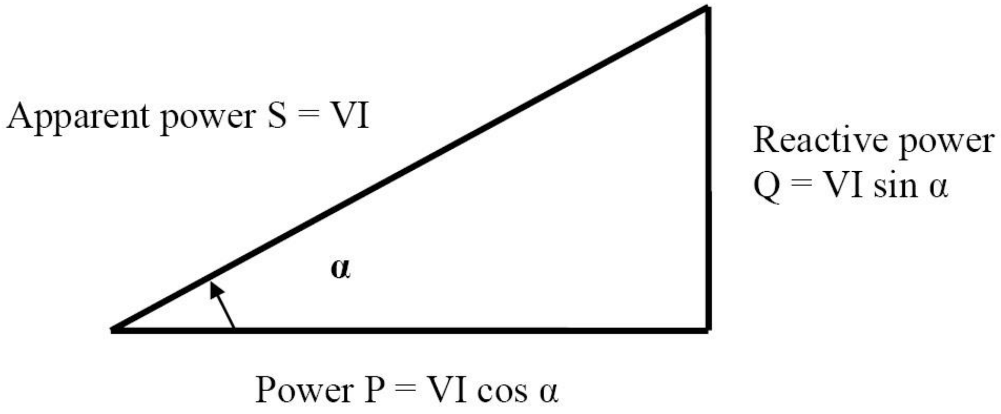

Figure 10. Phase angle determines the power consumed in a circuit.

For an electrical utility's AC grid system, power is consumed by both resistive or active power P, and inductive or reactive power Q, components. Each of these components accounts for its own share of the total power. In this mixed reactive and active case, the average active power component is given by:

$$P = V.I.\cos(\alpha) \tag{6}$$

and the peak reactive component is given by:

$$Q = V.I.\sin(\alpha) \tag{7}$$

where α is the phase angle between I and V.

## POWER FACTOR

The power factor of an AC circuit is the ratio of the useful power *W* consumed by a circuit to the apparent power *VA* consumed:

$$\begin{gathered} Power\ factor = \frac{Real\,power\,[Watts]}{Apparent\ power\,[Volt.Ampere]} \\ W = \frac{P}{S} = \frac{VI\cos\alpha}{VI} = \cos\alpha \end{gathered} \tag{8}$$

For an in phase *V* and *I* relationship, the power factor for the circuit is therefore:

$$W = \cos 0^{o} = 1 \tag{9}$$

In practice, the voltage stability in a grid network is optimized when the real power $P$ is consumed at minimum current $I$, thus ensuring that the value of (cos α) approaches unity, or the lag angle α is minimized, and the reactive power $Q$ is kept to a minimum. This may be facilitated by the electrical utility imposing special tariffs that penalties the consumer for a large $Q$ demand.

## SURGE IMPEDANCE LOADING (SIL)

The load-carrying ability or loadability of a transmission line is described in terms of the concept of Surge Impedance Loading (SIL). The SIL is a loading level at which the power line attains self-sufficiency in reactive power with no net reactive power flowing into or out of the line.

Using the SIL concept, three 500 kV or six 345 kV circuits would be required to achieve the loadability of a single 765 kV line. A 765 kV line can reliably transmit 2200-2400 MW with SIL = 1.0 for distances up to 300 miles, whereas the similarly situated 500 kV and 345 kV lines with bundled conductors can deliver only about 900 MW and 400 MW, respectively. For short distances, these relationships can differ reflecting the thermal capacities established primarily by the number/size of line conductors and the station equipment ratings.

## TRANSMISSION REACH

The relative loadabilities of the 765 kV, 500 kV and 345 kV lines can be viewed in terms of transmission “reach” over which a certain amount of power, say 1,500 MW, can be delivered. For a 765 kV line, this loading represents approximately 0.62 SIL which, according to the loadability characteristic, can be transported reliably over a distance of up to 550 miles.

In contrast, a 345 kV line carrying the same amount of power would operate at 3.8 SIL, transportable only up to about 50 miles assuming adequate thermal capacity. This distance would increase to about 110 miles for a double-circuit 345 kV line. The generalized line loadability characteristic incorporates the assumptions of a well-developed system at each terminal of the line and operating criteria designed to promote system reliability.

Table 8. Transmission reach and loadability for different transmission lines voltage classes [7].

| Voltage level [kV], Single Circuit | Loadability MW, 300 miles | Reach [Miles] for 1,500 MW |
|---|---|---|
| 765 | 2,200 – 2,400 | 550 |
| 500 | 900 | 140 |
| 345 | 400 | 50 |

## LINE LOSSES

## CORONA DISCHARGE FROM OVERHEAD POWER LINES

The construction of overhead power lines, particularly at high elevations and under particular high humidity atmospheric conditions are subject to the phenomenon of Corona Discharge. At high elevations above sea level the reduced air density affects the performance of transmission lines. As the air density declines so does its dielectric strength, resulting in greater discharge of energy from energized surfaces. Corona Discharge manifests itself as audible crackling noise and may have to be controlled to meet local regulations. Effective mitigation methods include using multiple conductors in each phase and the use of optimized phase bundle geometries. The reduced air density also can lower the flashover voltage threshold, necessitating more insulation or effective means for overvoltage control.

Corona losses result from undesirable discharge of electric energy, which can be visible and/or audible especially during rain, caused by air ionization around line conductors and hardware. Corona losses increase with voltage level and elevation above sea level of the line. The standard yearly corona losses at sea level assume a percentage partition of rain/snow/fair weather conditions of 20/2/78.

## OHMIC RESISTIVE HEATING LOSSES

An energized transmission line carrying a power load incurs power losses due to heating in addition to the corona effects. Ohmic heating or resistive losses increase linearly with line resistance and quadratically with loading.

The superior transmission efficiency of 765 kV transmission is attributable to its higher operating voltage and thermal capacity/low resistance compared to 500 kV and 345 kV lines.

Table 9. Line losses for Extra High Voltage (EHV) transmission lines at different voltages in normal weather with 1,000 MW of power load.

| Line Voltage [kV] | Resistive losses [MW/100 miles] | Corona losses [MW/100 miles] | Total [MW/100 miles] | Percent |
|---|---|---|---|---|
| 765, 4-conductor Rail bundle | 4.4 | 6.4 | 10.8 | 1.1 |
| 765, 4-conductor Dipper bundle | 3.3 | 3.7 | 7.0 | 0.7 |
| 765, 6-conductor, Tern bundle | 3.4 | 2.3 | 5.7 | 0.6 |
| 765, 6-conductor | 3.1 | 2.3 | 5.4 | 0.5 |

| | | | | |
|---|---|---|---|---|
| trapezoidal, Kettle bundle | | | | |
| 500, 2-conductor bundle | 11.0 | 1.6 | 12.6 | 1.3 |
| 345 2-conductor bundle | 41.9 | 0.6 | 42.5 | 4.2 |

## ELECTRICAL GENERATOR

The function of the wind turbine generator is to convert mechanical energy to electrical energy. Wind turbine generators are different compared with other generating units that are attached to the electrical grid. One important characteristic is that they must operate with the wind turbine rotor as a power source that supplies a very fluctuating mechanical torque.

On large wind turbines with a power rating above 100-150 kW, the voltage generated by the turbine is usually as 0.690 kV three-phase AC current. The current is then sent through a transformer next to the wind turbine or inside the tower to raise the voltage to 10-30 kV depending on the local electrical grid.

Large manufacturers supply 50 Hz wind turbine models for the electrical grids in most of the world and 60 Hz models for the electrical grid in the USA.

Generators require cooling by encapsulating the generator in a duct, using a large fan and finned surfaces for air cooling. Some manufacturers use water cooled generators. Water cooled generators would be more compact, which is also is associated with electrical efficiency advantages. However, they require a radiator in the nacelle to get rid of the heat from the liquid cooling system.

Great care must be exercised in connecting the generators to the grid. Connecting or disconnecting a large wind turbine generator to the grid is not done by just flicking an ordinary switch. This would damage the generator, the gearbox and the power quality in the grid, leading to the initiation of circuit breaking and protection equipment.

Wind turbines may be designed with either synchronous or asynchronous generators, and with various forms of direct or indirect grid connection of the generator. A direct grid connection implies that the generator is connected directly to the usual 3 phase alternating current grid.

Indirect grid connection implies that the current from the turbine passes through a series of electrical components which adjust the current to match that of the grid. With the choice of an asynchronous generator this occurs automatically.

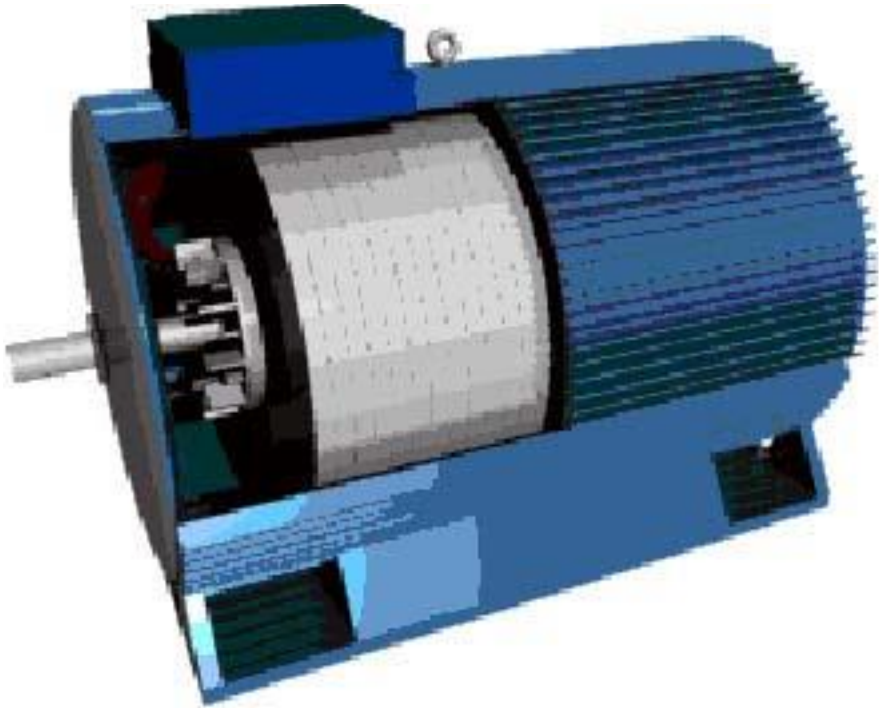

Figure 11. Cutout of electrical generator. The finned surface provides cooling. The rotor in enclosed inside the stator shown as the shining magnetic steel cylinder. An internal cooling fan is mounted at the end of the rotor. The ring on top is used in hoisting the generator.

## SYNCHRONOUS AC GENERATORS

Early alternators, which produce an AC voltage, were developed as a replacement for DC generators. Alternators have a number of advantages. They are generally cheaper and more durable, due to the use of slip rings rather than commutators. Another design improvement is their incorporation of the armature windings in the stator, with the rotor providing the magnetic field. If permanent magnets are used, the power is drawn from the alternator through fixed contacts, and wear due to the passage of high currents through moving contacts is eliminated. In excited field alternators, the magnetic field is provided by a supply of relatively low current to the field windings via slip rings.

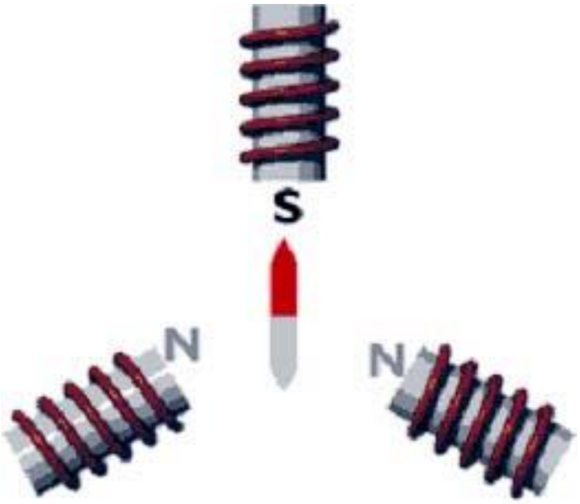

Figure 12. Two poles synchronous generator configuration.

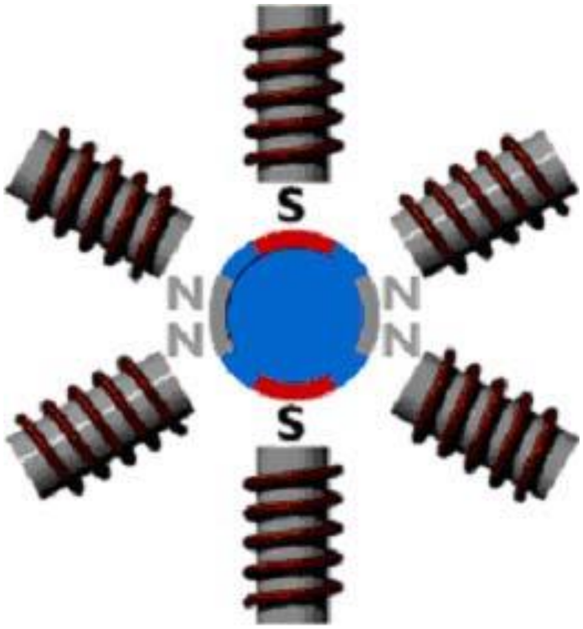

Figure 13. Four poles synchronous generator configuration.

The output frequency of the generator depends on the input frequency of the drive shaft and on the number of pole pairs in the generator. In order to be compatible with a utility's grid supply, the machine must be driven at a constant speed by the turbine rotors, to produce power which is in phase with the grid supply. This may be achieved by altering the pitch of the turbine rotor blades to alter their lift coefficient as the wind speed varies. However, in practice, the generator output is small enough in relation to that of the utility supply to allow it to lock-on to the grid frequency, ensuring a grid-compatible output frequency despite small variations in wind speed.

## ASYNCHRONOUS INDUCTION AC GENERATORS

An induction AC generator differs from a synchronous AC generator in that its rotor consists in its simplest form of an iron cylinder with slots on its periphery that carry insulated copper bars. These are short circuited by rings which are positioned on the flat faces of the cylinder. The currents that produce the magnetic field are in short circuited loops. If positioned on the stator, the field current in these loops is induced from currents in the stator windings, and vice versa. In operational terms, power generation can only occur when the induced closed loop field currents have been initiated and maintained.

Figure 14. Asynchronous induction generator.

Figure 15. Squirrel cage rotor for asynchronous induction generator.

This is achieved in one of three ways:

1. Reactive power is drawn from the live grid to which the generator is connected,
2. Capacitors, connected between the output and the ground, enable autonomous self

excited generation. In this case some residual magnetism in the system is necessary.
3. A small synchronous generator may be run in parallel, which may, if diesel fuelled, for instance, then acts as a backup system to provide power at times of inadequate wind.

Depending on the operating conditions such as wind speed, the generator may act either as a generator, supplying power to the grid, or as a motor acting as a sink of power from the grid. In either case, there will be a difference in speed between the shaft frequency $f_s$ and the output frequency $f_o$. This is known as the generator slip s:

$$s = \frac{f_0 - nf_s}{f_0} \tag{10}$$

where:

$f_0$ is the AC output power frequency
$f_s$ is the shaft rotational frequency
$n$ is the number of rotor windings

The generator slip is negative when the induction AC machine is acting as a generator, and is positive when it is acting as a motor.

## DIRECT CURRENT (DC) GENERATORS

Small scale stand alone wind turbines are most commonly used to charge a bank of batteries for energy storage at a relatively low voltage. They use simple DC generators similar to that shown. In these systems, the rotating generator shaft, connected to the turbine blades either directly or through a gearbox, turns the rotor within a magnetic field produced by either the field coil windings or by an arrangement of permanent magnets on the armature.

The rotation causes an electric current to flow in the rotor windings as the coils of wire cut through the magnetic field. This current, whose magnitude depends upon the number of turns in the windings, the strength of the magnetic field and the speed of rotation, is drawn off from the commutator through graphite brushes and fed directly to the bank of batteries. Voltage regulators which smooth out the fluctuations in the generated voltage are usually used.

## GEARBOX FOR WIND TURBINES

The rotational energy of the wind turbine rotor is transferred to the generator through the power train. The power train consists of a main shaft, a gearbox and a high speed shaft.

If an ordinary generator were directly connected to a 50 Hz AC three phase grid with two, four, or six poles, this would imply a high speed turbine rotating at 1,000-3,000 revolutions per minute (rpm).

With a 43 m rotor diameter that would further imply a rotor tip speed of twice the speed of sound, which is unrealistic.

A possibility is to build a slow moving AC generator with multiple poles. A direct connection of the generator to the grid would require a 200 pole generator with 300 magnets to reach a reasonable rotational speed of 30 rpm.

Additionally, the mass of the rotor of the generator would have to be roughly proportional to the amount of torque or moment it has to handle. Thus the complex option of a directly driven generator will be both costly and heavy in weight.

To attain a higher speed and less torque, the practical solution is to use a gearbox to increase the speed. This goes in the opposite direction of other type of industrial equipment where gear reduction reduces the rotational speed such as in automobiles engines and submarines propellers.

A gearbox associated with a wind turbine converts the slowly rotating high torque power from its rotor to a high speed, low torque power for the generator.

The gearbox in a wind turbine does not change gears and has a single gear ratio between the rotation of the rotor and the generator. For a 600 or 750 kW wind turbine, the gear ratio is 1 to 50.

Increasing the rotational speed is an undesirable feature since instabilities and vibrations are also magnified in the process. An alternative is tom use a screw or spiral gear or gearless multiple pole generators.

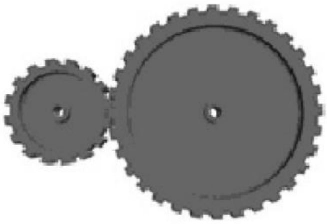

Figure 16. Wind generators gear boxes increase the rotational speed and decrease the torque rather than the opposite in other industrial equipment. A 600-750 kW wind turbine uses a gear ratio of 1 to 50.

Figure 17. Gearbox for a 1.5 MW wind generator with two flanges for two generators on the high speed side. The nacelle is shown in the back. Two hydraulically operated emergency disc brakes are shown at the bottom right.

## TRENDS IN WIND ENERGY ELECTRICAL GENERATORS

### INTRODUCTION

In addition to applying the basic process of energy conversion, the technological development of wind power systems also addresses the design and size of the machines used for the generation of electric power.

Whereas the asynchronous induction machine is now well established as the most popular generator for reliable, efficient, low-cost power production from the wind, other designs of machines are used and there are several "drivers" for change.

It is likely that future advances in turbine design will incorporate variable speed and direct drive technology. Furthermore, these advances are a clear indication of component development taking place specifically for the wind turbine market.

### EVOLUTIONARY DESIGNS

The traditional Danish design of a wind turbine is a fixed speed turbine connected to an asynchronous or induction generator. Existing commercial machines generate electricity at low voltage, with no move to voltages above 0.690 kV, although a 1.5 MWe turbine had a step up transformer incorporated adjacent to the generator in the nacelle. Evolution of this approach appears to be moving in the following directions:

1. The use of multiple generators connected to a single rotor and gear box.
2. The design of two speed asynchronous induction generators.
3. The design of induction machines with variable generator rotor resistance.

### VARIABLE SPEED MACHINES

A new trend in wind electrical generation is variable speed operation, which offers several advantages. Because of their ability to operate at tip speed ratios close to the optimal value, variable speed machines can be more efficient than fixed speed systems depending on the wind speed distribution function. Modification of the generator and the intermediate electronic control systems become necessary in order to provide a grid compatible supply.

A factor favoring variable speed machines is the requirement of some utilities for very smooth output power. Variable speed drive technology is being applied to wind turbines to bring various performance benefits to the overall system:

1. Increased in energy yield.
2. Reduction in loading on the mechanical components.
3. Reduction of the audible noise during low wind speed conditions.
4. Smoothing the energy flow.
5. Reducing disturbances in the power network.

The incorporation of high power variable speed drives into wind turbines introduces

a new set of engineering considerations in the design and operation of an electrical grid:
1. The fault level of the network.
2. Adequate voltage regulation.
3. Providing electromagnetic compatibility.
4. Satisfactory electrical system behavior during wind gust conditions.
5. Consideration of the power converter efficiency.

For variable speed turbines, complex power converter hardware would be necessary. The power conversion equipment must provide low harmonics and unity power factor control of the electrical current delivered to the network.

### DIRECT DRIVE LOW SPEED HIGH TORQUE GENERATORS

Interest exists in the development of direct drive generators. As the turbine sizes increase, the relative cost of the bulky and heavy gearbox becomes of paramount importance. Eliminating the need for the gearbox could save not only cost, but also mass, frictional losses, acoustic noise and failure and reliability problems.

A doubling of the wind turbine diameter would result in the quadrupling of its rated power output. The rotor torque, which is closely related to the gearbox cost, will increase by a factor of eight. Another important issue is the integration of the generator into the overall nacelle design.

The physical size of the generator is governed by the torque it is required to develop. A direct drive generator is therefore necessarily a large machine, but it is subject to very tight cost restrictions imposed by the economics of wind power. Low cost is the prime requirement in every aspect of the design, yet high efficiency is vital because of the high capitalized value of the losses and because the variable speed capability is increasingly being adopted. The development of designs which incorporate these factors can yield high efficiency and would be competitive in cost with the conventional gearbox asynchronous induction generator arrangement.

The possible approaches to fulfill these goals include:

1. The use of permanent magnet excitation for high generator efficiency.
2. Adopting standardized parts across a wide range of power and speed ratings to minimize the tooling costs and allow uninterruptible long production runs.
3. The use of ferrite magnets with flux concentration for low material cost.
4. Incorporating a small number of stator coils that are pre fitted to the stator core segments.
5. Using simple stator lamination packs fully prepared prior to assembly of the machine.
6. Integration of AC to DC conversion into the machine to simplify the winding and its connections.
7. Developing a structural design which avoids threading a magnetized rotor.

## DISCUSSION

The conditions that caused the August 14, 2003 blackout remain in place. One simple answer is to change the grid physically to accommodate the new trading patterns, mainly by expanding transmission capacity. The DOE and FERC, as well as organizations supported by the utilities, such as the Electric Power Research Institute (EPRI) and the

Edison Electric Institute, advocate this approach. They urged expanding transmission lines and easing environmental rules that limit their construction. The logic is simple: if increased energy trading causes congestion and, thus, unreliability, expand capacity so controllers can switch energy from line to line without overloading.

To pay the extensive costs, the utilities and the DOE advocate increases in utility rates. The logic is that the people who benefit from the system have to be part of the solution. That means the ratepayers are going to have to contribute. The costs involved would certainly be in the tens of billions of dollars. Thus, deregulation would result in large cost increases to consumers, not the savings initially promised.

Experts outside the utility industry point to serious drawbacks in the build-more solution other than increasing the cost of power. It is almost impossible to say what level of capacity will accommodate the long-distance wholesale trading. The data needed to judge that is now proprietary and unavailable in detail. Even if made available to planners, this data refers only to the present. Transmission lines take years to build, but energy flows can expand rapidly to fill new capacity. New lines could be filled by new trades as fast as they go up.

The solution advocated by the deregulation critics would revise the rules to put them back into accord with the grid physics. According to Casazza [2, 3]: “The system is not outdated, it is just misused. We should look hard at the new rules, see what is good for the system as a whole, and throw out the rest.”

FERC or Congress could rescind Order 888 and reduce the long-distance energy flows that stress the system. The data on energy flows and blackouts could again be made public so that planners would know what power flows are occurring and the reliability records of the utilities. Rehiring the thousands of fired workers to upgrade maintenance, would take longer and might require rewriting regulations and undoing more of the 1992 Energy Act. These changes would have costs to be borne by the shareholders and creditors of the banks and energy companies who bet so heavily on energy trading.

Concerning the sustainable implementation of wind and other renewable energy sources, the issue of intermittency must be seriously addressed by the implementation of energy storage systems, and the coupling to rapidly responding natural gas Combined Cycle Gas Turbine (CCGT) and Open Cycle Gas Turbine (OCGT) plants.

Another alternative comes to mind. Instead of putting the excess off-peak energy back into the grid, one can produce H2 and combine it with CO2 to create useful hydrocarbon fuels such a green diesel and methanol. The capital costs of energy storage by CAESr, pumped hydroelectric, flywheels, or batteries is in the range $150 - $1000/kWhr, whereas storing energy in stable liquid fuels like diesel, gasoline, and jet fuel in ordinary tanks is about $0.02/kWhr.

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