



Electric Power Transmission Systems

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Chapter-1

Smart Grid

A **smart grid** is a form of electricity network utilizing digital technology. A smart grid delivers electricity from suppliers to consumers using two-way digital communications to control appliances at consumers' homes; this could save energy, reduce costs and increase reliability and transparency if the risks inherent in executing massive information technology projects are avoided. The "Smart Grid" is envisioned to overlay the ordinary electrical grid with an information and net metering system, that includes smart meters. Smart grids are being promoted by many governments as a way of addressing energy independence, global warming and emergency resilience issues.

The idea of two way communications from suppliers to consumers to control appliances is not new, and systems have been implemented using analog technology for many years. The growth of an extensive digital communication network for the internet has made it practical to consider a more sophisticated type of smart grid. The increased data transmission capacity has made it conceptually possible to apply sensing, measurement and control devices with two-way communications to electricity production, transmission, distribution and consumption parts of the power grid at a more granular level than previously. These devices could communicate information about grid condition to system users, operators and automated devices, making it possible for the average consumer to dynamically respond to changes in grid condition, instead of only utilities and very large customers.

Like existing utility grids, a smart grid includes an intelligent monitoring system that keeps track of all electricity flowing in the system, but in more detail. Like the existing grid, it also has the capability of integrating renewable electricity such as solar and wind, but has the potential to do so more effectively. When power is least expensive the user can allow the smart grid to turn on selected home appliances such as washing machines or factory processes that can run at arbitrary hours. At peak times it could turn off selected appliances to reduce demand. There are many technical obstacles to be overcome to make this practical for the average homeowner; for example, if wind speeds decrease in the middle of a wash cycle, would consumers want their laundry "becalmed"?

A widely overlooked fact about the smart grid is that it is not a substitute for a real grid, but only an enhancement. The construction of a larger and better infrastructure of high-

voltage transmission lines for the efficient delivery of electric power is a prerequisite to the construction of an effective smart grid.

Other names for a smart grid (or for similar proposals) include **smart electric** or **power grid**, **intelligent grid** (or **intelligrid**), **futuregrid**, and the more modern **intergrid** and **intragrid**.

Goals

In principle, the smart grid is a simple upgrade of 20th century power grids which generally "broadcast" power from a few central power generators to a large number of users, to instead be capable of routing power in better ways to respond to a very wide range of conditions, and to charge a premium to those that use energy during peak hours.

Respond to many conditions in supply and demand

Broadly stated, a smart grid could respond to events which occur anywhere in the power generation, distribution and demand chain. Events may occur generally in the environment, e.g., clouds blocking the sun and reducing the amount of solar power or a very hot day requiring increased use of air conditioning. They could occur commercially in the power supply market, e.g., customers change their use of energy as prices are set to reduce energy use during high peak demand. Events might also occur locally on the distribution grid, e.g., an MV transformer fails, requiring a temporary shutdown of one distribution line. Finally these events might occur in the home, e.g., everyone leaves for work, putting various devices into hibernation, and data ceases to flow to an IPTV. Each event motivates a change to power flow.

Latency of the data flow is a major concern, with some early smart meter architectures allowing actually as long as 24 hours delay in receiving the data, preventing any possible reaction by either supplying or demanding devices.

Smart energy demand

Smart energy demand describes the energy user component of the smart grid. It goes beyond and means much more than even energy efficiency and demand response combined. Smart energy demand is what delivers the majority of smart meter and smart grid benefits.

Smart energy demand is a broad concept. It includes any energy-user actions to:

- Enhancement of reliability
- reduce peak demand,
- shift usage to off-peak hours,
- lower total energy consumption,
- actively manage electric vehicle charging,

- actively manage other usage to respond to solar, wind, and other renewable resources, and
- buy more efficient appliances and equipment over time based on a better understanding of how energy is used by each appliance or item of equipment.

All of these actions minimize adverse impacts on electricity grids and maximize consumer savings.

Smart Energy Demand mechanisms and tactics include:

- smart meters,
- dynamic pricing,
- smart thermostats and smart appliances,
- automated control of equipment,
- real-time and next day energy information feedback to electricity users,
- usage by appliance data, and
- scheduling and control of loads such as electric vehicle chargers, home area networks (HANs), and others.

Provision megabits, control power with kilobits, sell the rest

The amount of data required to perform monitoring and switching your appliances off automatically is very small compared with that already reaching even remote homes to support voice, security, Internet and TV services. Many smart grid bandwidth upgrades are paid for by over-provisioning to also support consumer services, and subsidizing the communications with energy-related services or subsidizing the energy-related services, such as higher rates during peak hours, with communications. This is particularly true where governments run both sets of services as a public monopoly, e.g. in India. Because power and communications companies are generally separate commercial enterprises in North America and Europe, it has required considerable government and large-vendor effort to encourage various enterprises to cooperate. Some, like Cisco, see opportunity in providing devices to consumers very similar to those they have long been providing to industry. Others, such as Silver Spring Networks or Google, are data integrators rather than vendors of equipment. While the AC power control standards suggest powerline networking would be the primary means of communication among smart grid and home devices, the bits may not reach the home via Broadband over Power Lines (BPL) initially but by fixed wireless. This may be only an interim solution, however, as separate power and data connections defeats full control.

Scale and scope

Europe's SuperSmart Grid, as well as earlier proposals (such as Al Gore's continental Unified Smart Grid) make semantic distinctions between local and national grids that sometimes conflict. Papers by Battaglini et al. associate the term "smart grid" with local clusters (page 6), whereas the intelligent interconnecting backbone provides an additional

layer of coordination above the local smart grids. Media use in both Europe and the US however tends to conflate national and local.

Regardless of terminology used, smart grid projects always intend to allow the continental and national interconnection backbones to fail without causing local smart grids to fail. As in the case of existing utility infrastructure, they would have to be able to function independently and ration whatever power is available to critical needs.

Municipal grid

Before recent standards efforts, municipal governments, for example in Miami, Florida, have historically taken the lead in enforcing integration standards for smart grids/meters. As municipalities or municipal electricity monopolies also often own some fiber optic backbones and control transit exchanges at which communication service providers meet, they are often well positioned to force good integration.

Municipalities also have primary responsibility for emergency response and resilience, and would in most cases have the legal mandate to ration or provision power, say to ensure that hospitals and fire response and shelters have priority and receive whatever power is still available in a general outage.

Home Area Network

A Home Area Network, or "home grid", extends some of these capabilities into the home using powerline networking and/or RF using standards such as ZigBee, INSTEON, Zwave, WiFi or others. In the smart grid, NIST is promoting interoperability between the different standards. OSHAN is one initiative that enables interoperability in the home.

Because of the communication standards both smart power grids and some Home Area Networks support more bandwidth than is required for power control and therefore may cost more than required. The existing 802.11 home networks generally have megabits of additional bandwidth for other services (burglary, fire, medical and environmental sensors and alarms, ULC and CCTV monitoring, access control and keying systems, intercoms and secure phone line services), and furthermore can't be separated from LAN and VoIP networking, nor from TV once the IPTV standards have emerged.

A number of companies have entered the Home Area Network space, such as Plug Smart, a brand of Juice Technologies, LLC, Tendril, Control4, and EnergyHub.

Consumer electronics devices now consume over half the power in a typical US home. Accordingly, the ability to shut down or hibernate devices when they are not receiving data could be a major factor in cutting energy use, but this would mean the electric company has information on whether a consumer is using their computer or not.

Other key devices that could aide in the utilities efforts to shed load during times of peak demand include air conditioning units, electric water heaters, pool pumps and other high

wattage devices. In 2009, smart grid companies may represent one of the biggest and fastest growing sectors in the "cleantech" market. It consistently receives more than half the venture capital investment.

In 2009 President Barack Obama asked the United States Congress "to act without delay" to pass legislation that included doubling alternative energy production in the next three years and building a new electricity "**smart grid**". On April 13, 2009, George W. Arnold was named the first National Coordinator for Smart Grid Interoperability.

What a smart grid is

The function of an Electrical grid is not a single entity but an aggregate of multiple networks and multiple power generation companies with multiple operators employing varying levels of communication and coordination, most of which is manually controlled. Smart grids increase the connectivity, automation and coordination between these suppliers, consumers and networks that perform either long distance transmission or local distribution tasks.

- Transmission networks move electricity in bulk over medium to long distances, are actively managed, and generally operate from 345kV to 800kV over AC and DC lines.
- Local networks traditionally moved power in one direction, "distributing" the bulk power to consumers and businesses via lines operating at 132kV and lower.

This paradigm is changing as businesses and homes begin generating more wind and solar electricity, enabling them to sell surplus energy back to their utilities. Modernization is necessary for energy consumption efficiency, real time management of power flows and to provide the bi-directional metering needed to compensate local producers of power. Although transmission networks are already controlled in real time, many in the US and European countries are antiquated by world standards, and unable to handle modern challenges such as those posed by the intermittent nature of alternative electricity generation, or continental scale bulk energy transmission. In the U.S., excellent planning for expansion by largely regulated utilities in the 1960s and 1970s resulted in the accommodation of substantial growth with relatively little capital investment in the subsequent decades, when the economic pressures and uncertainty brought on by deregulation discouraged previously effective planning and expansion of the grid.

Modernizes both transmission and distribution

A smart grid is an umbrella term that covers modernization of both the transmission and distribution grids. The modernization is directed at a disparate set of goals including facilitating greater competition between providers, enabling greater use of variable energy sources, establishing the automation and monitoring capabilities needed for bulk transmission at cross continent distances, and enabling the use of market forces to drive energy conservation.

Many smart grid features readily apparent to consumers such as smart meters serve the energy efficiency goal. The approach is to make it possible for energy suppliers to charge variable electric rates so that charges would reflect the large differences in cost of generating electricity during peak or off peak periods. Such capabilities allow load control switches to control large energy consuming devices such as hot water heaters so that they consume electricity when it is cheaper to produce.

Peak curtailment/leveling and time of use pricing

To reduce demand during the high cost peak usage periods, communications and metering technologies inform smart devices in the home and business when energy demand is high and track how much electricity is used and when it is used. To motivate them to cut back use and perform what is called **peak curtailment** or **peak leveling**, prices of electricity are increased during high demand periods, and decreased during low demand periods. It is thought that consumers and businesses will tend to consume less during high demand periods if it is possible for consumers and consumer devices to be aware of the high price premium for using electricity at peak periods. This could mean making trade-offs such as cooking dinner at 9pm instead of 5pm. When businesses and consumers see a direct economic benefit of using energy at off-peak times become more energy efficient, the theory is that they will include energy cost of operation into their consumer device and building construction decisions.

According to proponents of smart grid plans, this will reduce the amount of spinning reserve that electric utilities have to keep on stand-by, as the load curve will level itself through a combination of "invisible hand" free-market capitalism and central control of a large number of devices by power management services that pay consumers a portion of the peak power saved by turning their devices off.

Platform for advanced services

As with other industries, use of robust two-way communications, advanced sensors, and distributed computing technology will improve the efficiency, reliability and safety of power delivery and use. It also opens up the potential for entirely new services or improvements on existing ones, such as fire monitoring and alarms that can shut off power, make phone calls to emergency services, etc.

US and UK savings estimates and assumptions behind them

One United States Department of Energy study calculated that internal modernization of US grids with smart grid capabilities would save between 46 and 117 billion dollars over the next 20 years. As well as these industrial modernization benefits, smart grid features could expand energy efficiency beyond the grid into the home by coordinating low priority home devices such as water heaters so that their use of power takes advantage of the most desirable energy sources. Smart grids can also coordinate the production of power from large numbers of small power producers such as owners of rooftop solar

panels — an arrangement that would otherwise prove problematic for power systems operators at local utilities.

The above vision makes two assumptions. First, that consumers will act in response to market signals, and that there needs to be some sort of telecommunications network. In the UK, where consumers have for nearly 10 years had a choice in the company from which they purchase electricity, more than 80% have stayed with their existing supplier, despite the fact that there are significant differences in the prices offered by a given electricity supplier. End users may be less responsive to price signals than proponents of Smart Grids think. Second, in the case of the telecomms aspect of Smart Grids, this ignores the possibility of bringing autonomy to a given appliance. Various companies (such as RLTec) have developed low cost systems which allow products to react to network fluctuations (usually network frequency). This type of control is called "dynamic demand management". A feature of DDM being that, it is low cost, needs no telecomms network and is available now. Of course these are not points which proponents of a "power telecomms network" may wish to hear about or indeed see propagated.

Although there are specific and proven smart grid technologies in use, *smart grid* is an aggregate term for a set of related technologies on which a specification is generally agreed, rather than a name for a specific technology. Some of the benefits of such a modernized electricity network include the ability to reduce power consumption at the consumer side during peak hours, called Demand side management; enabling grid connection of distributed generation power (with photovoltaic arrays, small wind turbines, micro hydro, or even combined heat power generators in buildings); incorporating grid energy storage for distributed generation load balancing; and eliminating or containing failures such as widespread power grid cascading failures. The increased efficiency and reliability of the smart grid is expected to save consumers money and help reduce CO₂ emissions. These benefits are unlikely to be realized without a difficult transition period during which the luster of the promised potential of the technology is diminished by the extreme cost overruns and by reduced reliability (due to software bugs and unanticipated problems).

History

Today's alternating current power grid evolved after 1896, based in part on Nikola Tesla's design published in 1888. Many implementation decisions that are still in use today were made for the first time using the limited emerging technology available 120 years ago. Specific obsolete power grid assumptions and features (like centralized unidirectional electric power transmission, electricity distribution, and demand-driven control) represent a vision of what was thought possible in the 19th century.

Part of this is due to an institutional risk aversion that utilities naturally feel regarding use of untested technologies on a critical infrastructure they have been charged with defending against any failure, however momentary.

Over the past 50 years, electricity networks have not kept pace with modern challenges, such as:

- security threats, from either energy suppliers or cyber attack
- national goals to employ alternative power generation sources whose intermittent supply makes maintaining stable power significantly more complex
- conservation goals that seek to lessen peak demand surges during the day so that less energy is wasted in order to ensure adequate reserves
- high demand for an electricity supply that is uninterruptible
- digitally controlled devices that can alter the nature of the electrical load (giving the electric company the ability to turn off appliances in your home if they see fit) and result in electricity demand that is incompatible with a power system that was built to serve an “analog economy.” For a simple example, timed Christmas lights can present significant surges in demand because they come on at near the same time (sundown or a set time). Without the kind of coordination that a smart grid can provide, the increased use of such devices lead to electric service reliability problems, power quality disturbances, blackouts, and brownouts.

Although these points tend to be the "conventional wisdom" with respect to smart grids, their relative importance is debatable. For instance, despite the weaknesses of power network being publicly broadcast, there has never been an attack on a power network in the United States or Europe. However, in April 2009 it was learned that spies had infiltrated the power grids, perhaps as a means to attack the grid at a later time. In the case of renewable power and its variability, recent work undertaken in Europe (Dr. Bart Ummels et al.) suggests that a given power network can take up to 30% renewables (such as wind and solar) without any changes whatsoever.

The term smart grid has been in use since at least 2005, when the article "Toward A Smart Grid", authored by S. Massoud Amin and Bruce F. Wollenberg appeared in the September/October issue of *IEEE P&E Magazine* (Vol. 3, No.5, pgs 34-41). The term had been used previously and may date as far back as 1998. There are a great many smart grid definitions, some functional, some technological, and some benefits-oriented. A common element to most definitions is the application of digital processing and communications to the power grid, making data flow and information management central to the smart grid. Various capabilities result from the deeply integrated use of digital technology with power grids, and integration of the new grid information flows into utility processes and systems is one of the key issues in the design of smart grids. Electric utilities now find themselves making three classes of transformations: improvement of infrastructure, called the *strong grid* in China; addition of the digital layer, which is the essence of the *smart grid*; and business process transformation, necessary to capitalize on the investments in smart technology. Much of the modernization work that has been going on in electric grid modernization, especially substation and distribution automation, is now included in the general concept of the smart grid, but additional capabilities are evolving as well.

Smart grid technologies have emerged from earlier attempts at using electronic control, metering, and monitoring. In the 1980s, Automatic meter reading was used for monitoring loads from large customers, and evolved into the Advanced Metering Infrastructure of the 1990s, whose meters could store how electricity was used at different times of the day. Smart meters add continuous communications so that monitoring can be done in real time, and can be used as a gateway to demand response-aware devices and "smart sockets" in the home. Early forms of such Demand side management technologies were dynamic demand aware devices that passively sensed the load on the grid by monitoring changes in the power supply frequency. Devices such as industrial and domestic air conditioners, refrigerators and heaters adjusted their duty cycle to avoid activation during times the grid was suffering a peak condition. Beginning in 2000, Italy's Telegestore Project was the first to network large numbers (27 million) of homes using such smart meters connected via low bandwidth power line communication. Recent projects use Broadband over Power Line (BPL) communications, or wireless technologies such as mesh networking that is advocated as providing more reliable connections to disparate devices in the home as well as supporting metering of other utilities such as gas and water.

Monitoring and synchronization of wide area networks were revolutionized the early 1990s when the Bonneville Power Administration expanded its smart grid research with prototype sensors that are capable of very rapid analysis of anomalies in electricity quality over very large geographic areas. The culmination of this work was the first operational Wide Area Measurement System (WAMS) in 2000. Other countries are rapidly integrating this technology — China will have a comprehensive national WAMS system when its current 5-year economic plan is complete in 2012

First cities with smart grids

The earliest, and still largest, example of a smart grid is the Italian system installed by Enel S.p.A. of Italy. Completed in 2005, the Telegestore project was highly unusual in the utility world because the company designed and manufactured their own meters, acted as their own system integrator, and developed their own system software. The Telegestore project is widely regarded as the first commercial scale use of smart grid technology to the home, and delivers annual savings of 500 million euro at a project cost of 2.1 billion euro.

In the US, the city of Austin, Texas has been working on building its smart grid since 2003, when its utility first replaced 1/3 of its manual meters with smart meters that communicate via a wireless mesh network. It currently manages 200,000 devices real-time (smart meters, smart thermostats, and sensors across its service area), and expects to be supporting 500,000 devices real-time in 2009 servicing 1 million consumers and 43,000 businesses. Boulder, Colorado completed the first phase of its smart grid project in August 2008. Both systems use the smart meter as a gateway to the home automation network (HAN) that controls smart sockets and devices. Some HAN designers favor decoupling control functions from the meter, out of concern of future mismatches with

new standards and technologies available from the fast moving business segment of home electronic devices.

Hydro One, in Ontario, Canada is in the midst of a large-scale Smart Grid initiative, deploying a standards-compliant communications infrastructure from Trilliant. By the end of 2010, the system will serve 1.3 million customers in the province of Ontario. The initiative won the "Best AMR Initiative in North America" award from the Utility Planning Network.

The City of Mannheim in Germany is using realtime Broadband Powerline (BPL) communications in its Model City Mannheim "MoMa" project

Problem definition

The major driving forces to modernize current power grids can be divided in four, general categories.

- Increasing reliability, efficiency and safety of the power grid.
- Enabling decentralized power generation so homes can be both an energy client and supplier (provide consumers with an interactive tool to manage energy usage, as net metering).
- Flexibility of power consumption at the clients side to allow supplier selection (enables distributed generation, solar, wind, biomass).
- Increase GDP by creating more new, green-collar energy jobs related to renewable energy industry manufacturing, plug-in electric vehicles, solar panel and wind turbine generation, energy conservation construction.

Smart grid functions

Before examining particular technologies, a proposal can be understood in terms of what it is being required to do. The governments and utilities funding development of grid modernization have defined the functions required for smart grids. According to the United States Department of Energy's Modern Grid Initiative report, a modern smart grid must:

1. Be able to heal itself
2. Motivate consumers to actively participate in operations of the grid
3. Resist attack
4. Provide higher quality power that will save money wasted from outages
5. Accommodate all generation and storage options
6. Enable electricity markets to flourish
7. Run more efficiently
8. Enable higher penetration of intermittent power generation sources

Self-healing

Using real-time information from embedded sensors and automated controls to anticipate, detect, and respond to system problems, a smart grid can automatically avoid or mitigate power outages, power quality problems, and service disruptions.

As applied to distribution networks, there is no such thing as a "self healing" network. If there is a failure of an overhead power line, given that these tend to operate on a radial basis (for the most part) there is an inevitable loss of power. In the case of urban/city networks that for the most part are fed using underground cables, networks can be designed (through the use of interconnected topologies) such that failure of one part of the network will result in no loss of supply to end users. A fine example of an interconnected network using zoned protection is that of the Merseyside and North Wales Electricity Board (MANWEB).

It is envisioned that the smart grid will likely have a control system that analyzes its performance using distributed, autonomous reinforcement learning controllers that have learned successful strategies to govern the behavior of the grid in the face of an ever changing environment such as equipment failures. Such a system might be used to control electronic switches that are tied to multiple substations with varying costs of generation and reliability.

Consumer participation

A smart grid, is, in essence, an attempt to require consumers to change their behavior around variable electric rates or to pay vastly increased rates for the privilege of reliable electrical service during high-demand conditions. Historically, the intelligence of the grid in North America has been demonstrated by the utilities operating it in the spirit of public service and shared responsibility, ensuring constant availability of electricity at a constant price, day in and day out, in the face of any and all hazards and changing conditions. A smart grid incorporates consumer equipment and behavior in grid design, operation, and communication. This enables consumers to better control (or be controlled by) "smart appliances" and "intelligent equipment" in homes and businesses, interconnecting energy management systems in "smart buildings" and enabling consumers to better manage energy use and reduce energy costs. Advanced communications capabilities equip customers with tools to exploit real-time electricity pricing, incentive-based load reduction signals, or emergency load reduction signals.

There is marketing evidence of consumer demand for greater choice. A survey conducted in the summer of 2007 interviewed almost 100 utility executives and sought the opinions of 1,900 households and small businesses from the U.S., Germany, Netherlands, England, Japan and Australia. Among the findings:

1. 83% of those who cannot yet choose their utility provider would welcome that option

2. Roughly two-thirds of the customers that do not yet have renewable power options would like the choice
3. Almost two-thirds are interested in operating their own generation, provided they can sell power back to the utility

And as already noted, in the UK where the experiment has been running longest, 80% have no interest in change (source: National Grid).

Proponents incorrectly assert that the real-time, two-way communications available in a smart grid will enable consumers to be compensated for their efforts to save energy and to sell energy back to the grid through net-metering. By enabling distributed generation resources like residential solar panels, small wind and plug-in hybrid, proponents assert that the smart grid will spark a revolution in the energy industry by allowing small players like individual homes and small businesses to sell power to their neighbors or back to the grid. This is actually not necessary, and many utilities promote small independent distributed generation and successfully integrate it with no impact. These sources of power are only likely to become significant if taxpayer supported government subsidies are available to help consumers purchase the very expensive equipment that is required.

The same will hold true for larger commercial businesses that have renewable or back-up power systems that can provide power for a price during peak demand events, typically in the summer when air condition units place a strain on the grid. This participation by smaller entities has been called the "democratization of energy"—it is similar to former Vice President Al Gore's vision for a Unified Smart Grid.

Resist attack

Smart grid technologies better identify and respond to man-made or natural disruptions. Real-time information enables grid operators to isolate affected areas and redirect power flows around damaged facilities.

One of the most important issues of resist attack is the smart monitoring of power grids, which is the basis of control and management of smart grids to avoid or mitigate the system-wide disruptions like blackouts. The traditional monitoring is based on weighted least square (WLS) which is very weak and prone to fail when gross errors (including topology errors, measurement errors or parameter errors) are present. New technology of state monitor is needed to achieve the goals of the smart grids.

High quality power

Outages and power quality issues cost US businesses more than \$100 billion on average each year. It is asserted that assuring more stable power provided by smart grid technologies will reduce downtime and prevent such high losses, but the reliability of complex systems is very difficult to analyze and guarantee. A more practical approach to improving reliability and power quality is to simply follow the well established and well

documented engineering principles developed by federal agencies like the USDA's Rural Utility Service.

Accommodate generation options

As smart grids continue to support traditional power loads they also seamlessly interconnect fuel cells, renewables, microturbines, and other distributed generation technologies at local and regional levels. Integration of small-scale, localized, or on-site power generation allows residential, commercial, and industrial customers to self-generate and sell excess power to the grid with minimal technical or regulatory barriers. This also improves reliability and power quality, reduces electricity costs, and offers more customer choice. It will be a long time before a smart grid is actually necessary to realize these benefits. The existing grid can typically accommodate an order of magnitude more than the existing small-scale localized generation without the benefit of the smart grid. Most obstacles to the integration of larger renewable projects, like wind farms, is due to limitations of traditional infrastructure.

Enable electricity market

Significant increases in bulk transmission capacity will require construction of new transmission lines before improvements in transmission grid management proposed by smart grids can make a difference. Such improvements are aimed at creating an open marketplace where alternative energy sources from geographically distant locations can easily be sold to customers wherever they are located.

Intelligence in distribution grids are not required to enable small producers to generate and sell electricity at the local level using alternative sources such as rooftop-mounted photo voltaic panels, small-scale wind turbines, and micro hydro generators. For example Chelan PUD's SNAP program promotes distributed, consumer owned small scale generation. Only after very high penetration of these types of resources is additional intelligence provided by sensors and software designed to react instantaneously to imbalances caused by intermittent sources, such as distributed generation, necessary.

Optimize assets

A smart grid can optimize capital assets while minimizing operations and maintenance costs. Optimized power flows reduce waste and maximize use of lowest-cost generation resources. Harmonizing local distribution with inter-regional energy flows and transmission traffic improves use of existing grid assets and reduces grid congestion and bottlenecks, which can ultimately produce consumer savings.

Enable high penetration of intermittent generation sources

Climate change and environmental concerns will increase the amount of renewable energy resources. These are for the most part intermittent in nature. Smart Grid technologies will enable power systems to operate with larger amounts of such energy

resources since they enable both the suppliers and consumers to compensate for such intermittency.

Features

Existing and planned implementations of smart grids provide a wide range of features to perform the required functions.

Load adjustment

The total load connected to the power grid can vary significantly over time. Although the total load is the sum of many individual choices of the clients, the overall load is not a stable, slow varying, average power consumption. Imagine the increment of the load if a popular television program starts and millions of televisions will draw current instantly. Traditionally, to respond to a rapid increase in power consumption, faster than the start-up time of a large generator, some spare generators are put on a dissipative standby mode. A smart grid may warn all individual television sets, or another larger customer, to reduce the load temporarily (to allow time to start up a larger generator) or continuously (in the case of limited resources). Using mathematical prediction algorithms it is possible to predict how many standby generators need to be used, to reach a certain failure rate. In the traditional grid, the failure rate can only be reduced at the cost of more standby generators. In a smart grid, the load reduction by even a small portion of the clients may eliminate the problem.

Demand response support

Demand response support allows generators and loads to interact in an automated fashion in real time, coordinating demand to flatten spikes. Eliminating the fraction of demand that occurs in these spikes eliminates the cost of adding reserve generators, cuts wear and tear and extends the life of equipment, and allows users to cut their energy bills by telling low priority devices to use energy only when it is cheapest.

Currently, power grid systems have varying degrees of communication within control systems for their high value assets, such as in generating plants, transmission lines, substations and major energy users. In general information flows one way, from the users and the loads they control back to the utilities. The utilities attempt to meet the demand and succeed or fail to varying degrees (brownout, rolling blackout, uncontrolled blackout). The total amount of power demand by the users can have a very wide probability distribution which requires spare generating plants in standby mode to respond to the rapidly changing power usage. This one-way flow of information is expensive; the last 10% of generating capacity may be required as little as 1% of the time, and brownouts and outages can be costly to consumers.

Greater resilience to loading

Although multiple routes are touted as a feature of the smart grid, the old grid also featured multiple routes. Initial power lines in the grid were built using a radial model, later connectivity was guaranteed via multiple routes, referred to as a network structure. However, this created a new problem: if the current flow or related effects across the network exceed the limits of any particular network element, it could fail, and the current would be shunted to other network elements, which eventually may fail also, causing a domino effect. A technique to prevent this is load shedding by rolling blackout or voltage reduction (brownout).

Decentralization of power generation

Another element of fault tolerance of traditional and smart grids is decentralized power generation. Distributed generation allows individual consumers to generate power onsite, using whatever generation method they find appropriate. This allows individual loads to tailor their generation directly to their load, making them independent from grid power failures. Classic grids were designed for one-way flow of electricity, but if a local sub-network generates more power than it is consuming, the reverse flow can raise safety and reliability issues. A smart grid can manage these situations, but utilities routinely manage this type of situation in the existing grid.

Price signaling to consumers

In many countries, including Belgium, the Netherlands and the UK, the electric utilities have installed double tariff electricity meters in many homes to encourage people to use their electric power during night time or weekends, when the overall demand from industry is very low. During off-peak time the price is reduced significantly, primarily for heating storage radiators or heat pumps with a high thermal mass, but also for domestic appliances. This idea will be further explored in a smart grid, where the price could be changing in seconds and electric equipment is given methods to react on that. Also, personal preferences of customers, for example to use only green energy, can be incorporated in such a power grid.

Technology

The bulk of smart grid technologies are already used in other applications such as manufacturing and telecommunications and are being adapted for use in grid operations. In general, smart grid technology can be grouped into five key areas:

Integrated communications

Some communications are up to date, but are not uniform because they have been developed in an incremental fashion and not fully integrated. In most cases, data is being collected via modem rather than direct network connection. Areas for improvement include: substation automation, demand response, distribution automation, supervisory

control and data acquisition (SCADA), energy management systems, wireless mesh networks and other technologies, power-line carrier communications, and fiber-optics. Integrated communications will allow for real-time control, information and data exchange to optimize system reliability, asset utilization, and security.

Sensing and measurement

Core duties are evaluating congestion and grid stability, monitoring equipment health, energy theft prevention, and control strategies support. Technologies include: advanced microprocessor meters (smart meter) and meter reading equipment, wide-area monitoring systems, dynamic line rating (typically based on online readings by Distributed temperature sensing combined with Real time thermal rating (RTTR) systems), electromagnetic signature measurement/analysis, time-of-use and real-time pricing tools, advanced switches and cables, backscatter radio technology, and Digital protective relays.

Smart meters

A smart grid replaces analog mechanical meters with digital meters that record usage in real time. Smart meters are similar to Advanced Metering Infrastructure meters and provide a communication path extending from generation plants to electrical outlets (smart socket) and other smart grid-enabled devices. By customer option, such devices can shut down during times of peak demand.

Phasor measurement units

High speed sensors called PMUs distributed throughout their network can be used to monitor power quality and in some cases respond automatically to them. Phasors are representations of the waveforms of alternating current, which ideally in real-time, are identical everywhere on the network and conform to the most desirable shape. In the 1980s, it was realized that the clock pulses from global positioning system (GPS) satellites could be used for very precise time measurements in the grid. With large numbers of PMUs and the ability to compare shapes from alternating current readings everywhere on the grid, research suggests that automated systems will be able to revolutionize the management of power systems by responding to system conditions in a rapid, dynamic fashion.

A Wide-Area Measurement Systems (WAMS) is a network of PMUS that can provide real-time monitoring on a regional and national scale. Many in the power systems engineering community believe that the Northeast blackout of 2003 would have been contained to a much smaller area if a wide area phasor measurement network was in place.

Advanced components

Innovations in superconductivity, fault tolerance, storage, power electronics, and diagnostics components are changing fundamental abilities and characteristics of grids. Technologies within these broad R&D categories include: flexible alternating current transmission system devices, high voltage direct current, first and second generation superconducting wire, high temperature superconducting cable, distributed energy generation and storage devices, composite conductors, and “intelligent” appliances.

Advanced control

Power system automation enables rapid diagnosis of and precise solutions to specific grid disruptions or outages. These technologies rely on and contribute to each of the other four key areas. Three technology categories for advanced control methods are: distributed intelligent agents (control systems), analytical tools (software algorithms and high-speed computers), and operational applications (SCADA, substation automation, demand response, etc.). Using artificial intelligence programming techniques, Fujian power grid in China created a wide area protection system that is rapidly able to accurately calculate a control strategy and execute it. The Voltage Stability Monitoring & Control (VSMC) software uses a sensitivity-based successive linear programming method to reliably determine the optimal control solution.

Improved interfaces and decision support

Information systems that reduce complexity so that operators and managers have tools to effectively and efficiently operate a grid with an increasing number of variables. Technologies include visualization techniques that reduce large quantities of data into easily understood visual formats, software systems that provide multiple options when systems operator actions are required, and simulators for operational training and “what-if” analysis.

Standards and groups

IEC TC57 has created a family of international standards that can be used as part of the smart grid. These standards include IEC61850 which is an architecture for substation automation, and IEC 61970/61968 — the Common Information Model (CIM). The CIM provides for common semantics to be used for turning data into information.

MultiSpeak has created a specification that supports distribution functionality of the smart grid. MultiSpeak has a robust set of integration definitions that supports nearly all of the software interfaces necessary for a distribution utility or for the distribution portion of a vertically integrated utility. MultiSpeak integration is defined using extensible markup language (XML) and web services.

The IEEE has created a standard to support synchrophasors — C37.118.

A User Group that discusses and supports real world experience of the standards used in smart grids is the UCA International User Group.

There is a Utility Task Group within LonMark International, which deals with smart grid related issues.

There is a growing trend towards the use of TCP/IP technology as a common communication platform for Smart Meter applications, so that utilities can deploy multiple communication systems, while using IP technology as a common management platform.

IEEE P2030 is an IEEE project developing a "Draft Guide for Smart Grid Interoperability of Energy Technology and Information Technology Operation with the Electric Power System (EPS), and End-Use Applications and Loads".

NIST has included ITU-T G.hn as one of the "Standards Identified for Implementation" for the Smart Grid "for which it believed there was strong stakeholder consensus". G.hn is standard for high-speed communications over power lines, phone lines and coaxial cables.

OASIS EnergyInterop' – is an OASIS technical committee developing XML standards for energy interoperation. It's starting point is the California OpenADR standard.

Recent studies

Many different concepts have been used to model intelligent power grids. They are generally studied within the framework of complex systems. In a recent brainstorming session, the power grid was considered within the context of optimal control, ecology, human cognition, glassy dynamics, information theory, microphysics of clouds, and many others. Here is a selection of the types of analyses that have appeared in recent years.

Kuramoto oscillators

The Kuramoto model is a well-studied system. The power grid has been described in this context as well. The goal is to keep the system in balance, and/or to maintain phase synchronization (also known as phase locking). Non-uniform oscillators also help to model different technologies, different types of power generators, patterns of consumption, and so on. The model has also been used to describe the synchronization patterns in the blinking of fireflies.

Bio-systems

Power grids have been related to complex biological systems in many other contexts. In one study, power grids were compared to the dolphin social network. These creatures

streamline and/or intensify communication in case of an unusual situation. The intercommunications that enable them to survive are highly complex.

Random fuse networks

In percolation theory, random fuse networks have been studied. The current density might be too low in some areas, and too strong in others. The analysis can therefore be used to smooth out potential problems in the network. For instance, high-speed computer analysis can predict blown fuses and correct for them, or analyze patterns that might lead to a power outage. It is difficult for humans to predict the long term patterns in complex networks, so fuse and/or diode networks are used instead.

Neural networks

Neural networks have been considered for power grid management as well. The references are too numerous to list.

Markov processes

As wind power continues to gain popularity, it becomes a necessary ingredient in realistic power grid studies. Off-line storage, wind variability, supply, demand, pricing, and other factors can be modelled as a mathematical game. Here the goal is to develop a winning strategy. Markov processes have been used to model and study this type of system.

Maximum entropy

All of these methods are, in one way or another, maximum entropy methods, which is an active area of research. This goes back to the ideas of Shannon, and many other researchers who studied communication networks. Continuing along similar lines today, modern wireless network research often considers the problem of network congestion, and many algorithms are being proposed to minimize it, including game theory, innovative combinations of FDMA, TDMA, and others.

Obstacles

In Europe and the US, significant impediments exist to the widespread adoption of smart grid technologies, including:

- regulatory environments that don't reward utilities for operational efficiency, excluding U.S. awards.
- consumer concerns over privacy,
- social concerns over "fair" availability of electricity,
- social concerns over Enron style abuses of information leverage,
- limited ability of utilities to rapidly transform their business and operational environment to take advantage of smart grid technologies.

- concerns over giving the government mechanisms to control the use of all power using activities.

Before a utility installs an advanced metering system, or any type of Smart System, it must make a business case for the investment. Some components, like the Power System Stabilizers (PSS) installed on generators are very expensive, require complex integration in the grid's control system, are needed only during emergencies, but are only effective if other suppliers on the network have them. Without any incentive to install them, power suppliers don't. Most utilities find it difficult to justify installing a communications infrastructure for a single application (e.g. meter reading). Because of this, a utility must typically identify several applications that will use the same communications infrastructure – for example, reading a meter, monitoring power quality, remote connection and disconnection of customers, enabling demand response, etc. Ideally, the communications infrastructure will not only support near-term applications, but unanticipated applications that will arise in the future. Regulatory or legislative actions can also drive utilities to implement pieces of a smart grid puzzle. Each utility has a unique set of business, regulatory, and legislative drivers that guide its investments. This means that each utility will take a different path to creating their smart grid and that different utilities will create smart grids at different adoption rates.

Some features of smart grids draw opposition from industries that currently are, or hope to provide similar services. An example is competition with cable and DSL Internet providers from broadband over powerline internet access. Providers of SCADA control systems for grids have intentionally designed proprietary hardware, protocols and software so that they cannot inter-operate with other systems in order to tie its customers to the vendor.

Market outlook

In 2009, the US smart grid industry was valued at about \$21.4 billion — by 2014, it will exceed at least \$42.8 billion. Given the success of the smart grids in the U.S., the world market is expected to grow at a faster rate, surging from \$69.3 billion in 2009 to \$171.4 billion by 2014. With the segments set to benefit the most will be smart metering hardware sellers and makers of software used to transmit and organize the massive amount of data collected by meters.

Deployments and deployment attempts

In the so called E-Energy projects several German utilities are creating first nucleolus in six independent model regions. A technology competition identified this model regions to carry out research and development activities with the main objective to create an "Internet of Energy"

One of the first attempted deployments of "smart grid" technologies in the United States was rejected in 2009 by electricity regulators in the Commonwealth of Massachusetts, a US state. According to an article in the Boston Globe, Northeast Utilities' Western

Massachusetts Electric Co. subsidiary actually attempted to create a "smart grid" program using public subsidies that would switch low income customers from post-pay to pre-pay billing (using "smart cards") in addition to special hiked "premium" rates for electricity used above a predetermined amount. This plan was rejected by regulators as it "eroded important protections for low-income customers against shutoffs". According to the Boston Globe, the plan "unfairly targeted low-income customers and circumvented Massachusetts laws meant to help struggling consumers keep the lights on". A spokesman for an environmental group supportive of smart grid plans and Western Massachusetts' Electric's aforementioned "smart grid" plan, in particular, stated "If used properly, smart grid technology has a lot of potential for reducing peak demand, which would allow us to shut down some of the oldest, dirtiest power plants... It's a tool."

In the Netherlands a large scale project (>5000 connections, >20 partners) was initiated to demonstrate integrated smart grids technologies, services and business cases.

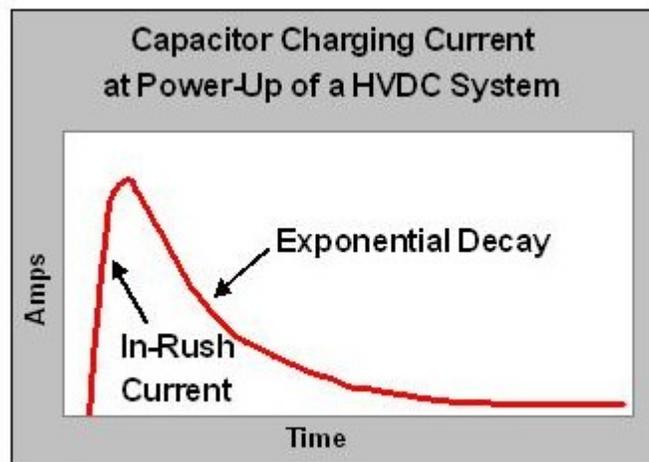
General economics developments

As customers can choose their electricity suppliers, depending on their different tariff methods, the focus of transportation costs will be increased. Reduction of maintenance and replacements costs will stimulate more advanced control.

A smart grid precisely limits electrical power down to the residential level, network small-scale distributed energy generation and storage devices, communicate information on operating status and needs, collect information on prices and grid conditions, and move the grid beyond central control to a collaborative network.

Chapter-2

Pre-charge



Peak inrush current into a high voltage capacitor upon power up can stress the component, reducing its reliability.

Pre-charge of the powerline voltages in a high voltage DC application is a preliminary mode which current-limits the power source such that a controlled rise time of the system voltage during power up is achieved.

When a high-voltage system is designed appropriately to handle the flow of maximum rated power through its distribution system, the components within the system can still undergo considerable stress upon the system "power up". In some applications, the occasion to activate the system is a rare occurrence, such as in commercial utility power distribution which is typically on almost all of the time. Yet in other systems such as in vehicle applications, activation will occur with every individual use of the system. When a long life of the components and a high reliability of the high voltage system is needed, then a power-up method which reduces and limits the power-up stress is required.

Background: in-rush currents into capacitors

In-rush currents into capacitive components are a key concern in power-up stress to components. When DC input power is applied to a capacitive load, the step response of the voltage input will cause the input capacitor to charge. The capacitor charging starts with an inrush current and ends with an exponential decay down to the steady state condition. When the magnitude of the inrush peak is very large compared to the maximum rating of the components, then component stress is to be expected. The current into a capacitor is known to be $I = C(dV / dT)$: the peak inrush current will depend upon the capacitance C and the rate of change of the voltage (dV/dT). The inrush current will increase as the capacitance value increases, and the inrush current will increase as the voltage of the power source increases. This second parameter is of primary concern in high voltage power distribution systems. By their nature, high voltage power sources will deliver high voltage into the distribution system. Capacitive loads will then be subject to high inrush currents upon power-up. The stress to the components must be understood and minimized.

The objective of a pre-charge function is to limit the magnitude of the inrush current into capacitive loads during power-up. This may take several seconds depending on the system. In general, higher voltage systems benefit from longer pre-charge times during power-up.

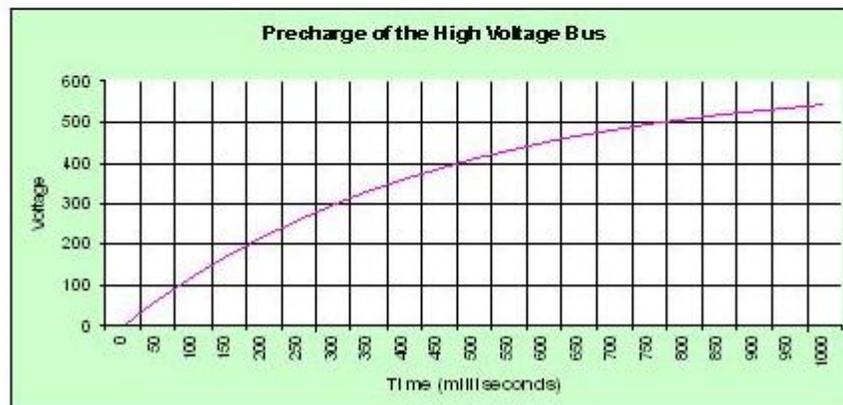
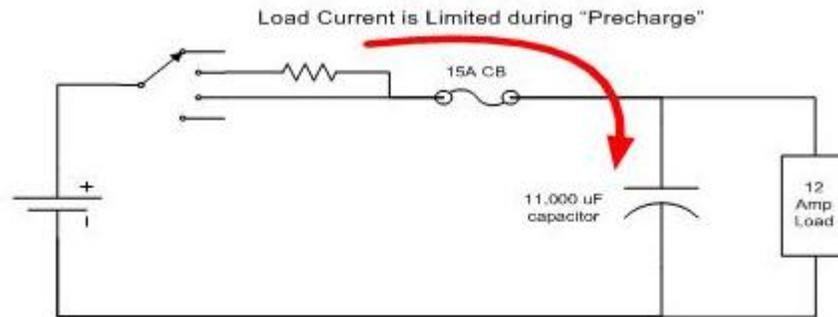
Peak Inrush Current Into Powerline Capacitors Increases with Power-up dV/dT				
11,000 μ F Powerline Capacitor	Peak In-rush Current at Power-Up of a 15 A Feed			
	1 ms	10 ms	100 ms	1 s
$v = 28 \text{ V}$	310 A	31 A	3.1 A	0.31 A
$v = 610 \text{ V}$	6710 A	671A	67A	7A

Color Key:

- = High Risk of Tripping the Breaker
- = Careful Selecting the Breaker Rating
- = Good

Consider an example where a high voltage source powers up a typical electronics control unit which has an internal power supply with 11000 μ F input capacitance. When powered from a 28 V source, the inrush current into the electronics unit would approach 31 amperes in 10 milliseconds. If that same circuit is activated by a 610 V source, then the inrush current would approach 670 A in 10 milliseconds. It is wise not to allow unlimited inrush currents from high voltage power distribution system activation into capacitive loads: instead the inrush current should be controlled to avoid power-up stress to components.

Definition of a pre-charge function



Precharging a high voltage DC power distribution line can control the inrush current into capacitive components, reducing stress and supporting a long component life.

The functional requirement of the high voltage pre-charge circuit is to minimize the peak current out from the power source by slowing down the dV/dT of the input power voltage such that a new "pre-charge mode" is created. Of course the inductive loads on the distribution system must be switched off during the precharge mode. While pre-charging, the system voltage will rise slowly and controllably with power-up current never exceeding the maximum allowed. As the circuit voltage approaches near steady state, then the pre-charge function is complete. Normal operation of a pre-charge circuit is to terminate pre-charge mode when the circuit voltage is 90% or 95% of the operating voltage. Upon completion of pre-charging, the pre-charge resistance is switched out of the power supply circuit and returns to a low impedance power source for normal mode. The high voltage loads are then powered up sequentially.

The simplest inrush-current limiting system, used in many consumer electronics devices, is a NTC resistor. When cold, its high resistance allows a small current to pre-charge the reservoir capacitor. After it warms up, its low resistance more efficiently passes the working current.

Many active power factor correction systems also include soft start.

If the example circuit from before is used with a pre-charge circuit which limits the dV/dT to less than 600 volts per second, then the inrush current will be reduced from 670 amperes to 7 amperes. This is a “kinder and gentler” way to activate a high voltage DC power distribution system.

Benefits of pre-charging

The primary benefit of avoiding component stress during power-up is to realize a long system operating life due to reliable and long lasting components.

There are additional benefits: pre-charging reduces the electrical hazards which may occur when the system integrity is compromised due to hardware damage or failure. Activating the high voltage DC system into a short circuit or a ground fault or into unsuspecting personnel and their equipment can have undesired effects. Arc flash will be minimized if a pre-charge function slows down the activation time of a high voltage power-up. A slow pre-charge will also reduce the voltage into a faulty circuit which builds up while the system diagnostics come on-line. This allows a diagnostic shut down before the fault is fully realized in worst case proportions.

In cases where unlimited inrush current is large enough to trip the source circuit breaker, a slow precharge may even be required to avoid the nuisance trip.

Pre-charging is commonly used in battery electric vehicle applications. The current to the motor is regulated by a *controller* that employs large capacitors in its input circuit. Such systems typically have *contactors* (a high-current relay) to disable the system during inactive periods and to act as an emergency disconnect should the motor current regulator fail in an active state. Without pre-charge the high voltage across the contactors and inrush current can cause a brief arc which will cause pitting of the contacts. Pre-charging the controller input capacitors (typically to 90 to 95 percent of applied battery voltage) eliminates the pitting problem. The current to maintain the charge is so low that some systems apply the pre-charge at all times other than when charging batteries, while more complex systems apply pre-charge as part of the starting sequence and will defer main contactor closure until the pre-charge voltage level is detected as sufficiently high.

Chapter-3

Open Access Same-Time Information System

The **Open Access Same-Time Information System (OASIS)**, is an Internet-based system for obtaining services related to electric power transmission in North America. It is the primary means by which high-voltage transmission lines are reserved for moving wholesale quantities of electricity. The OASIS concept was originally conceived with the Energy Policy Act of 1992, and formalized in 1996 through Federal Energy Regulatory Commission (FERC) Orders 888 and 889.

Before OASIS

Electric utility systems in North America developed over time as regulated monopolies, jurisdictional utilities given rights to own and operate transmission and distribution networks in a given geographical area along with the responsibility to serve all loads in that same area. At first, utility companies generally served their own system load demand by building local power generation facilities within their systems. Social, economical and ecological influences later led to new arrangements where a utility company might enter into long-term power purchase or sale agreements with neighboring utility companies, or locate new generation facilities outside of their system and enter into long-term agreements for transmission rights to deliver that energy to their own system. In the short-term world of day-to-day operations, utility companies would agree to "preschedule" (day ahead) or "real time" (same day or next hour) energy transactions with adjacent companies to supplement their own generation asset capabilities.

Vertically Integrated Utilities

As utility companies began integrating their operations in more complex ways with their neighbors, they evolved into a vertical organizational structure with three tiers: Generation, Transmission, and Scheduling. On a day-to-day or day-ahead operational level these functions might be performed by three or more people at large utilities, but might be combined into a single employee's job at a small utility. The size of the back office support for each function varies greatly depending upon the size of the utility.

Generation

The generation group manages the maintenance and operations of generation assets, with an eye on the future regarding when, where and how much generation assets will need to be developed to keep up with future demand.

Transmission

The transmission group concerns itself with maintaining the high voltage transmission system and lower voltage distribution system. As load demands increase or new generation assets come online in their systems, they upgrade existing facilities or construct new transmission corridors to maintain the reliable delivery of energy.

Scheduling

The scheduling group is responsible for ensuring that there is adequate power supply to meet the demand of the customer load on a day-to-day and hour-to-hour basis, and also for procuring resources to meet long term needs. These resources can be procured through the generation group, or through purchases and sales with other companies.

Internal Customers

Unlike a typical residential or commercial/industrial customer, large bulk users of electricity such as mills, mines and large factories generally have the opportunity to negotiate the rates they will pay their supplier for electricity. In some cases they might even have their own generation assets as well. If they chose to use their supplier's generation instead of their own, they might also be required to pay a fee for the transmission to deliver it, since that transmission might be built specifically to serve their needs. Fees for services provided by the transmission group were defined in a pro forma tariff, a document the transmission group supplied that detailed requirements and responsibilities for the purchaser and provider, and definitions and costs of the types of transmission services available.

Impact of the Energy Policy Act of 1992

The Energy Policy Act of 1992 (EPAct) laid the initial foundation for the eventual deregulation of the North American electricity market. This Act called for utility companies to allow external entities fair access to the electric transmission systems in North America. The act's intent was to allow large customers (and in theory, every customer) to choose their electricity supplier and subsequently pay for the transmission to deliver it from the generation to serve their load.

Based on the premise that new generating facilities would be allowed fair access to their regional transmission system, and precipitated by the EPAct of 1992, construction of new independently-owned generation assets began in response to the development of the North American electricity market. Recognizing competition was coming, electric utility

companies began modifying their scheduling functions by forming affiliated Power Marketing departments. Similarly, financial trading interests and existing energy companies (outside of electricity) saw the opportunities in the emerging electricity market and began to organize unaffiliated power marketing divisions. With open access, anyone with the proper resources and/or creditworthiness could purchase the rights to generation, move it across the transmission network (provided adequate capacity was available), and deliver it to a place of higher demand.

Following passage of the EAct of 1992, independent generation owner/operators (also called independent power producers or IPP's) and unaffiliated power marketers lodged frequent complaints with FERC about unfair treatment under the new open access requirements. The complaints generally followed the same theme: vertically integrated electric utility companies would favor their own affiliated power marketing division over external parties trying to move power on the system. In many cases, the power marketers operated side by side with the transmission operators (or it might even be the same person) and there were no rules to prevent unfair treatment of external transmission system users.

FERC Orders 888 and 889

To protect and promote generation competition and also enforce fair treatment of external users of the transmission system, FERC issued Order 888 and Order 889 on April 24, 1996. The EAct of 1992 was the beginning of electric deregulation in North America, but Orders 888 and 889 marked the point where the trading of electricity gained a firm foothold.

Order 888, the "Standards of Conduct" order

Order 888's primary objective was to establish and promote competition in the generation market, by ensuring fair access and market treatment of transmission customers. FERC outlined six points to accomplish this goal:

- Require all jurisdictional utilities (within the United States) to file an open-access transmission tariff (OATT)
- Require investor-owned utilities (IOU's) to functionally unbundle wholesale generation and power marketing from transmission services
- Create Independent System Operators (ISO's) and operating guidelines
- Encourage reciprocity for non-jurisdictional (Canadian and Mexican) utilities
- Allow utilities to recover stranded costs
- Identify ancillary services and comparable services to properly operate the bulk power system

One fairly immediate result of this order was the functional separation and isolation of the power schedulers and power marketers within vertically integrated utilities from their company's area of transmission operations. Affiliated power marketers could no longer work alongside the transmission operators who were charged with treating them and

external parties equally, and at the same time affiliated power marketers would no longer have any “inside information” on the availability of the transmission system nor the transactions being scheduled on it.

Order 889, the “Open Access” order

Order 889 went to great lengths to detail exactly how all participants in the electricity market should interact with transmission providers. It laid out the structure and function of what became known as OASIS “nodes,” which are secure, web-based interfaces to each transmission system’s market offerings and transmission availability announcements. Each OASIS node was to be the single point of information dissemination to the market as well as the customer portal for transmission service requests, even for affiliated power marketers wanting access to their own parent company’s transmission.

OASIS Nodes

OASIS nodes are entirely web-based, and public access is limited. Power marketers that become signatories to a transmission provider’s OATT gain more complete access so they can view existing transmission and service availability and existing service requests made by other parties. There are also market observers who have read-only access, who may view activity but not request services.

Transmission facilities have power transfer limits that must be maintained to allow the power grid to operate reliably. Transmission operators perform system studies in various future time frames to determine how much transfer capacity is required to serve their own “native load”, and how much capacity must remain as a buffer to prevent unscheduled or accidental overflows that can damage high voltage equipment. The difference between the capacity needed to serve load and to maintain safe flow margins can be made available for purchase on the OASIS node.

Unplanned outages and other system emergencies can adversely impact the total power transfer capability across transmission systems, and it sometimes becomes necessary for transmission providers to curtail power flows across the system by revoking transmission rights given to buyers on the OASIS. Some transmission buyers are willing to pay higher rates to avoid having their transactions curtailed, and as such transmission companies offer different priorities of transmission service at varying rates. The least expensive type of transmission is generally “non-firm” and purchased on an hour to hour basis. Daily non-firm is a slightly higher priority (because the buyer committed to purchasing all day), and increments go up from there to weekly, monthly, seasonally, yearly, or longer with the cost for each also rising incrementally. “Firm” transmission services are even more expensive, but are the last transactions to be curtailed.

Even before the appearance of the OASIS nodes, many groups of transmission owners had already turned over operational control of their collective bulk transmission systems to Independent System Operators of various forms. These ISO's offered OASIS access to

their collective systems very early on, so that it was often possible to make a single OASIS transmission service request that could cross multiple transmission systems. Since the inception of OASIS, and under the prodding of FERC to move transmission assets under the control of ISO's, the number of OASIS nodes is decreasing as ISO's assume control of transmission systems and consolidate their related OASIS functions.

OASIS impacts

After the doors opened to allow power marketers to move their electricity purchases across multiple transmission systems, many transmission operators saw their transmission systems loaded to much higher levels. Even though transmission services are generally obtained "point-to-point", in actuality power flows divide among numerous paths according to the properties of electricity and thus the actual energy flows follow the paths of least resistance.

A result of the long distance electricity transactions being scheduled was the impact of "loop flows" caused by energy flowing on these alternate paths. Transmission system operators were faced with a dilemma: The problems were often being caused by external influences, and the only way available to them to reduce the stress on the transmission system was to curtail their own transmission sales. This resulted in a loss of revenue and still did not always solve the overloading problems.

The North American Reliability Council (NERC) stepped in to address this new problem that threatened the North American power grid by introducing the NERC Tagging application. NERC Tags captured entire transactions from beginning to end. This let them string together all the transmission legs obtained on various OASIS nodes, and then determine how the total schedule impacted transmission systems, and what priorities of transmission were used in the schedule. This let them determine which schedules should be curtailed to relieve loading on transmission systems.

NERC also assumed control of a database of electric power system data. The Transmission System Information Networks (TSIN) web-based database contains a comprehensive listing of generation points, transmission facilities and delivery points as well as transmission and generation priority definitions with regard to the applications that use it, namely the various OASIS nodes as well as the NERC Tagging application.

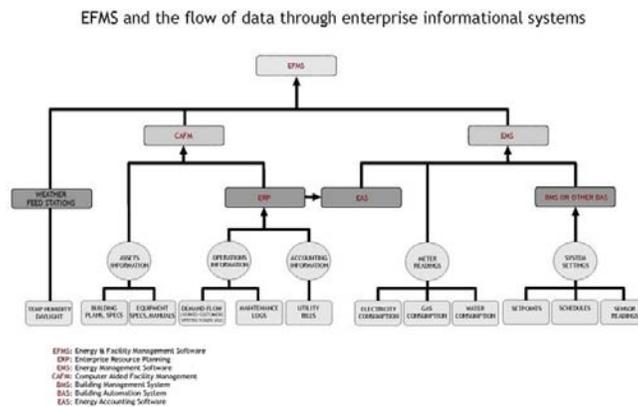
Chapter-4

Energy & Facility Management Software and National Grid

Energy & Facility Management Software

Definition and Purpose

Definition



EFMS

The term **Energy & Facility Management Software** refers to an enterprise-wide platform for handling technical data related to buildings and stems from the merger of EMS (energy management software), CAFM (Computer Aided Facility Management) and EAS (Energy Accounting Software). As such it involves the gathering and processing of information that is required for maintaining acceptable indoor comfort level while minimizing energy use.

Purpose

An EFMS serves a dual purpose:

- Tactical:** On a day-to-day operational level an EFMS will help improve comfort level where required while minimizing energy consumption. Should comfort level not be an issue, the EFMS will focus processes and resources on reducing energy spending.
- Strategic:** On a mid-to-long term scope an EFMS will support the development strategy of the organization with information that will support managerial decisions such as systems, vendors or processes efficiencies, ratings and critical areas etc.

Method

Information Classes

To achieve its purpose an EFMS integrates several informational classes in a common processing environment, mainly:

- Energy consumption information** information commonly handled by an EMS and derived from online metering devices (such as Energy meters, Gas meters etc).
- System information** such as HVAC systems settings, sensor readings etc commonly resident in a BMS.
- Assets Information**, such as building size, floor number and area, cooling capacity of installed HVAC systems, maintenance logs etc commonly found in a CAFM system.
- Weather information** commonly derived from internet weather feeds or locally installed sensors.
- Occupancy / Use information** such as room occupancy of a hotel or customers served at a retail store commonly found in an ERP.
- Utility bills information** commonly resident in an EAS (Energy Accounting Software).

Components

An EFMS should be consisted of at least the following modules:

- Visualization / Dashboard Module** which will present graphical or table illustrations of energy information (from EMS), system information (from BMS) and Billing information (from EAS).
- Alarming Module** which will create and manage alarms based on given threshold values and / or Faults Detection & Diagnosis detection methods.
- Work Order Module** which will create and manage notifications of alarms directed towards appropriate users. The Work Order Module will manage actions of users related to each fault along the Fault Cycle (birth, detection, diagnosis, action, evaluation).
- Data Sources Module** which will manage the connection to and synchronization with the various data sources such as energy management systems and metering devices, BMS, EAS, ERP etc.
- Reporting Module** which will manage the creation and distribution of energy and facility reports.

Processes

The processes performed in an EFMS fall under the categories of:

- Entry Processes** which may be *tactical* such as the automated synchronization with a BMS or ERP or *ad-hoc* such as the manual entry of utility bills data or the upload of a maintenance log.
- FDD Processes** (*Faults Detection & Diagnosis*) which may include subprocesses for setting various thresholds, selecting from a list of rules which ones should be applied to each specific building / installation and the tactical application of rule sets and threshold values to an FDD scanning process of building related data.
- Work Order Processes** which include processes for relaying alerts and faults to users and managing the actions they undertake until the issue is resolved.
- Reporting Processes** which involve tactical creation of visualization elements and reports or ad hoc querying processes for data mining and faults investigation.

Applications

Applications of integrated EFMS suites will benefit mostly organizations with either very large and busy facilities, such as malls, hotel complexes and transportation hubs the complexity of which challenges operational efficiency and organizations with many buildings dispersed across remote locations such as retail chains, restaurant chains, banks and foodstore chains which operate medium sized buildings that stretch facility management operations to high costs.

National Grid



A 500 kV transmission line passing the North-South Expressway near Taiping.

National Grid, Malaysia (Malay: *Grid Nasional*) is the high-voltage electric power transmission network in Peninsular Malaysia. It is operated and owned by Tenaga Nasional Berhad (TNB) by its Transmission Division. There are two other electrical grids in Sabah and Sarawak operated by Sabah Electricity Sdn Bhd and Sarawak Electricity Supply Corporation respectively.

The system spans the whole of Peninsular Malaysia, connecting electricity generation stations owned by TNB and Independent Power Producers (IPPs) to energy consumers. A small number of consumers, mainly steel mills and shopping malls also take power directly from the National Grid.

History

The beginnings of the National Grid was slowly taking shape in 1964 when the Bangsar Power Station was connected to the Connaught Bridge Power Station, with the line subsequently extended to Malacca.

By 1965, a plan was set to connect the electricity generating plants that were spread out all over the country. Plants identified to be linked were located at Paka in Terengganu, Temengor, Kenering, Bersia and Batang Padang in Perak, Connaught Bridge, Kapar and Serdang in Selangor, Cameron Highlands in Pahang, Perai in Penang, Port Dickson in Negeri Sembilan, Pergau in Kelantan, Pasir Gudang in Johor and in Malacca.

The central area network with Connaught Bridge Power Station in Klang was the precursor of the energy grid; it also tapped into the Cameron Highlands Hydro scheme from the Sultan Yussuf Power Station, and was extended into a western network. Late in the 1980s, the loop was finally complete with the placement of Kota Bahru within the grid.

Grid description

Transmission system

More than 420 transmission substations in the Peninsular are linked together by approximately 11,000 km of transmission lines operating at 132, 275 and 500 kilovolts (kV). The 500 kV transmission system is the single largest transmission system to be ever developed in Malaysia. Begun in 1995, Phase 1 involved the design and construction of the 500kV overhead transmission lines from Gurun, Kedah in the North along the west coast to Kapar, in the central region and from Pasir Gudang to Yong Peng in the south of Peninsular Malaysia.

The total distance covered for the 500 kV transmission lines is 522 km and the 275 kV portion is 73 km. Of the lines constructed, only the Bukit Tarek to Kapar sections had been energized at 500 kV. The remaining lines are presently energized at 275 kV. Later, in order to cater for the additional power transmission requirements from the 2,100 megawatt (MW) Manjung Power Station, the 500 kV system was extended from Bukit Tarek to Air Tawar and from Air Tawar to Manjung Power Station. In 2006, the 500 kV lines between Bukit Batu and Tanjung Bin were commissioned to carry the power generated by the 2,100 MW Tanjung Bin Power Station.

A project involving laying a 730 km high-voltage direct current transmission line and a 670 km undersea cable for the 2,400-megawatt Bakun hydroelectric dam has been considered. This may connect all three of Malaysia's electric utility companies with state grids: Tenaga Nasional Berhad (TNB), Sarawak Electricity Supply Corporation (SESCO) and Sabah Electricity Sdn Bhd (SESB). Many of Sabah and Sarawak's generation plants are still not interconnected to a grid.

Connection to Thailand

The original 117 MVA, 132 kV Single Circuit Line HVAC interconnection of 80 MW with Electricity Generating Authority of Thailand (EGAT) was commissioned in 1981, linking Bukit Ketri in the state of Perlis with Sadao in Thailand. A second

interconnection was made via the HVDC Thailand-Malaysia rated at 300 kV HVDC and 300 MW transmission capacity.

Connection to Singapore

In the South of Malaysia, the National Grid is connected to the transmission system of Singapore Power Limited (SP) at Senoko via two 230 kV submarine cables with a transmission capacity of 200 MW.

Power Generation

Power generation capacity connected to the Malaysian National Grid is 19,023 megawatt, with a maximum demand of 13,340 megawatt as of July 2007 according to Suruhanjaya Tenaga. The generation fuel mix is 62.6% gas, 20.9% coal, 9.5% hydro and 7% from other forms of fuel.

Distribution level

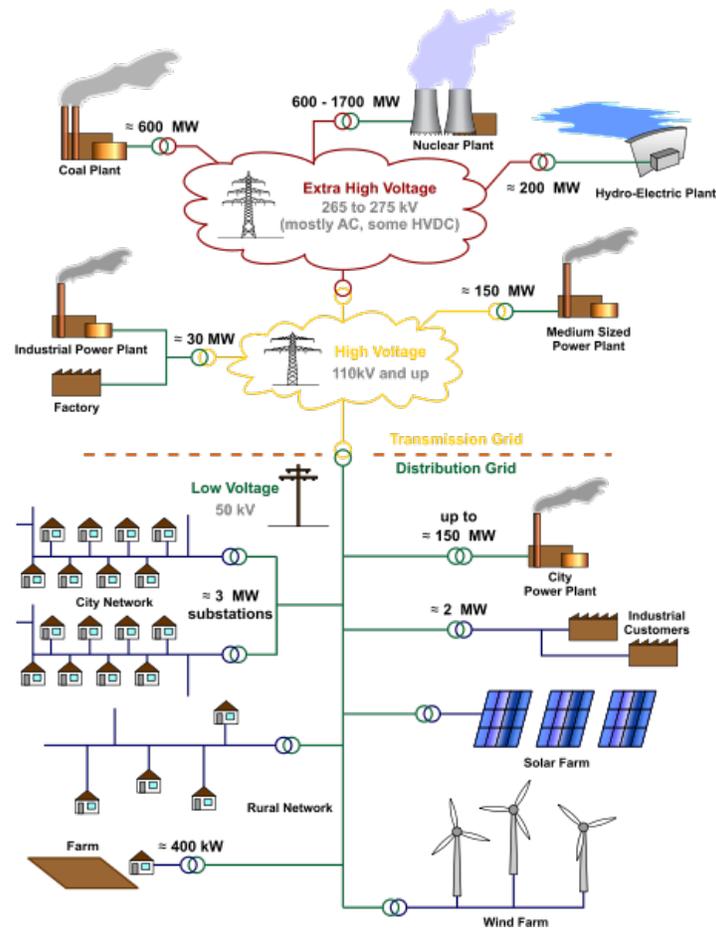
Distribution lines of 33 kV, 22 kV, 11 kv, 6.6 kV and 415/240 volt in the Malaysia distribution network connect to the National Grid via transmission substations where voltages are stepped down by transformers.

Major incidents

- Following a major system collapse in 3 August 1996, TNB has undertaken joint studies with Tokyo Electric Power Company (TEPCO) to develop a controlled islanding scheme to prevent the occurrence of a complete system collapse by ensuring continuity of supply to the Kuala Lumpur Metropolitan and Multimedia Super Corridor (MSC). The islanding scheme would basically be a "last line of defense" after all the normal emergency countermeasures such as underfrequency load shedding have operated.
- In 13 January 2005 a power blackout on northern peninsular Malaysia occurred when a transmission line near Serendah, Selangor, had broken down. In response to this, the Central Area Reinforcement (CAR) project was approved to ensure security of power supply to the Klang Valley.
- In 22 April 2008 Sabah had the worst power outage since the commissioning of the east west power grid. Suspected vandals are believed to have removed steel pieces of a 132kV transmission tower that led to its collapse, triggering a major power blackout. An emergency temporary tower was to be built immediately but it also collapsed during construction killing a TNB personnel. On 1 May 2008, another tower collapsed due to missing structural members of the tower that were suspected of being stolen.

Chapter-5

Electrical Grid



General layout of electricity networks. Voltages and depictions of electrical lines are typical for Germany and other European systems.

An **electrical grid** is an interconnected network for delivering electricity from suppliers to consumers.

Overview

When referring to the power industry, *grid* is a term used for an electricity network which may support all or some of the following four distinct operations:

1. Electricity generation
2. Electric power transmission
3. Electricity distribution
4. Electricity control

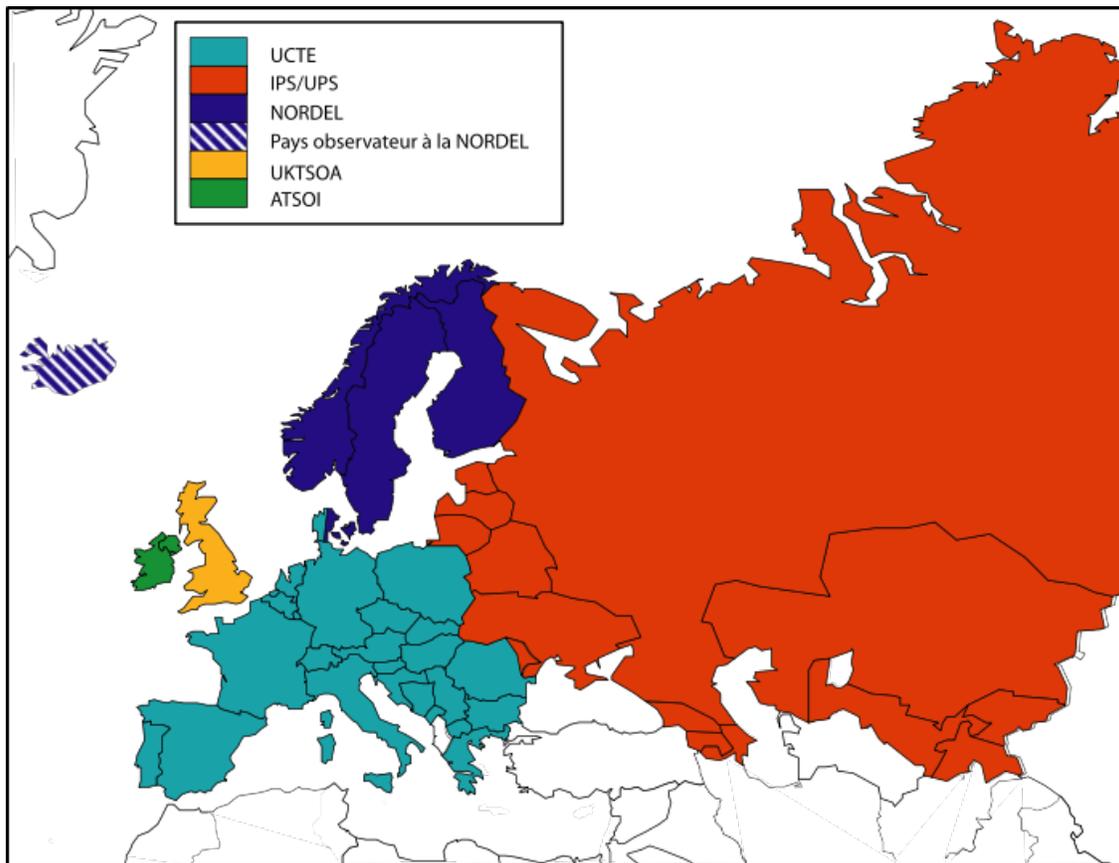
The sense of grid is as a network, and should not be taken to imply a particular physical layout, or breadth. *Grid* may be used to refer to an entire continent's electrical network, a regional transmission network or may be used to describe a subnetwork such as a local utility's transmission grid or distribution grid.

Electricity in a remote location might be provided by a simple distribution grid linking a central generator to homes. The traditional paradigm for moving electricity around in developed countries is more complex. Generating plants are usually located near a source of water, and away from heavily populated areas. They are usually quite large in order to take advantage of the economies of scale. The electric power which is generated is stepped up to a higher voltage—at which it connects to the transmission network. The transmission network will move (wheel) the power long distances—often across state lines, and sometimes across international boundaries—until it reaches its wholesale customer (usually the company that owns the local distribution network). Upon arrival at the substation, the power will be stepped down in voltage—from a transmission level voltage to a distribution level voltage. As it exits the substation, it enters the distribution wiring. Finally, upon arrival at the service location, the power is stepped down again from the distribution voltage to the required service voltage(s).

This traditional centralized model along with its distinctions are breaking down with the introduction of new technologies. For example, the characteristics of power generation can in some new grids be entirely opposite of those listed above. Generation can occur at low levels in dispersed locations, in highly populated areas, and not outside the distribution grids. Such characteristics could be attractive for some locales, and can be implemented if the grid uses a combination of new design options such as net metering, electric cars as a temporary energy source, or distributed generation.

Features

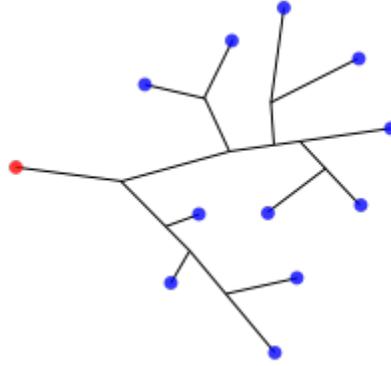
Structure of distribution grids



The wide area synchronous grids of Europe. Most are members of the European Transmission System Operators association.

The structure, or "topology" of a grid can vary considerably. The physical layout is often forced by what land is available and its geology. The logical topology can vary depending on the constraints of budget, requirements for system reliability, and the load and generation characteristics.

The cheapest and simplest topology for a distribution or transmission grid is a *radial* structure. This is a *tree* shape where power from a large supply radiates out into progressively lower voltage lines until the destination homes and businesses are reached.



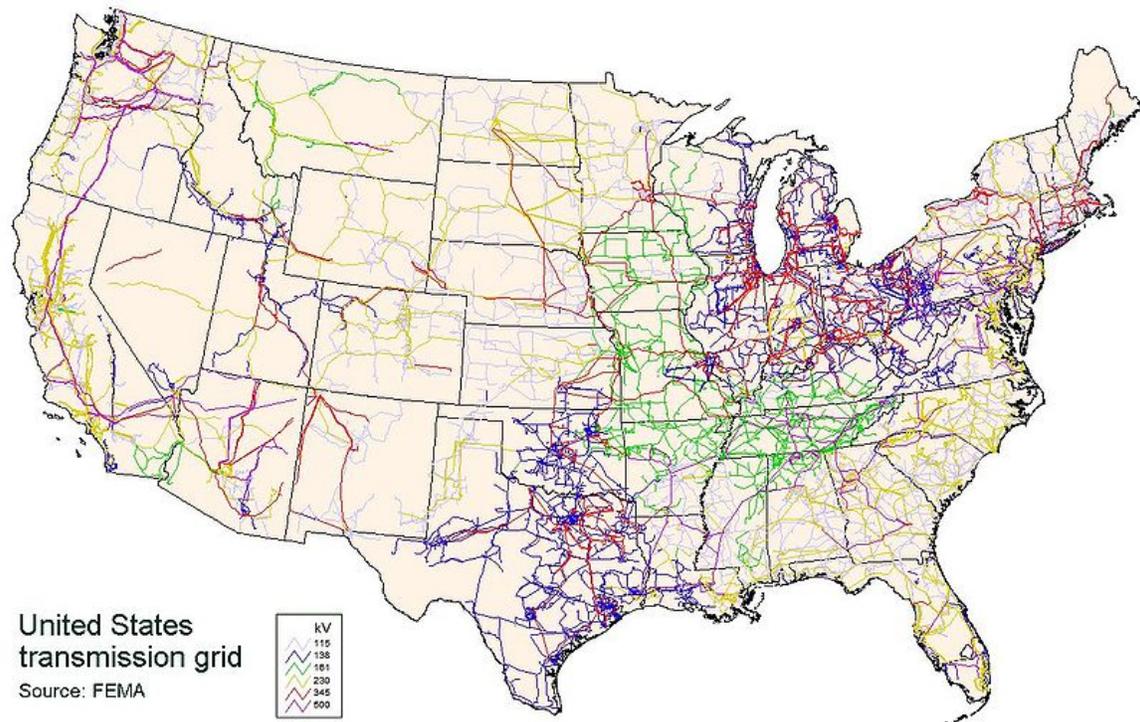
Classic North American electricity distribution grids were simple "radial" trees, sending power from a source (red dot representing power generation or a substation) to delivery points (blue dots representing homes, businesses, or other subnetworks).

Most transmission grids require the reliability that more complex *mesh networks* provide. If one were to imagine running redundant lines between limbs/branches of a tree that could be turned in case any particular limb of the tree were severed, then this image approximates how a mesh system operates. The expense of mesh topologies restrict their application to transmission and medium voltage distribution grids. Redundancy allows line failures to occur and power is simply rerouted while workmen repair the damaged and deactivated line.

Other topologies used are *looped* systems found in Europe and *tied ring* networks.

In cities and towns of North America, the grid tends to follow the classic "radially fed" design. A substation receives its power from the transmission network, the power is stepped down with a transformer and sent to a bus from which feeders fan out in all directions across the countryside. These feeders carry three-phase power, and tend to follow the major streets near the substation. As the distance from the substation grows, the fanout continues as smaller laterals spread out to cover areas missed by the feeders. This tree-like structure grows outward from the substation, but for reliability reasons, usually contains at least one unused backup connection to a nearby substation. This connection can be enabled in case of an emergency, so that a portion of a substation's service territory can be alternatively fed by another substation.

Geography of transmission networks



The Continental U.S. power transmission grid consists of about 300,000 km of lines operated by approximately 500 companies.

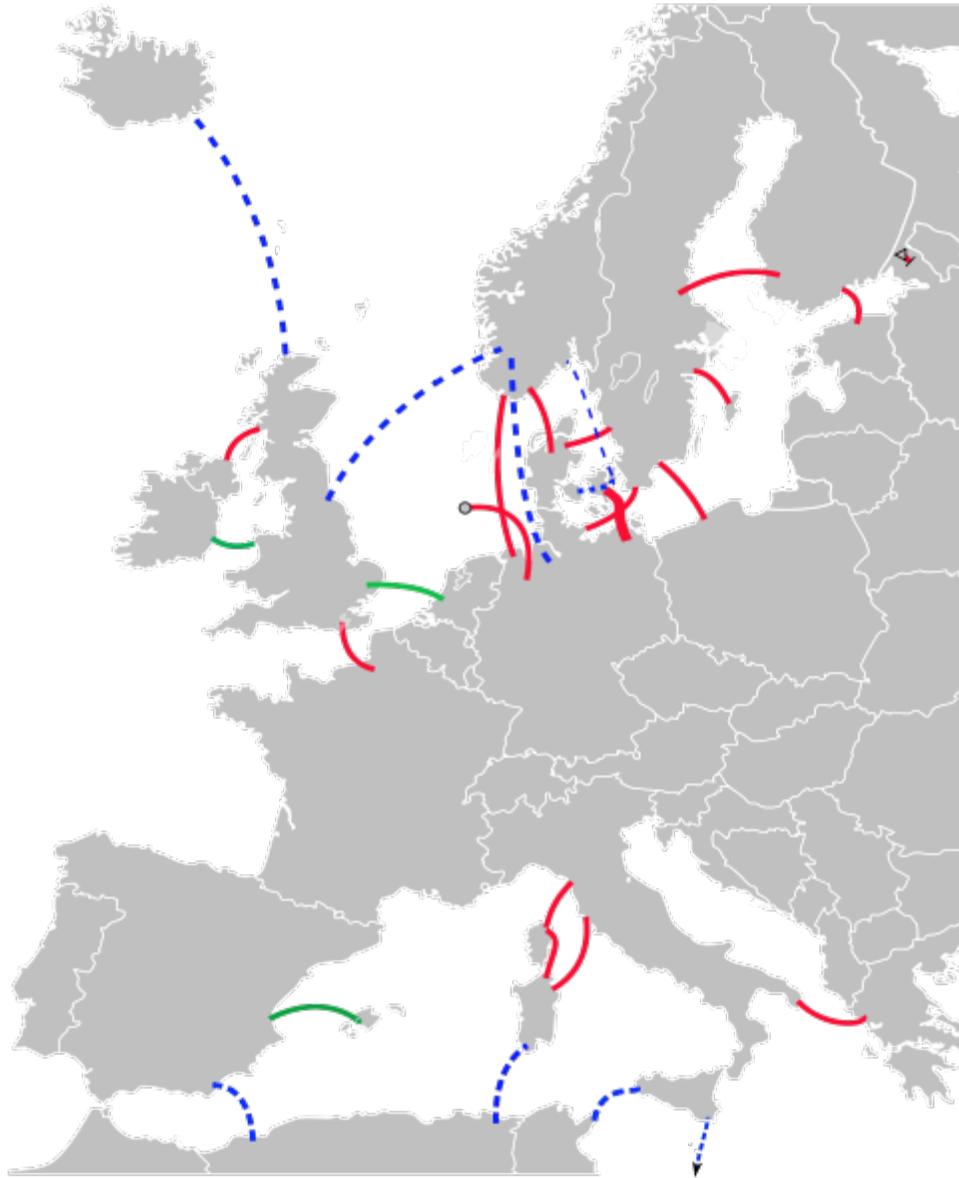
Transmission networks are more complex with redundant pathways.

A wide area synchronous grid or "interconnection" is a group of distribution areas all operating with alternating current (AC) frequencies synchronized (so that peaks occur at the same time). This allows transmission of AC power throughout the area, connecting a large number of electricity generators and consumers and potentially enabling more efficient electricity markets and redundant generation. Interconnection maps are shown of North America (right) and Europe (below left).

Electricity generation and consumption must be balanced across the entire grid, because energy is consumed almost immediately after it is produced. A large failure in one part of the grid - unless quickly compensated for - can cause current to re-route itself to flow from the remaining generators to consumers over transmission lines of insufficient capacity, causing further failures. One downside to a widely connected grid is thus the possibility of cascading failure and widespread power outage. A central authority is usually designated to facilitate communication and develop protocols to maintain a stable grid. For example, the North American Electric Reliability Corporation gained binding powers in the United States in 2006, and has advisory powers in the applicable parts of Canada and Mexico. The U.S. government has also designated National Interest Electric Transmission Corridors, where it believes transmission bottlenecks have developed.

Some areas, for example rural communities in Alaska, do not operate on a large grid, relying instead on local diesel generators.

High-voltage direct current lines or variable frequency transformers can be used to connect two alternating current interconnection networks which are not synchronized with each other. This provides the benefit of interconnection without the need to synchronize an even wider area. For example, compare the wide area synchronous grid map of Europe (below left) with the map of HVDC lines (below right).



High-voltage direct current interconnections in western Europe - red are existing links, green are under construction, and blue are proposed. Many of these transfer power from renewable sources such as hydro and wind. For names.

Redundancy and defining "grid"

A town is only said to have achieved grid connection when it is connected to several redundant sources, generally involving long-distance transmission.

This redundancy is limited. Existing national or regional grids simply provide the interconnection of facilities to utilize whatever redundancy is available. The exact stage of development at which the supply structure becomes a *grid* is arbitrary. Similarly, the term *national grid* is something of an anachronism in many parts of the world, as transmission cables now frequently cross national boundaries. The terms *distribution grid* for local connections and *transmission grid* for long-distance transmissions are therefore preferred, but *national grid* is often still used for the overall structure...

Distributed generation

Utilities are under pressure to evolve their classic topologies to accommodate distributed generation. As generation becomes more common from rooftop solar and wind generators, the differences between distribution and transmission grids will continue to blur.

Modern trends

Deregulation

The three components of a complete grid: generation, transmission, and distribution of electrical power, can all be found in most large utilities. A utility can be completely self-sufficient, but finds it advantageous to have the opportunity to buy and sell power to and from neighboring utilities. This improves their reliability, and that of their neighbors. Utilities are often awarded a "monopoly" status (at least at the distribution level) simply because it doesn't make sense to have competing utilities installing their hardware in the same location as another utility. The idea of a monopoly becomes less compelling as one considers the generation of electrical power. Wildly varying costs for the production of electricity, and the opportunity to encourage free market competition spurs many legislatures to move towards deregulation of the electric utilities (also known as "liberalization" in some parts of the world.) The idea of de-regulation usually involves the separation of the generation, transmission, and distribution operations into separate financial entities. Generation assets in particular can often be sold-off in piecemeal fashion to the highest bidders. With the aging infrastructure present at many utilities, and the pressure to de-regulate, there are numerous opportunities to re-engineer the system.

Transitioning utilities from regulated monopolies to a deregulated market has run into a number of challenges such as those surfaced by the California electricity crisis.

Demand response

Demand response is a grid management technique where retail or wholesale customers are requested either electronically or manually to reduce their load. Currently, transmission grid operators use demand response to request load reduction from major energy users such as industrial plants.

Distributed generation

With everything interconnected, and open competition occurring in a free market economy, it starts to make sense to allow and even encourage distributed generation (DG). Smaller generators, usually not owned by the utility, can be brought on-line to help supply the need for power. The smaller generation facility might be a home-owner with excess power from their solar panel or wind turbine. It might be a small office with a diesel generator. These resources can be brought on-line either at the utility's behest, or by owner of the generation in an effort to sell electricity. Many small generators are allowed to sell electricity back to the grid for the same price they would pay to buy it.

Smart grid

Numerous efforts are underway to develop a "smart grid". In the U.S., the Energy Policy Act of 2005 and Title XIII of the Energy Independence and Security Act of 2007, are providing funding to encourage smart grid development. The hope is to enable utilities to better predict their needs, and in some cases involve consumers in some form of time-of-use based tariff. Funds have also been allocated to develop more robust energy control technologies.

Micro grid

Decentralization of the power transmission distribution system is vital to the success and reliability of this system. Currently the system is reliant upon relatively few generation stations. This makes current systems susceptible to impact from failures not within said area. Micro grids would have local power generation, and allow smaller grid areas to be separated from the rest of the grid if a failure were to occur. Furthermore, micro grid systems could help power each other if needed. Generation within a micro grid could be a downsized industrial generator or several smaller systems such as photo-voltaic systems, or wind generation. When combined with Smart Grid technology, electricity could be better controlled and distributed, and more efficient.

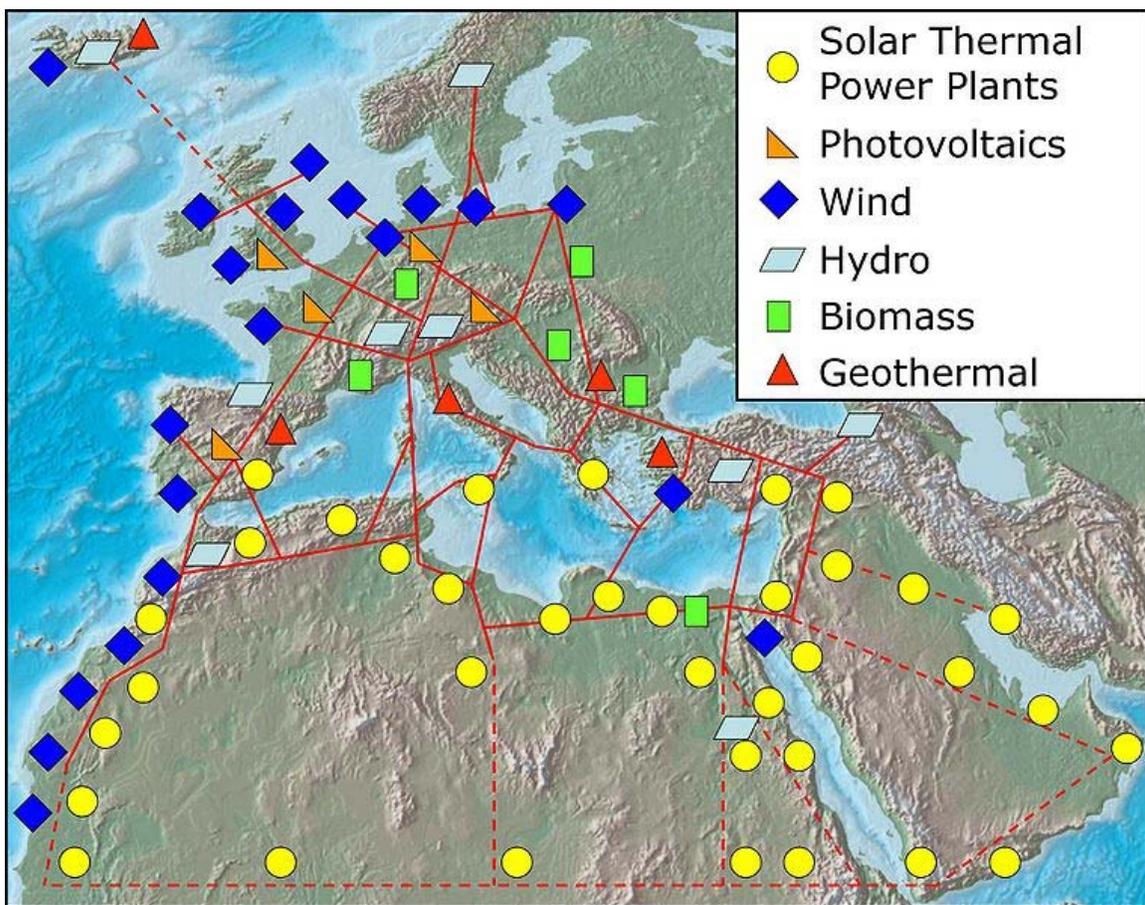
Super grid

Various planned and proposed systems to dramatically increase transmission capacity are known as super, or mega grids. The promised benefits include enabling the renewable energy industry to sell electricity to distant markets, the ability to increase usage of intermittent energy sources by balancing them across vast geological regions, and the removal of congestion that prevents electricity markets from flourishing. Local

opposition to siting new lines and the significant cost of these projects are major obstacles to super grids.

Chapter-6

Super Grid



One conceptual plan of a super grid linking renewable sources across North Africa, the Middle East and Europe. (DESERTEC)

A **super grid** is a wide area transmission network that makes it possible to trade high volumes of electricity across great distances. It is sometimes also referred to as a "mega grid".

History

The idea of creating long distance transmission lines in order to take advantage of renewable sources distantly located is not new. In the US in the 1930s, a proposal was made to ship hydroelectric power from dams being constructed in the Pacific Northwest to consumers in Southern California, but was opposed and scrapped. By 1961, U.S. president John F. Kennedy authorized a large public works project using new HVDC technology from Sweden. The project was undertaken as a close collaboration between General Electric of the U.S. and ASEA of Sweden and is now known as the Pacific Intertie.

The concept of a "Super grid" dates back to the 1960s and was used to describe the emerging unification of the Great Britain grid. In the code that governs the British Grid, the Grid Code , the Supergrid is currently defined - and has been since this code was first written, in 1990 - as referring to those parts of the British electricity transmission system that are connected at voltages in excess of 200 kV (200,000 volts). British power system planners and operational staff therefore invariably speak of the Supergrid in this context; in practice the definition used, captures all of the equipment owned by the National Grid company in England and Wales, and no other equipment.

What has changed during the past 40 years is the scale of energy and distances that are imagined possible in a super grid. Europe began unifying its grids since the 1950s and its largest unified grid is the synchronous grid of Continental Europe serving 24 countries. Serious work is being conducted on unification of the European UCTE grid with the neighboring IPS/UPS grid. If completed, this massive grid would span 13 time zones stretching from the Atlantic to the Pacific.

While such grids cover great distances, due to congestion and control issues, the capacity to transmit large volumes of electricity remains limited. The SuperSmart Grid (Europe) and the Unified Smart Grid (US) specify major technological upgrades that proponents claim are necessary to assure the practical operation and promised benefits of such transcontinental mega grids.

Dr Eddie O'Connor, founder and CEO of Mainstream Renewable Power and formerly founder and CEO of Airtricity, was, in 2001 wrestling with the problem of taking wind energy from the periphery to a central position in meeting future electricity demand. His intuitive knowledge of weather systems from previous work was reinforced by a research article from the University of Kassel in Germany. His reasoning was that if we could build a grid system large enough to capture wind energy over say 5000km and connect up to large hydro reserves in Scandinavia and central Europe then a firm source of electricity generation, rivalling nuclear in its invariability, would be created using wind energy. This concept Eddie called the Supergrid and the concept was launched at a conference which Airtricity co hosted with the European Wind Energy Association, in Brussels in December 2001.

Concept

In current usage, "super grid" has two senses – one of being a superstructure layer overlaid or super-imposed upon existing regional transmission grid or grids, and the second of having some set of superior abilities exceeding those of even the most advanced grids.

Mega grid

In the "overlay", or "superstructure" meaning, a super grid is a very long distance equivalent of a wide area synchronous network capable of large-scale transmission of renewable electricity. In some conceptions, a transmission grid of HVDC transmission lines forms a layer that is distinctly separate in the way that a superhighway system is separate from the system of city streets and regional highways. In more conventional conceptions such as the proposed unification of the European UCTE and IPS/UPS system of the CIS, such a mega grid is no different from typical wide area synchronous transmission systems where electricity takes an ad-hoc transit route directly through local utility transmission lines or HVDC lines as required. Studies for such continental sized systems report there are scaling problems as a result of network complexity, transmission congestion, and the need for rapid diagnostic, coordination and control systems. Such studies observe that transmission capacity would need to be significantly higher than current transmission systems in order to promote unimpeded energy trading across distances unbounded by state, regional or national, or even continental borders. As a practical matter, it has become necessary to incorporate smart grid features such as wide area sensor networks (WAMS) into even modest sized regional grids in order to avert major power outages such as the Northeast Blackout of 2003. Dynamic interactions between power generation groups are increasingly complex, and transient disturbances that cascade across neighboring utilities can be sudden, large and violent, accompanied by abrupt changes in the network topology as operators attempt to manually stabilize the network.

Superior grid

In the second sense of an advanced grid, the "super grid" is not only superior because it is a wide area mega grid, but it is highly coordinated from a macro level spanning nations and continents, all the way down to the micro level scheduling low priority loads like water heater and refrigeration. In the European SuperSmart Grid proposal and the US Unified Smart Grid concept, such super grids have intelligence features in the wide area transmission layer which integrate the local smart grids into a single wide area super grid. This is similar to how the internet bound together small networks into single ubiquitous network.

Wide area transmission can be viewed as a horizontal extension of the Smart grid. In a paradigm shift, the distinction between transmission and distribution blurs with the integration as energy flow becomes bidirectional. For example, distribution grids in rural areas might generate more energy than they use turning the local smart grid into a virtual

power plant, or a city's fleet of one million vehicles could be used to trim peaks in transmission supply by integrating them to the smart grid using vehicle to grid technology.



A 765 kV AC transmission grid designed to carry 400 GW of wind power to cities from Midwest at a cost of \$60 billion.

One advantage of such a geographically dispersed and dynamically balanced system is that the need for baseload generation is significantly reduced since intermittency of some sources such as ocean, solar and wind can be smoothed. A series of detailed modeling studies by Dr. Gregor Czigor, which looked at the European wide adoption of renewable energy and interlinking power grids using HVDC cables, indicates that the entire European power usage could come from renewables, with 70% total energy from wind at the same sort of costs or lower than at present.

To some critics, such a wide area transmission layer is not novel – pointing out that the technology has little difference from that used for regional and national power transmission networks. Proponents respond that beyond the qualitative smart grid features that allow instantaneous coordination and balancing of intermittent power sources across international boundaries, the quantitative comprehensiveness has a quality all its own. The claim is made that super grids open up markets. In the same way that freeways revolutionized interstate transport and the internet revolutionized online commerce when comprehensive high capacity networks for them were built, it is argued that a high capacity super grid must be built in order to provide a distribution network so

comprehensive and with such available capacity that energy trading is only limited by how much electricity that entrepreneurs can bring to market.

Technology

Wide area super grids plans typically call for bulk transmission using high voltage direct current lines. Europe's SuperSmart Grid proposal relies on HVDC, and in the US, key decision makers such as Steven Chu favor a national long distance DC grid system. There are industry advocates of HVAC. Although FACTS alternating current have drawbacks for long distances, American Electric Power has championed a 765 kV super grid they call I-765 that would provide 400 GW of extra transmission capacity required for producing 20% of US energy from wind farms based in the midwest. Advocates of HVAC point out that HVDC systems are oriented to point bulk transmission and multiple connections to them would require expensive complex communication and control equipment as opposed to the simple step up transformers needed if AC lines were used. Currently, there is only one multipoint long distance HVDC transmission system. In the more distant future the voltage loss of current methods could be avoided using experimental superconducting "SuperGrid" technology where the transmission cable is cooled by a liquid hydrogen pipeline which is also used to move energy nationwide. The energy losses for creating, containing, and re-cooling liquid hydrogen need to be accounted for.

Coordination and control of the network would use smart grid technologies such as phasor measurement units to rapidly detect imbalances in the network caused by fluctuating renewable energy sources and potentially respond instantaneously with programmed automatic protection schemes to reroute, reduce load, or reduce generation in response to network disturbances.

Government policy

Significant scale

One study for a European super grid estimates that as much as 750 GW of extra transmission capacity would be required- capacity that would be accommodated in increments of 5 GW HVDC lines. A recent proposal by Transcanada priced a 1,600-km, 3-GW HVDC line at \$3 billion USD and would require a corridor 60 meters wide. In India, a recent 6 GW, 1,850-km proposal was priced at \$790 million and would require a 69 meter wide right of way. With 750 GW of new HVDC transmission capacity required for a European super grid, the land and money needed for new transmission lines would be considerable.

Energy independence

In Europe, the energy security implication of a super grid has been discussed as a way in part to prevent Russian energy hegemony. In the U.S., advocates such as T. Boone Pickens have promoted the idea of a national transmission grid in order to promote

United States energy independence. Al Gore advocates the Unified Smart Grid which has comprehensive super grid capabilities. Gore and other advocates such as James E. Hansen believe super grids are essential for the eventual complete replacement of the greenhouse gas producing fossil fuel use that feeds global warming .

Permits for corridors

Large amounts of land would be required for the electricity transmission corridors used by the new transmission lines of a super grid. There can be significant opposition to the siting of power lines out of concerns about visual impact, anxiety over perceived health issues, and environmental concerns. The US has a process of designating National Interest Electric Transmission Corridors, and it is likely that this process would be used to specify the pathways for a super grid in that country. In the EU, permits for new overhead lines can easily reach 10 years. In some cases, this has made underground cable more expedient. Since land required can be one fifth than that for overhead and the permit process can be significantly faster, underground cable can be more attractive despite its weaknesses of being more expensive, lower capacity, shorter lived, and suffers significantly longer downtimes.

Business interests

Siting

Just as superhighways change valuations of land due to the proximity to the ability to transport valuable commodities, businesses are strongly motivated to influence the siting of a super grid to their benefit. The cost of alternative power is the delivered price of electricity, and if production of electricity from North Dakota wind or Arizona solar is to be competitive, the distance of the connection from the wind farm to the interstate transmission grid must not be great. This is because the feeder line from the generator to the transmission lines is usually paid for by the owner of the generation. Some localities will help pay for the cost of these lines, at the cost of local regulation such as that of a public utilities commission. T. Boone Pickens' project has chosen to pay for the feeder lines privately. Some localities, such as Texas give such projects the power of eminent domain which allows companies to seize land in the path of the planned construction.

Technology preferences

Energy producers are interested in whether the super grid employs HVDC technology, or uses AC, because the cost of connection to an HVDC line is generally greater than that if the AC is used. The Pickens plan favors 765 kV AC transmission, which is considered to be less efficient for long distance transmission.

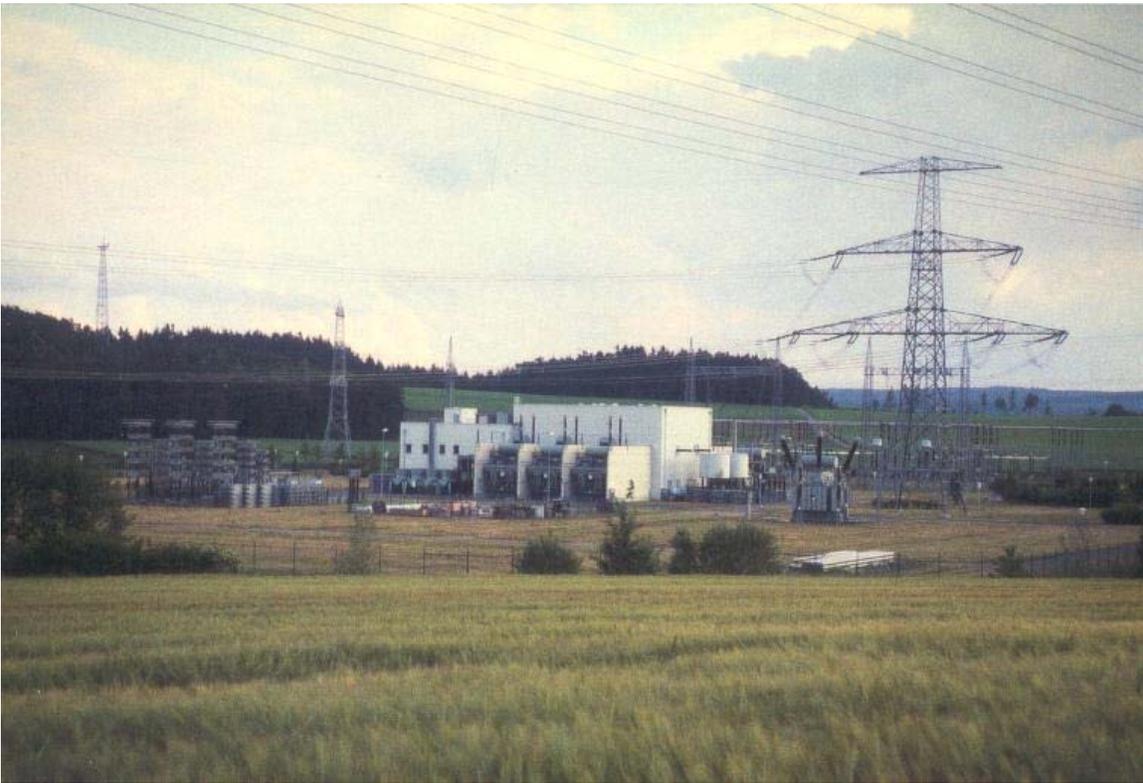
Competition

In the 1960s, private California power companies opposed the Pacific Intertie project with a set of technical objections that were overruled. When the project was completed,

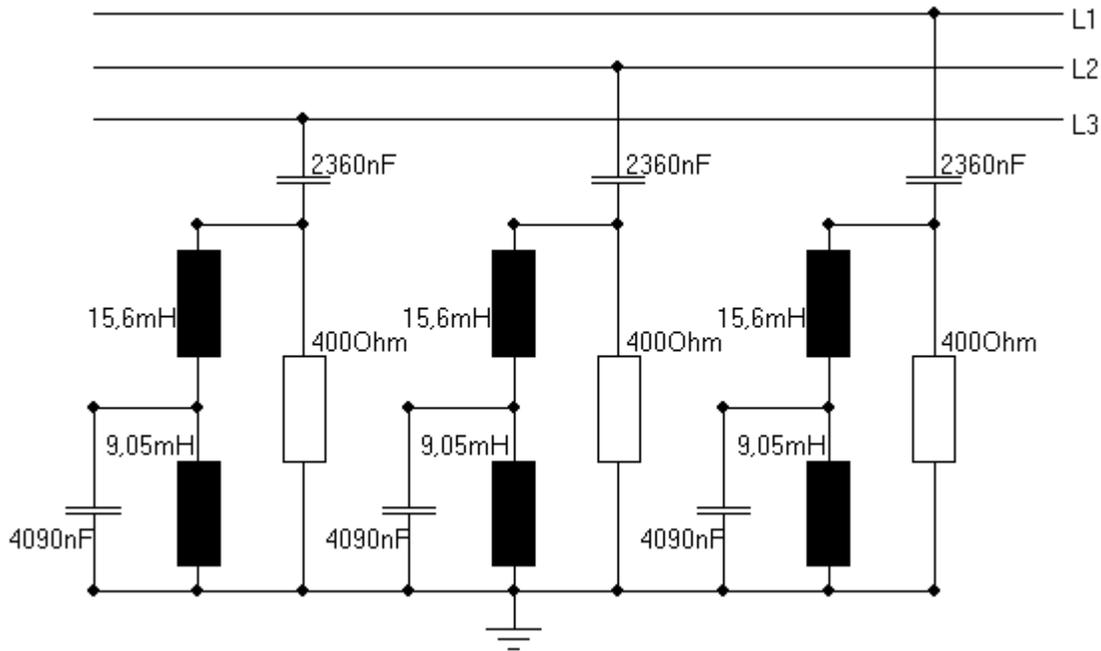
consumers in Los Angeles saved approximately U.S. \$600,000 per day by use of electric power from projects on the Columbia River rather than local power companies burning more expensive fossil fuel.

Chapter-7

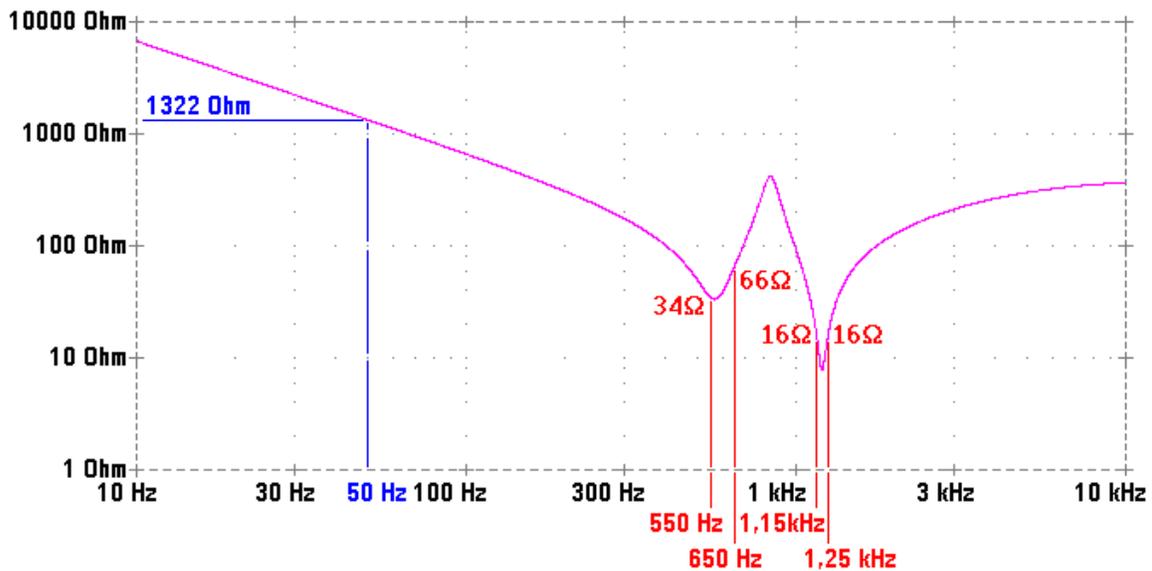
GKK Etzenricht



GKK Etzenricht



Harmonics filter of HVDC back-to-back station in Etzenricht



Impedance of AC filter used at GKK Etzenricht in dependence of frequency. Power grid frequency and their 11th, 13th, 23rd and 25th harmonics are marked

GKK Etzenricht, abbreviation for **Gleichstromkurzkupplung) Etzenricht**, that means Etzenricht HVDC-back-to-back station was an HVDC back-to-back facility near Etzenricht in the district of Neustadt in Bavaria, Germany. It was built up on area of Etzenricht substation, a 380 kV/220 kV/110 kV-substation, which went in service in 1970 and expanded afterwards several times. The operator of this facility, which was used

between 1993 and 1995 for exchange of power between Germany and Czech was Bayernwerk AG (now E.ON Netz GmbH).

History

April 26, 1991	Construction started
September 1991	Building complete
May 1992	First power
September 3, 1992	Completion of powerline to Hradec, Czech
January 27, 1993	Start trial operation
July 9, 1993	Official opening
October 18, 1995	Shutdown after synchronisation of the German and the Czech Power Grid

After the synchronization of the power grids between Germany and Czech the maximum amount of power, which can be transmitted between Etzenricht and Hradec increased from 600 MW to 1316 MW. The inauguration of the second 380 kV-interconnection to Prestice substation on July 29, 1997 increased the transmission capacity from Etzenricht to Czech to further 1579 MW, so via Etzenricht substation today a maximum power exchange of 2895 MW between Czech and Germany is possible.

In 1997, after inauguration of the second 380 kV-powerline to Czech, which ends at Prestice substation, most external components of GKK Etzenricht were dismantled and stored on the area of the facility. Since beginning of this dismantling, the facility was not workable any more. Only the transformers, the smoothing reactor and one harmonic filter remained on their original sites. Since shutdown of the static inverter, it was planned to sell the installation to eastern Europe, where it would have allowed the construction of an HVDC back-to-back station for exchanging power between eastern Europe and the former Soviet Union. As the static inverter went more and more out of date and one was meanwhile able to build static inverters like that of GKK Etzenricht much simpler by using photo thyristors, no such deal ever took place. In 2006 the facility was sold to IDPC, an Austrian recycling company, which wanted first to sell the installation completely and as this did not work, part by part. However only a few components were sold. In spring 2009 all remaining components of GKK Etzenricht were dismantled and scrapped.

The hall is transformed into a party location. For celebrating the 20th anniversary of German reunification, on October 3, 2010 an ACDC-concert was planned on the former switchyard, but this was canceled for safety reasons after the Love Parade stampede in Duisburg.

Technical features

GKK Etzenricht had a maximum transmission power of 600 megawatts (MW) and worked with a DC voltage of 160 kV. The two static inverters are in a 13 metres (43 ft) high hall with 430 square metres (4,630 sq ft) of surface area, which was built in a combination of local and finished concrete building method. Each static inverter consists of 432 thyristors, which are put in six thyristor towers arranged in a row. Each thyristor tower has 2 valve functions and consist of 8 thyristor modules, which are arranged one on top of the other. Each thyristor module consists of 9 thyristors switched in series and the necessary auxiliary equipment as the saturation coils, which are in series with the thyristors. Parallel to each thyristor a series combination of a resistor and a capacitor is switched, which limits the speed of current grow. From this combination the power for the supply of the electronic used for thyristor steering is gained. The electronic used for thyristor steering has at operation a high voltage potential against ground. It is connected to the main control electronic on ground potential by fiber-optic cables, which allow a bidirectional data transmission. Parallel to each thyristor module a capacitor and parallel to each valve function a varistor is switched. As thyristors the model U78 S346 S34 manufactured by Siemens, which has a maximum power rating of 4100 amperes and which was when GKK Etzenricht was built the most powerful thyristor in the world. At both ends of the hall there are three bays for the accommodation of the static inverter transformers, which are built as single-phase units.

Pictures

Images of August 2008



Valve Hall at Etzenricht



The only remaining AC filter of GKK Etzenricht



Smoothing reactors of GKK Etzenricht

Pictures of June 2009



Close view at valve hall with empty transformer bays. Also the smoothing reactors are gone



Wall of valve hall where once the smoothing reactors were. The door was installed after removal of smoothing reactors.

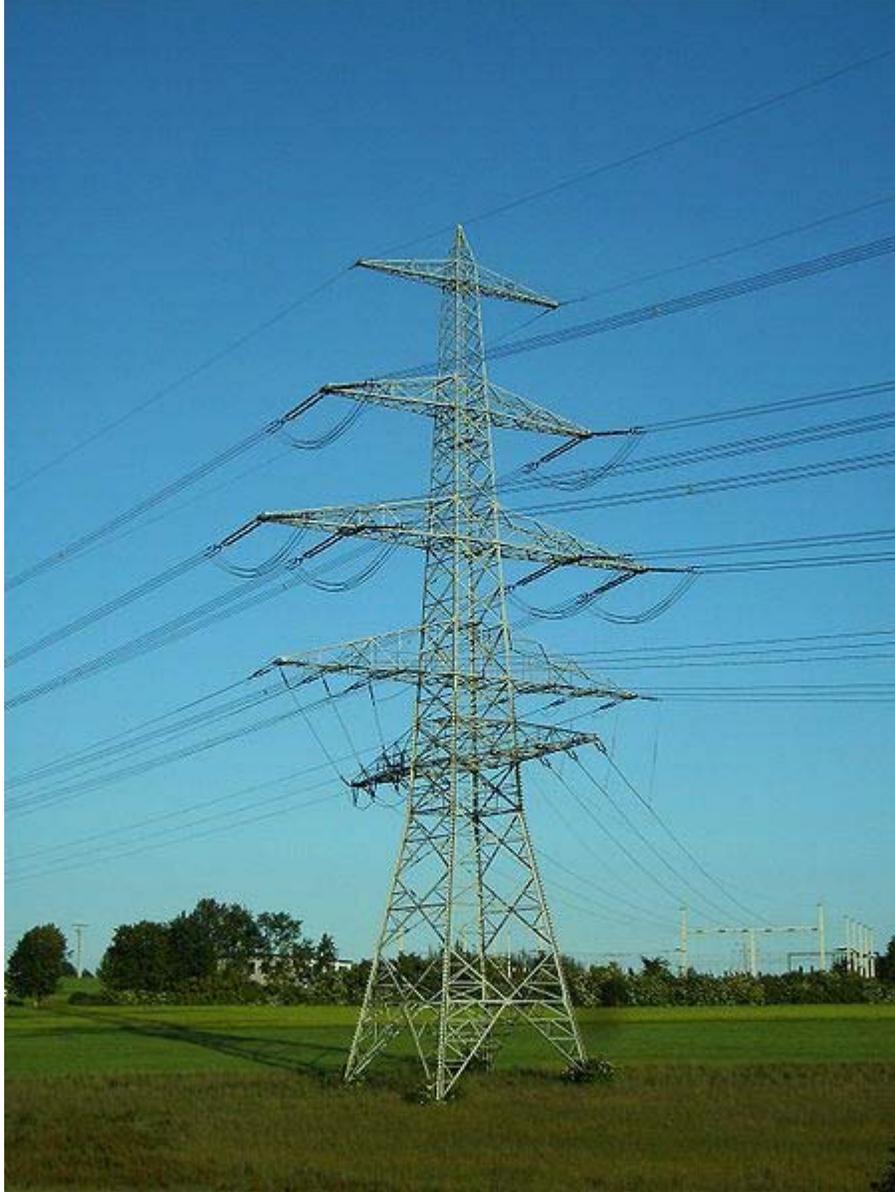


Also the transformer bays on the south side are empty

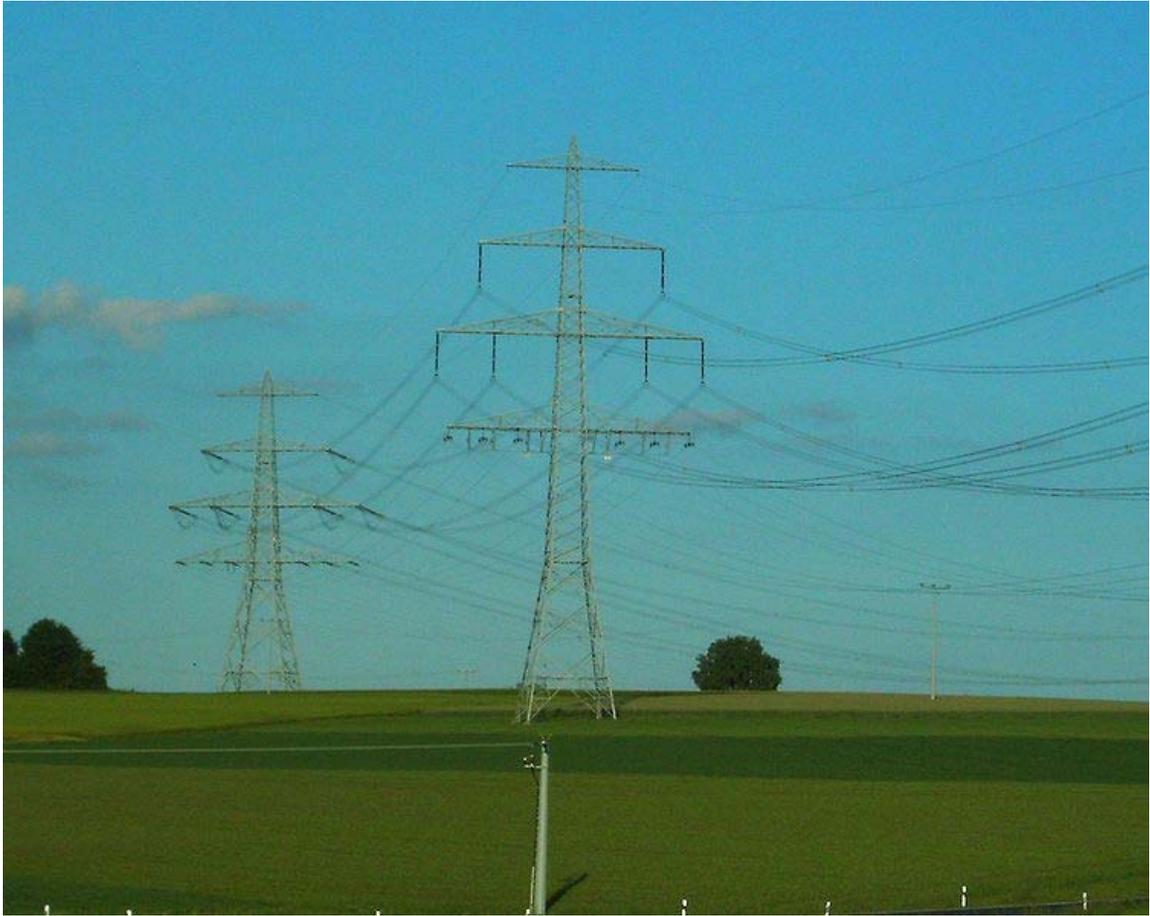
Power transmission line to the Czech Republic



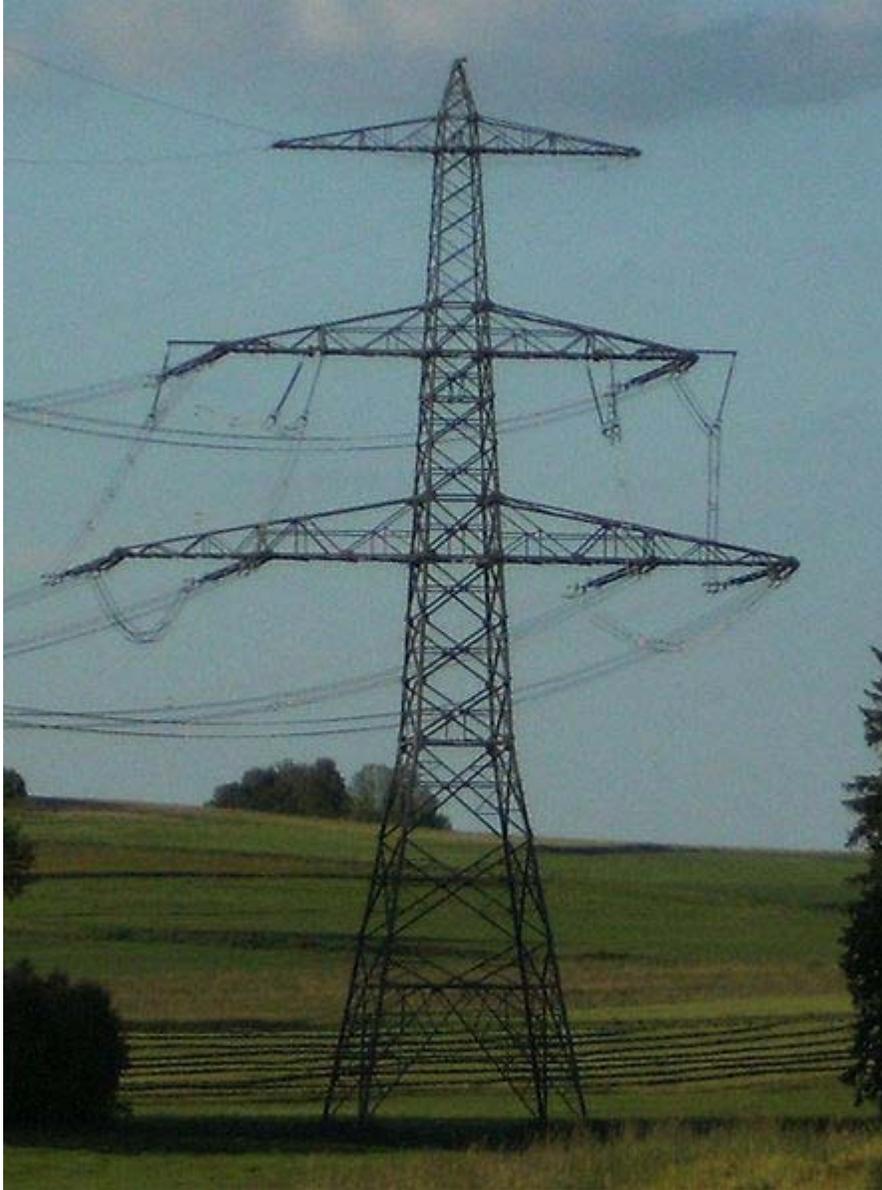
380 kV-Powerline from Etzenricht (Germany) to Hradec (Czech) between Etzenricht and Weiden (right). On the left, the 110 kV-powerline from Etzenricht to Weiden



Branch pylon Vohenstrauss



Feeding of 30 kV-circuits of powerline Vohenstrauss-Eslarn into conductors on lowest crossbar at next pylon



Twisting pylon on the section Riedlhof - Bavarian/Czech-border



The line crosses the international border between Bavaria and Czech near Waidhaus. The pylon in the foreground stands in Bavaria the others are in Czech



Splitting the lines to Hradec (left) and Prestice (right) near Stráž u Tachova

GKK Etzenricht was used in connection with the power transmission line between Germany and the Czech Republic. The 380kV power transmission line runs from the (Ex) GKK Etzenricht to the Czech substations at Hradec. In 1997 a branch to Přeštice substation was realized. For overvoltage protection the whole powerline is equipped with two ground conductors, which are installed on a separate crossbar on the top of the pylons. One conductor contains a fiber optic cable for data transmission.

The power transmission line has two circuits with a maximum power transmission capacity of 1630 MW at an operating voltage of 380 kV. On the German section of the line the conductors are bundles of four ropes consisting of steel and aluminum. Each conductor has a cross section of 340 mm² aluminum and 30 mm² steel. Between Weiden and Etzenricht this line is installed on 14 pylons of the "Danube type". One of these pylons was built after the shutdown of the GKK, in order to run the line directly - past the static inverter hall - into the switchyard of the Etzenricht substation. Except of the first pylon, these pylons were used before 1992 for the 110 kV-powerline from Etzenricht to Weiden. In 1992 this line was rebuilt on pylons running parallel to the old 110 kV-powerline to Weiden, whose pylons were equipped with a third crossbar for the ground conductors and with the 380 kV-conductors for the line to Czech.

The section between Weiden/Oberpfalz and Eslarn consists of 60 pylons with a fourth crossbar under the crossbars for the 380 kV conductors in order to carry the two 110 kV circuits of the powerline Weiden/Oberpfalz - Vohenstrauss and the two 30 kV-circuits for the powerline between Vohenstrauss and Eslarn. This was necessary because, due to environmental protection, only one right of way was available. Therefore the circuits of these lines, which existed in 1992 already since several years, had to be installed on the pylons of the powerline with the 380 kV-circuits to the Czech Republic. In Vohenstrauss the 110 kV-circuits run to the local substation, which is situated close to the right of way of the powerline to the Czech Republic.

Behind Vohenstrauss on the lowest crossbar the circuits of the 30 kV-line Vohenstrauss-Eslarn are installed. For a future upgrade of this line to 110 kV, the conductors of this line are mounted on insulators for 110 kV on the pylons. Near Riedlhof this line leaves the track of the line to Czech and runs on concrete pylons to Eslarn substation. From Riedlhof the 380 kV-line to the Czech Republic runs on 15 pylons of "Danube type" to the border between Germany and the Czech Republic. The border is crossed close north of the border crossing of the motorway A6 near Furth in Forest.

After the border the construction type of pylon does not change, but their design and the type of conductors. In the Czech Republic the line uses conductors, which are bundles of 3 conductors with a cross section of 450 mm² aluminum and 50 mm² steel. 31.5 kilometers behind the frontier near Straz the line splits off in two 380kV-lines with a single circuit. One of these lines is the 97.5 kilometres (60.6 mi) long line section to Hradec in Northern Bohemia and the other is the line to Přeštice, which was built in 1997. Both lines are installed on Delta type pylons.

Directional Radio Tower



55 metres tall lattice tower south of Etzenricht substation used for directional radio links by E.ON

South of the facility on a hill at $49^{\circ}37'28''$ N and $12^{\circ}6'55''$ E there is a 55 meters tall free-standing lattice tower, which was built in 1973. It is used for directional radio links for remote controlling Etzenricht substation and GKK Etzenricht, which are both not permanently manned.

Natural gas compressor station

Southwest of the facility at 49°37'29" N and 12°7'33" E there is a compressor station for natural gas owned by MEGAL.

Chapter-8

Hydro-Québec's Electricity Transmission System



735 kV substation near the Robert-Bourassa generating station

Hydro-Québec's electricity transmission system is an expansive, international power transmission system located in Quebec, Canada with extensions into the Northeastern United States. Major expansion of the network began with the commissioning of the alternating current 735 kV power line in November 1965, as there was a need for

electricity transmission over vast distances from hydroelectric power stations in northwestern Quebec and Labrador to southern Quebec.

The transmission system, containing over 32,000 kilometres (20,000 mi) of power lines, is managed by Hydro-Québec TransÉnergie, a division of the crown corporation Hydro-Québec. One unique feature of the power system is its alternating current (AC) 735 / 765 kV power lines that stretch from the population centers of Montreal and Quebec City to the distant hydroelectric dams and power stations of the James Bay Project and Churchill Falls. The 735 kV power lines serve as the main backbone of the entire transmission system, and thus much of Quebec's population is powered by a handful of 735 kV power lines. This contributed to the severity of the blackout that ensued after the Ice Storm of 1998. The extent and duration of this blackout has generated criticism of the transmission system, and there is controversy concerning the use of hydroelectric dams.

Hydro-Québec's electric system is part of the Northeast Power Coordinating Council, even though it technically is its own interconnection, and its own system is minimally connected with other NPCC member utilities.

History



Headquarters of Hydro-Québec in Montreal

Quebec's power transmission history began with the inauguration of a 135 kilometres (84 mi)-long, 50 kV power line running from Shawinigan to Montreal. At that time,

regional monopolies dominated the Quebec electricity market. The Quebec government created Hydro-Québec on April 14, 1944, which eventually (in 1962) nationalized all electricity generation and distribution in Québec.

Planning for Hydro-Québec's 735 kV power grid began in 1955, when engineers looked to transmit 5,000 megawatts (MW) hydroelectric power from the Manicouagan-Outardes (Manic-Outardes) dams to Montreal, a distance of 600 kilometres (400 mi). At that time, by using the world standard 300–400 kV voltage level, this feat would have required at least 30 individual power lines. Initially, a voltage level of 500 kV was chosen to transmit electric power, but 500 kV was considered to be a small improvement over the existing voltage level of 315 kV.

To effectively resolve this issue, Jean-Jacques Archambault, now regarded as the pioneer of the 735 kV power line, decided on a voltage level of 735 kV, a level over twice as high as the previous 315 kV. In 1962, Hydro-Québec proceeded with the construction of the first 735 kV power line in the world. The line, stretching from the Manic-Outardes dam to the Levis substation, was brought into service on November 29, 1965 at 1:43 pm.

Over the next twenty years, from 1965 to 1985, Quebec underwent a massive expansion of its 735 kV power grid and its hydroelectric generating capacity. Hydro-Québec Équipement, another division of Hydro-Québec, and Société d'énergie de la Baie James built these transmission lines, electrical substations, and generating stations. Constructing the transmission system for the La Grande Phase One, part of the James Bay Project, took 12,500 electrical pylons, 13 electrical substations, 10,000 kilometres (6,000 mi) of ground wire, and 60,000 kilometres (40,000 mi) of electrical conductor at a cost of C\$3.1 billion alone. In less than four decades, Hydro-Québec's generating capacity went from 3,000 MW in 1963 to nearly 33,000 MW in 2002, with 25,000 MW of that power sent to population centers on 735 kV power lines.

Source of the electricity

Much of the electricity generated by Hydro-Québec Generation comes from hydroelectric dams located far from load centres such as Montreal. Of the 33,000 MW of electrical power generated, over 93% of that comes from hydroelectric dams and 85% of that generation capacity comes from three hydroelectric generation centers: James Bay, Manic-Outardes, and Churchill Falls.

James Bay



The spillway of the Robert-Bourassa Dam (formerly La Grande-2 Dam), one of many hydroelectric dams supplying power to the load centres of Montreal, Quebec City, and the Northeastern United States

The James Bay Project encompasses the La Grande project, which is located on the La Grande River and on its tributaries, such as the Eastmain River, in northwestern Quebec. The La Grande project was built in two phases; the first phase lasted twelve years from 1973 to 1985 and the second phase lasted from 1985 to present time. In all, the nine hydroelectric dams there produce over 16,500 MW of electric power, with the Robert-Bourassa or La Grande-2 station generating over 5,600 MW alone. In total, the project cost over C\$20 billion to construct.

Manic-Outardes power stations

The Manic-Outardes river area in the Côte-Nord or North Shore region consists of several hydroelectric facilities located on three principal rivers, from west to east: Betsiamites River, Rivière aux Outardes, and the Manicouagan River. A single plant named Sainte-Marguerite-3 is located to the east on the Sainte-Marguerite River. The facilities located in the region were constructed over a period of five decades, from 1956 to 2005. The total generation capacity from these power stations is 10,500 MW. A 21-MW hydroelectric power station, the Lac-Robertson generating station on the Lower North Shore, is not connected to the main Quebec grid.

Churchill Falls

Churchill Falls is a single underground generation station located on the Churchill River near the town of Churchill Falls and the Smallwood Reservoir in Labrador. It was constructed over a period of five to six years from 1966 to 1971–72 by the Churchill Falls (Labrador) Corporation (CFLCo), though generators were installed after major construction was completed. The single generation facility cost C\$946 million to construct and produced 5,225 MW of power initially after all eleven generating units were installed. A station upgrade in 1985 raised the generating capacity to over 5,400 MW. Hydro-Québec Generation owns a 34.2% interest in CFLCo, which is the same company that constructed the generating plant. However, Hydro-Québec has rights to most of the 5,400 MW of power the station produces under a 65-year power purchase agreement, expiring in 2041.



View of Churchill Falls, the electrical substation, and the three 735 kV lines that span the river gorge

Electricity transmission system features

Hydro-Québec TransÉnergie's operates the largest power grid in North America, with nearly 33,000 kilometres (21,000 mi) of power transmission lines. The system is also unlike any other, with electrical transmission lines reaching to power generation facilities located more than 1,000 kilometres (600 mi) away from population centers. For this reason, TransÉnergie uses a voltage of AC 735 kV to transmit and distribute electrical power produced from Hydro-Québec's dams, although 315 kV is used as well. The total value of TransÉnergie's entire electricity transmission system is C\$15.9 billion. For these reasons, Hydro-Québec TransÉnergie is considered to be a world leader in power transmission.

AC 735 / 765 kV power lines



A Mae West pylon from an Hydro-Québec TransÉnergie 735 kV power line, recognizable by the *x-shaped* spacers separating the three 4-conductor sets.

From 1965 onwards, the 735 kV power line became an inaugural part of Québec's power transmission grid. More than one-third of Hydro-Québec TransÉnergie's system consists of ultra high voltage AC 735 / 765 kV power lines, totaling 11,422 kilometres (7,097 mi) strung between 38 substations with equipment of that voltage.

The physical size of the Hydro-Québec's 735 kV transmission lines is unmatched in North America. Only two other utility companies in the same region, the New York Power Authority (NYPA) and American Electric Power (AEP) contain at least one 765 kV line in their power system. However, only AEP has a significant mileage of 765 kV power lines, with over 3,400 kilometres (2,100 mi) of 765 kV line traversing its broad transmission system; this system contains the most mileage in the United States under one electrical company. NYPA has only 219 kilometres (136 mi) of 765 kV line, all of it contained in a single direct interconnection with Hydro-Québec.

The 735 kV power line is said to lessen the environmental impact of power lines, as one single power line operating at this voltage carries the same amount of electric power as four 315 kV power lines, which would require a right-of-way wider than the 80.0 metres (262.5 ft)–91.5 metres (300.2 ft) width required for a single 735 kV line. Each 735 kV line is capable of transmitting 2,000 MW of electric power at a distance of over 1,000 kilometres (600 mi) and the entire 735 kV grid can carry 25,000 MW of power. Power transmission losses over the 735 kV grid range from 4.5 to 8%, varying due to temperature and operating situations. The *Ordre des ingénieurs du Québec* named the 735 kV power line system as the technological innovation of the 20th century for Quebec.

For de-icing at Lever a de-icing facility, the Levis De-Icer was installed.

Routes



Cross rope "Chainette" ("little necklace") suspension pylons used on some parts of 735 kV lines between the James Bay hydroelectric complex and Montreal.

Hydro-Québec TransÉnergie's 735 kV system consists of a set of six lines running from James Bay to Montreal and a set of four lines from Churchill Falls and the Manic-Outardes power stations to Quebec City. The South Shore region of Montreal and the Saint Lawrence River between Montreal and Quebec City contain 735 kV power line loops or rings.

James Bay

The James Bay hydroelectric dam complex contains several relatively short 735 kV power lines that send electricity to three principal substations, ordered from west to east: Radisson, Chissibi, and Lemoyne. From these substations, six 735 kV power lines traverse the vast expanses of taiga and boreal forest in clear-cut stretches of land; this shows up clearly in aerial photos. The terrain that the power lines cross is for the most part not mountainous, but smooth and replete with lakes. Generally, four of the lines runs together in two pairs and the other two run solo, although the two single lines sometimes do run in a pair. Two intermediate 735 kV power lines, one in the north and one in the south, connect all six power lines along their path to southern Quebec.

As the lines continue south, they diverge into two sets of three 735 kV transmission lines. The eastern set heads to Quebec City, where it connects with power lines from Churchill Falls and the 735 kV power line loops in the Saint Lawrence River region. The western set heads to Montreal, where it too forms a ring of 735 kV power lines around the city, linking to other power loops in the region. This section of Hydro-Québec TransÉnergie's power grid contains 7,400 km (4,600 mi) of 735 kV AC and 450 kV DC power line.

Manic-Outardes power stations / Churchill Falls



The Micoua substation, on Quebec's North Shore. The substation is one of TransÉnergie's transmission hubs.

Electrical power generated from the Churchill Falls power station is sent to Montreal and the population centers of the Northeastern United States, more than 1,200 kilometres (700 mi) away. Starting from the generation station in Labrador, the power lines span a distance of 1,800 metres (6,000 ft) over the Churchill River gorge and run generally south-southwest for 203 kilometres (126 mi) as three side-by-side power lines in a cleared right-of-way with a width of 216 metres (710 ft). As they head southwest through boreal forest, the lines generally traverse flat, smooth rolling hills.

After the lines cross the Quebec-Labrador border, also known as the Hydro-Québec point of delivery, the direction of the lines becomes due south, and they head to the Montagnais Substation, a substation accessible only by an airport adjacent to it. A lone 735 kV line stems off from the substation, heading to an open pit mine 142 kilometres (88 mi) the northwest. The terrain crossed by the power lines becomes hilly and mountainous south of the border. The lines reach over 800 metres (2,600 ft) in elevation before descending. The three lines continue heading south until they reach a substation on the North Shore of the Gulf of Saint Lawrence. From there on, the three lines parallel the North Shore as the Gulf narrows to the southwest toward the Saint Lawrence River discharge mouth. The northernmost power line then diverges from the other two to connect with Manic-

Outardes power stations located on and around the Rivière aux Outardes and the Manicouagan River.



Triple 735kV Mae West towers at Boischatel / L'Ange-Gardien limits, on Route 138 east of Quebec City, as lines cross the St. Lawrence River south towards the Île d'Orléans.

As the lines near Quebec City, the northern power line rejoins the other two 735 kV power lines. The three lines, paralleled by another 735 kV power line some distance to the north, span over the Saint Lawrence River to the South Shore region, where the lines form loops encompassing part of the Saint Lawrence River and the south shore. The loops are also connected to the ring of 735 kV power lines around Montreal and power lines running south from James Bay.

Electricity pylons

Quebec's transmission system contains a variety of electrical pylons depending on era and voltage level. Older pylon designs tend to consume more material than the newer pylons and the higher the voltage level, the larger the tower.

735 kV pylons



Two types of single-circuit 735 kV delta pylons near St-Jean-sur-Richelieu paralleled by a dual-circuit 315 kV line. The center 735 kV line uses a larger version delta pylon while the one to the right uses smaller one.

Hydro-Québec TransÉnergie uses several different types of electricity pylons to support their 735 kV power lines. All of them are single-circuit, meaning that each pylon carries one power line with three bundles of four electrical subconductors separated by spacers, with each bundle transmitting one phase of current.



A series of V-guyed towers, near Chapais, Quebec.

The earliest type of tower used was a massive self-supporting delta pylon, or waist pylon, which consumed 21 tonnes of steel per kilometre of line. This type of pylon was used for the first 735 kV power line from the Manic-Outardes power stations to the load centre of Montreal. There are two significant variations of the delta pylon; one has longer side crossbars such that all three bundles of conductors are suspended on V-shaped insulators. The other has shorter side crossbars, such that the two outside bundles are hung on a vertical insulator string and only the middle bundle is hung with a V-shaped insulator.

Over the years, Hydro-Québec researchers engineered a new type of pylon, the V-guyed tower, which reduced materials consumption to 11.8 tonnes of steel per kilometre of power line. This type of tower also includes a variation with longer side crossbars, where all conductors are hung with a V-shaped insulator and one with shorter side crossbar, where only the middle bundle hangs from the insulator and the side bundles are strung on vertical insulator strings.

During the construction of the James Bay transmission system, the cross-rope suspension tower was invented. This type of tower features two guyed-tower legs similar to the V-guyed tower, but the two legs don't converge at the tower base. In the case of the cross-rope suspension tower, the tower legs are spread apart on two different foundations. In

addition, the crossbar is replaced by a series of suspension cables with three vertical insulator strings to support the three bundles, which allows this design to consume only 6.3 tonnes of steel per kilometre of line. The design is also known as the Chainette (little necklace).

TransÉnergie uses two-level pylons for angle towers or structures on 735 kV power lines to change the direction of the line or switch the position of the conductor bundles. Delta pylons and three-leg guyed towers are also used as angle towers; they are referred to as "penguins" by Hydro-Québec linemen.

Pylons for other voltage levels

Hydro-Québec TransÉnergie uses a combination of double-circuit three-level pylons and single-circuit delta pylons to suspend electrical conductors of other voltages, such as 315 kV. The ± 450 kV high-voltage direct current line in Hydro-Québec's power grid uses a T-shaped tower, lattice or pole, to support two bundles of three conductors on each side. The direct current power line sometimes uses two poles or a wider, pyramidal, self-supporting lattice structure for angle towers.



174.6 metre pylon adjacent to Hydro-Québec's Tracy power plant.
Other pylons

Hydro-Québec usually uses tall, large pylons to cross large bodies of water, like lakes and rivers. These towers are said to be prominent and the tallest pylon in Hydro-Québec's power grid is of this function. The tallest of these is located near the Tracy power station on the shore of the Saint Lawrence River, carrying a 735kV circuit between Lanoraie and Tracy. The pylon, the largest of its kind in Canada, is 174.6 metres (572.8 ft) tall, the same height as the Montreal Olympic Stadium, and slightly larger than the Washington Monument in the United States (555 feet (169.2 m)).

Pylon strength

The pylons and conductors are designed to handle 45 millimetres (1.8 in) of ice accumulation without failure, since Hydro-Québec raised the standards in response to ice storms in Ottawa in December 1986 and Montreal in February 1961, which left 30 to 40 millimetres (1.2 to 1.6 in) of ice. This has led to the belief that Hydro-Québec TransÉnergie's electrical pylons are "indestructible". Despite being more than three times higher than the Canadian standard of only 13 millimetres (0.5 in) of ice tolerance, an ice storm in the late-1990s deposited well over 45 millimetres (1.8 in) of ice.

Interconnections



The Outaouais substation, the newest of 19 interconnections between Hydro-Québec's network and neighboring power grids.

The international transmission grid contains 18 interconnections between power grids located in the adjacent provinces or states of Ontario, New Brunswick, Newfoundland and Labrador, Vermont and New York. Several of those connections involve one or more 735 kV power lines, but most involve lines with a voltage lower than 735 kV. Another connection consists of a ± 450 kV high-voltage direct current (HVDC) transmission line crossing the international border into Vermont. These interconnections allow Hydro-Québec to import as much as 7,100 MW of electric power or export as much as 9,575 MW to neighboring regions. A 19th interconnection is planned between Ontario and Quebec, with an expected completion year of 2009. This new interconnection has generated some debate over the need to transmit an additional 1,250 MW of power to Ontario.

High voltage direct current (HVDC) 450 kV

In addition to the six 735 kV power lines that stem from the James Bay Project, a seventh power line was constructed as an 1,100 kilometres (680 mi) northward extension of an existing high-voltage direct current (HVDC) line connecting Quebec and New England. This power line expansion was completed in 1990. As a result, the direct current power line is unique because there are multiple static converter and inverter stations along the 1,480 kilometres (920 mi) long power line. It is also the first multiterminal HVDC line in the world. The ± 450 kV power line can transmit about 2,000 MW of hydroelectric power to Montreal and the Northeastern United States.

Route

Beginning in the converter station next to the Radisson substation, the HVDC line heads south and roughly parallels the six 735 kV power lines some distance to the west. It traverses the same type of terrain as the other six lines; the land is replete with lakes, wetlands, and forested rolling hills. Gradually, the power line turns to the southeast, as it crosses under several 735 kV power lines.



450kV high-voltage direct current (HVDC) line (at right), on south side of Autoroute 20 east of the Nicolet station.

After the six 735 kV wires split up into two groups of three power lines each, the HVDC line follows the eastern group, and the western set diverges away. The line remains overhead until it reaches the north shore of the Saint Lawrence River near Grondines, where the 450 kV HVDC line descends into an underwater tunnel traversing the river. The power line surfaces on the south shore near Lotbinière substation. After the river crossing, the line enters into the Nicolet terminal near Sainte-Eulalie, northeast of Drummondville. South of the terminal, the line heads south and after a relatively short distance, it enters the Des Cantons close to Sherbrooke.

Leaving the Des Cantons station, the power line crosses the United States-Canada border and passes through the hilly Appalachian Mountains in the U.S. state of Vermont, reaching an elevation of about 650 metres (2,130 ft). The line then continues heading south-southeast and enters the state of New Hampshire, where it reaches the Comerford terminal near Monroe. Continuing southward into Massachusetts, the line reaches the Sandy Pond terminal outside of Boston in Ayer. The terminal is the southernmost extent of the HVDC line.

In December 2008, Hydro-Québec, along with American utilities Northeast Utilities and NSTAR, created a joint venture to build a new HVDC line from Windsor, Quebec to Deerfield, New Hampshire. Hydro-Québec will own the segment within Quebec, while the segment within the US will be owned by *Northern Pass Transmission LLC*, a partnership between Northeast Utilities (75%) and NSTAR (25%). Estimated to cost US\$1.1 billion to build, it is projected that the line will either run in existing right-of-way adjacent to the HVDC line that runs through New Hampshire, or it will connect to a right-of-way in northern New Hampshire that will run through the White Mountains. This 180-to-190-mile (290 to 310 km) line, projected to carry 1,200 megawatts, will bring electricity to approximately one million homes.

Other features

TransÉnergie uses series compensation to alter the way electricity behaves in power transmission lines, which improves the electricity transmission efficiency. This reduces the need to construct new power lines and increases the amount of electric power sent to population centres. Series compensation is based on capacitor technology. To maintain its transmission system performance, TransÉnergie sets aside funds for research and application of new technologies. In addition to power transmission technology, Hydro-Québec plans to offer high-speed internet over its transmission lines within a few years; the utility started testing internet over its lines in January 2004.

Major disruptions

In spite of the transmission system's reputation and the fact Quebec escaped unscathed from the Northeast Blackout of 2003, the system has experienced damage and service interruptions from severe storms in the past. Examples include the 1982 and 1988 Quebec blackouts prior to the large 1989 and 1998 power interruptions.

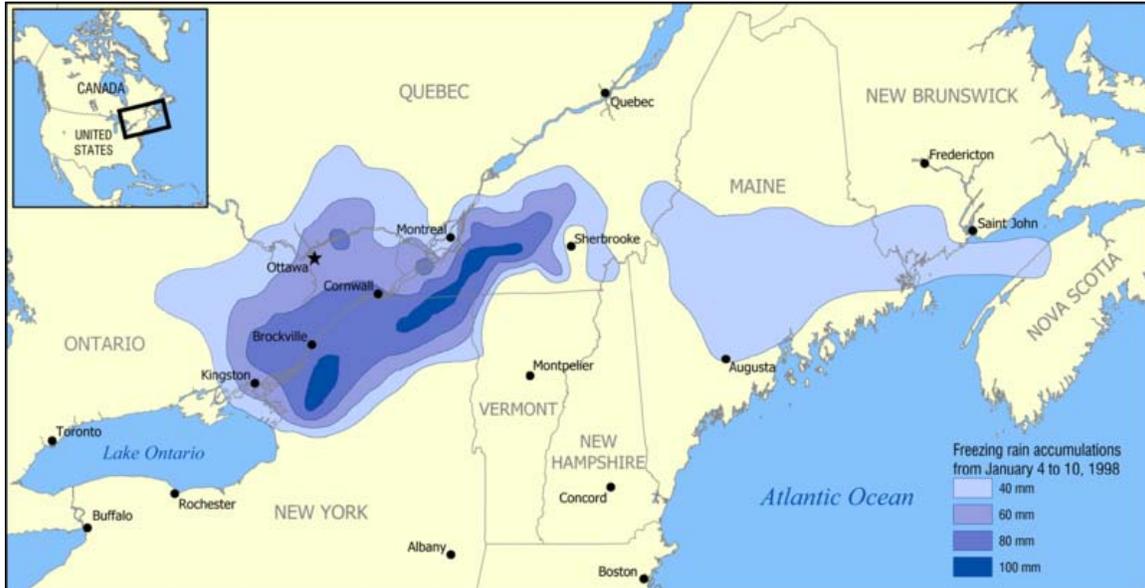
1989 Geomagnetic storm

At 2:44 am on March 13, 1989, a severe geomagnetic storm, due to a coronal mass ejection from the Sun, struck Earth. Fluctuations within the magnetic field of the storm caused geomagnetically induced currents (GICs) to flow through Quebec's power lines, which are direct current, instead of the alternating current carried by the power lines. The insulating nature of the Canadian Shield igneous rock directed the GICs to the power lines. The conductors then forwarded this current to sensitive electrical transformers, which require a certain voltage amplitude and frequency to function properly. Although most GICs are relatively feeble, the nature of those currents destabilized the voltage of the power grid and current spikes erupted everywhere.

Accordingly, protective measures were taken in response. To save the transformers and other electrical equipment, the power grid was taken out of commission, as circuit breakers tripped all over Quebec and shut off the power. Within less than 90 seconds, this wave of breaking circuits left the entire transmission grid out of service. The collapsed power grid left six million people and the rest of Quebec without electricity for hours on

a very cold night. Even though the blackout lasted around nine hours for most places, some locations were in the dark for days. This geomagnetic storm caused about C\$10 million in damage to Hydro-Québec and tens of millions to the customers of the utility.

1998 ice storm



Map showing precipitation amounts for Quebec and the Northeastern United States

From January 4/5 to January 10, 1998, warm moist air from the south overriding cold air from the north produced an ice storm, leading to over 80 hours of freezing rain and drizzle. For days, a continuous shower of mostly freezing rain amounted to 70–110 millimetres (2.8–4.3 in) of water equivalent of precipitation. Places like Montreal and the South Shore were especially hard hit, with 100 mm (3.9 in) of largely freezing rain falling. These heavy precipitation totals wreaked havoc on the regional power transmission system.

Physical damage

Five to six days of freezing rain and precipitation crippled the Hydro-Québec power grid in the Montreal and South Shore regions. In an area 100 by 250 kilometres (60 by 150 mi), some 116 transmission lines were out of commission, including several major 735 kV power lines and the Quebec–New England HVDC ± 450 kV line.



Damage to trees and a power distribution line

Through successive waves of freezing precipitation, more than 75 millimetres (3.0 in) of radial ice accumulated on the electrical conductors and the pylons themselves. This ice coating adds an additional weight of 15 to 20 kilograms per metre of conductor (10 to 20 lb/ft). Even though the electrical wires can withstand this extra weight, when combined with the effects of wind and precipitation, these conductors may break and fall. The pylons, designed to withstand only 45 millimetres (1.8 in) of ice accretion, buckled and collapsed into twisted heaps of mangled steel. Cascading failures occurred on several transmission lines, where the collapse of one or more towers left a row of fallen pylons.

Of all the pylons damaged, some 150 were pylons supporting 735 kV lines, and 200 towers carrying 315 kV, 230 kV, or 120 kV power lines collapsed as well. In a region bounded by Montreal between Saint-Hyacinthe, Saint-Jean-sur-Richelieu and Granby, dubbed the "triangle of darkness", half of the overhead power grid was out of service. Quebec ordered myriad conductors, crossarms, and wire connections to repair the ones disabled by the storm in the electrical transmission and distribution system. In all of Quebec, 24,000 poles, 4,000 transformers, and 1,000 electrical pylons were damaged or destroyed, more than 3,000 km (2,000 mi) of downed electrical wires; this cost a total of C\$800 million to repair.

Power outage

With over 100 transmission lines paralyzed by the ice, Quebec fell into a massive power outage in the cold Canadian winter. Even though power restoration initiated after the first blackouts, large numbers of Quebecers were in the dark. At the height of the blackout, some 1.4–1.5 million homes and customers, housing three to more than four million people, were in the dark. Private companies and other utilities from other parts of Canada and the United States were sent in to help Hydro-Québec undertake this massive

restoration task, but these efforts were complicated by the widespread damage of the power grid. Blackouts in some areas lasted for 33 days, and 90% of those affected by the blackout had no power for more than seven days. Although power was fully restored to all locations in Quebec by February 8, 1998, it wasn't until mid-March that the power facilities were back in service. By then, much social and economic damage had occurred, such as ruined food and deaths resulting from lack of electric heating.

After the power outage was over, Hydro-Québec made numerous upgrades to its system in order to improve the power grid. Examples include the strengthening of electrical pylons and power poles, and increasing the power supply. This was done to enable the utility to restore power more rapidly in the case of a massive ice striking Quebec again. Hydro-Québec has stated that it is better-prepared to handle an ice storm with the same magnitude as the one of 1998.

2004 hydro tower bombing

In 2004, shortly before U.S. President George W. Bush's visit to Canada, a tower along the Quebec – New England Transmission HVDC circuit in the Eastern Townships near the Canada-U.S. border was damaged by explosive charges detonated at its base. The CBC reported that a message, purportedly from the Résistance internationaliste and issued to the *La Presse* and *Le Journal de Montréal* newspapers and the CKAC radio station, stated that the attack had been carried out to "denounce the 'pillaging' of Quebec's resources by the United States."

Criticism

The performance of Hydro-Québec TransÉnergie's power grid during 1998 Ice Storm raised questions about the fundamental concept, vulnerability, and reliability of the grid. Critics noted that the power generation facilities were located approximately 1,000 km (600 mi) away from population centres and that there was a lack of local power stations around Montreal, which is served by only six 735 kV feeder lines. In addition, the 735 kV transmission system received scorn from the public and the media. The power transmission grid was said to concentrate power transmission on only a few 735 kV lines, such as those that run from James Bay to Montreal. Out of the six 735 feeder lines in Montreal, five of them form a loop called the "ring of power" around the city. When the ring failed on January 7, 1998, roughly 60% of Greater Montreal's power supply was offline. Hydro-Québec's large above-ground transmission and distribution system was considered to be exposed to natural disasters, although the cost of undergrounding the grid was prohibitive.

The technology utilized on Hydro-Québec TransÉnergie grid also came under fire from critics. It is claimed that this technology, used to improve performance, safety, and reliability, made people in Quebec over-dependent on the power grid for their energy needs, since electricity, especially hydroelectric power, makes up over 40% of Quebec's energy supply. This dependence, evidenced by the fact Ontario farmers had more backup

generators than farmers in Quebec, can increase the severity of the consequences when the grid fails, as it did in January 1998.

Chapter-9

North Sea Offshore Grid and Submarine Power Cable

North Sea Offshore Grid

The **North Sea Offshore Grid**, officially the **North Seas Countries Offshore Grid Initiative (NSCOGI)**, is a collaboration between EU member-states and Norway to create an integrated offshore energy grid which links wind farms and other renewable energy sources across the northern seas of Europe.

History

The North Sea Offshore Grid was proposed by the European Commission in the Second Strategic Energy Review, published in November 2008. The initiative was identified as one of the six priority energy infrastructure actions of the European Union. According to the European Commission, the North Sea Offshore Grid should become one of the building blocks of a future European super grid.

The political declaration of the North Seas Countries Offshore Grid Initiative was signed on 7 December 2009 at the European Union Energy Council. The declaration was signed by Germany, United Kingdom, France, Denmark, Sweden, the Netherlands, Belgium, Ireland and Luxembourg.

In 2010, the European Commission plans to publish a "Blueprint for a North Sea Grid".

Description

Electricity would be transmitted via high-voltage direct current cables, allowing it to be sold and exchanged in all involved countries. It would also make it easier to optimise energy production, and make the system overall less susceptible to the climate; Norway's hydroelectric power plants could act as a "giant battery", storing the power produced and releasing it at peak times, or when wind strength is low. Several high-voltage direct current interconnectors such as proposed cable between Norway and the United Kingdom have been seen as integral parts of the project.

Significance

Minister for Communications, Energy and Natural Resources for the Government of Ireland, Eamon Ryan, said of the initiative:

“ This project is another example of European vision and ambition in energy policy. It is a huge step towards meeting our common renewable energy goals and in guaranteeing a low carbon future.

Irish wind farms will be able to connect directly to Europe, not only securing our energy supply but allowing us to sell the electricity produced on a wider market.

It makes economic, as well as environmental sense. By working together, all of the countries involved will reap the benefits.” ”

—Minister Eamon Ryan, speaking at the Energy Council.

Submarine power cable

Submarine power cables are major transmission cables for carrying electric power below the surface of the water. These are called "submarine" because they usually carry electric power beneath salt water (arms of the ocean, seas, straits, etc.) but it is also possible to use submarine power cables beneath fresh water (large lakes and rivers). Examples of the latter exist that connect the mainland with large islands in the St. Lawrence River.

Design technologies

The majority of submarine power cables use high-voltage direct current (HVDC) electric power transmission. This is a form of power transmission that was favored by Thomas Edison long ago, but mostly rejected in the late 19th century in favor of alternating-current (AC) transmission. This is the kind of electricity that is now used to power almost everything that is significant. However, high-voltage alternating-current (HVAC) power lines are sometimes difficult to use, because the electromagnetic interactions between the current and the metal casing of the cable can drive up voltages to unusable peaks - damaging insulation and causing many other problems.) However, there are several significant engineering advantages in using HVDC to transmit large amounts of electric power underwater. (what are the advantages?)

Direct-current transmission has also undergone a modest revival over dry land, over long distances, because in this case its power losses (due to waste heat) are smaller, and its current flows are easier to control.

A DC power-transmission system can use the earth (including seafloor)s and seawater as the return path for current. However, this method cannot always be used because of deleterious ecological effects of electrochemical reactions below ground and where the electrical conductors are connected to the ground.

The overall length of AC submarine cables is restricted by the capacitance between their active electric conductors and their surrounding metallic shields. If the cable were to be made long enough, the reactive power produced by an AC cable would take up the entire current carrying capacity of the conductor, so no usable power would be transmitted. Therefore, for transmission of large amounts of electric power via long submarine cables, DC transmission is nearly-always preferable over AC transmission, because DC cables have no such effect as mentioned above.

Operational submarine power cables

Alternating current cables

Alternating-current (AC) submarine cable systems for transmitting lower amounts of three phase electric power can be constructed with three-core cables in which all three insulated conductors are placed into a single underwater cable. Most offshore-to-shore wind-farm cables are constructed this way.

For larger amounts of transmitted power, the AC systems are composed of three separate single-core underwater cables, each containing just one insulated conductor and carrying one phase of the three-phase electric current. A fourth identical cable is often added in parallel with the other three, simply as a spare in case one of the three primary cables is damaged and needs to be replaced. This damage can happen, for example, from a ship's anchor carelessly dropped onto it. The fourth cable can substitute for any one of the other three, given the proper (and complicated) electrical switching system.

- Mainland British Columbia to Nelson Island to Texada Island to Vancouver Island, the destination of the power. This is a high-capacity 500 kilovolt (kV) three-phase system.
- Mainland Sweden to Bornholm Island, Denmark (110 kilovolts, but some sources state 72 kV).
- Under the Strait of Messina, connecting southern tip of the mainland of Italy with the large island of Sicily (380 kV). This submarine cable replaced an earlier, and very long overhead line crossing (the "Pylons of Messina")
- Negros Island to Panay Island, in the Philippines (138 kV)

Direct current cables

- Baltic-Cable - between Germany and Sweden beneath the Baltic Sea
- Basslink - between the mainland State of Victoria and the island of Tasmania, Australia, 500 kilovolts (kV), with a length of 290 kilometers beneath the Bass Strait

- BritNed - between the Netherlands and Great Britain beneath the North Sea
- Cross Sound Cable - between Long Island, New York, and the State of Connecticut beneath Long Island Sound
- Estlink - between northern Estonia and southern Finland beneath the Gulf of Finland
- Fenno-Skan - between Sweden and Finland beneath the Baltic Sea
- HVDC Cross-Channel - very high power cable between the French mainland and the island of Great Britain beneath the English Channel
- HVDC Gotland - the first HVDC submarine power cable (non-experimental) - between the Swedish mainland and the Swedish island of Gotland beneath the Baltic Sea
- HVDC Inter-Island - between the power-rich South Island (much hydroelectric power) of New Zealand and the more-populous North Island beneath the Cook Strait
- HVDC Italy-Corsica-Sardinia (SACOI) - between the Italian mainland, the Italian island of Sardinia, and its neighboring French island of Corsica beneath the Mediterranean Sea
- HVDC Italy-Greece - between Italy and Greece beneath the Adriatic Sea
- HVDC Leyte - Luzon - between Leyte Island and Luzon in the Philippines, beneath the Pacific Ocean
- HVDC Moyle - connecting Scotland with Northern Ireland within the United Kingdom, and thence to the Republic of Ireland, beneath the Irish Sea
- HVDC Vancouver Island - between Vancouver Island and the mainland of the Province of British Columbia, beneath the Strait of Juan de Fuca
- Kii Channel HVDC system - now (2010) the world's highest-capacity long-distance submarine power cable (rated at 1400 megawatts). This power cable connects the large islands of Honshu and Shikoku beneath the Kii Channel in the Japanese Home Islands
- Kontek - between Germany and Denmark beneath the Baltic Sea
- Konti-Skan - between Sweden and Denmark beneath the Baltic Sea
- Neptune Cable - between the State of New Jersey and Long Island, New York - 64 miles beneath the Atlantic Ocean
- Swepol - between Poland and Sweden beneath the Baltic Sea

Longest

- NorNed (between Eemshaven, Netherlands and Feda, Norway), HVDC, 700 MW, 580 km (360 mi)

Proposed submarine power cables

- Champlain Hudson Power Express, 335-mile line. The Transmission Developers Company of Toronto, Ontario, is proposing "to use the [Hudson River] for the most ambitious underwater transmission project yet. Beginning south of Montreal, a 335-mile line would run along the bottom of Lake Champlain, [and then] down the bed of the Hudson all the way to New York City."

- Power Bridge, Hawaii
- Power Bridge, State of Maine
- Puerto Rico to the Virgin Islands
- 400 kV HVDC India to Sri Lanka
- Atlantic Wind Connection between Delaware and New Jersey, potentially between Virginia and New York
- 100 megawatts 165 km Canadian province of Newfoundland and Labrador and province of Nova Scotia
- 200 megawatts 95 km Magħtab (Malta) and Marina the Ragusa (Sicily)

Chapter-10

Amtrak's 25 Hz Traction Power System



An Amtrak HHP-8 under 25 Hz wire

Amtrak's 25 Hz Traction Power System is a traction power grid operated by Amtrak along the southern portion of its Northeast Corridor(NEC). This includes both the 363 route mile portion between Washington, DC and New York as well as the 104 route mile portion between Philadelphia, PA and Harrisburg, PA. The Pennsylvania Railroad originally constructed it between 1915 and 1938. Amtrak inherited the system from Penn Central, the successor to Pennsylvania Railroad, in 1976 along with the Northeast Corridor itself. In addition to serving the NEC, the system provides power to some rail lines of New Jersey Transit (NJT) and the Southeastern Pennsylvania Transportation Authority (SEPTA). Only about half of the system's electrical capacity is used by Amtrak. The remainder is sold to the commuter railroads who operate trains along the corridor.

History



Old substation built for the 1915 electrification project at Bryn Mawr, PA. Outdoor yard is an addition.

The Pennsylvania Railroad (PRR) began experimenting with electric traction in 1910, coincident with their completion of the trans-Hudson tunnels and New York Penn Station. These initial systems were (relatively) low-voltage, direct current, third-rail systems. While they performed adequately for tunnel service, the PRR ultimately determined them to be inadequate for long distance, high-speed electrification.

Other railroads had by this time experimented with low frequency (that is, less than 60 Hz) alternating current systems. These low-frequency systems had the AC advantage of higher transmission voltages, reducing resistive losses over long distances, as well as the typically DC advantage of easy motor control as universal motors could be employed with transformer tap changer control gear. Pantograph contact with trolley wire is also more tolerant of high speeds and variations in track geometry. The New York, New Haven and Hartford Railroad had already had already electrified a portion of its Main Line in 1908 with 11 kV AC current at 25 Hz and this served as a template for the PRR which installed its own trial main line electrification scheme between Philadelphia and Paoli, PA in 1915. Power was transmitted along the tops of the catenary supports using

four single phase, 2 wire, 44 kV distribution circuits. Tests on the line using experimental electric locomotives such as the PRR FF1 revealed that the 44 kV distribution lines would be insufficient for heavier loads over longer distances.

In the 1920s the PRR decided to electrify major portions of its eastern rail network and because any sort of commercial electric grid simply did not yet exist at the time the railroad constructed its own distribution system to transmit power from a select number of generating sites to trains possibly hundreds of miles distant. To accomplish this the PRR chose to implement a pioneering system of single-phase high voltage transmission lines running at 132,000 volts which would then be stepped down to the 11 kV catenary voltage at regularly spaced substations along the right of way.

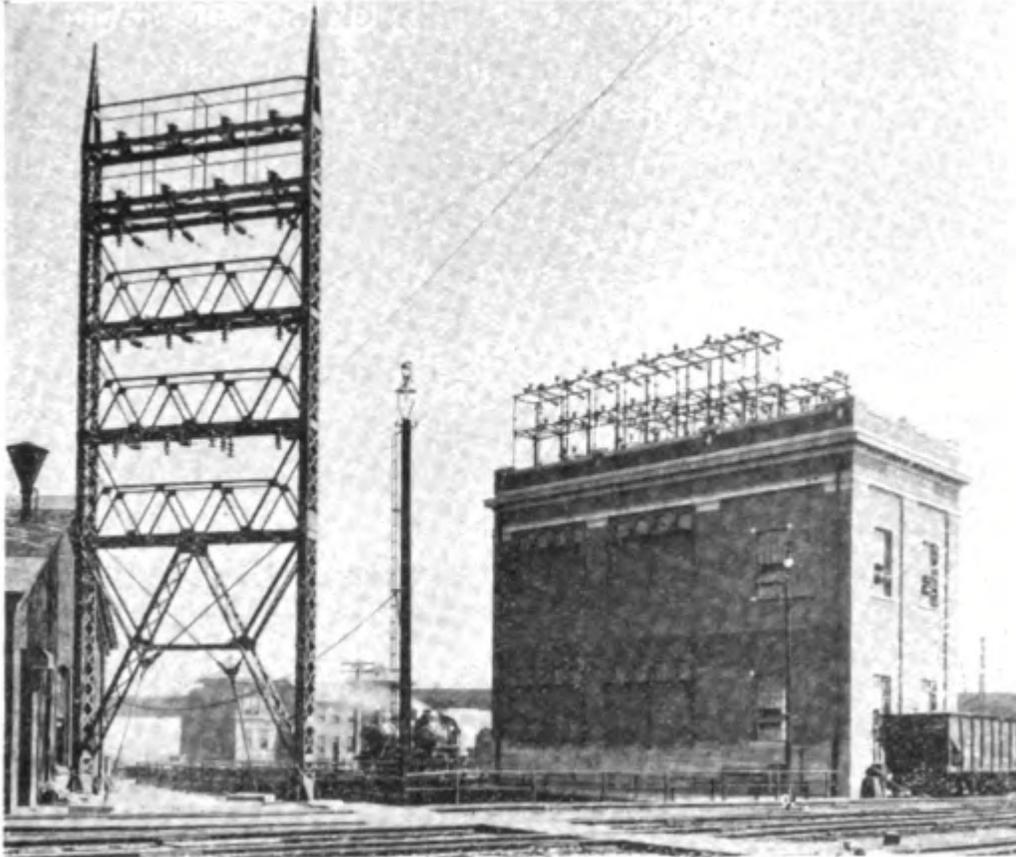
The first line to be electrified under this new system was between Philadelphia and Wilmington, Delaware in the late 1920s. By 1930, catenary extended from Philadelphia to Trenton, NJ, by 1933 to New York City, and by 1935 south to Washington, D.C. Finally in 1939 the main line from Paoli west to Harrisburg, PA was completed along with several freight-only lines were also included the Trenton cutoff and the Port Road Branch. Superimposed on these electrified lines was an independent power grid delivering 25 Hz current from the point of generation to electric locomotives anywhere on nearly 500 route miles of track, all under the control of electric power dispatchers located in Harrisburg, Baltimore, Philadelphia and New York City.

Northeast Railroads atrophied in the years following World War II; the PRR was no exception. The infrastructure of the northeast corridor remained essentially unchanged through the series of mergers and bankruptcies which ended in Amtrak's creation and acquisition of the former PRR lines which came to be known as the Northeast Corridor. The circa 1976 Northeast Corridor Improvement Project had originally planned to convert the PRR's system to the utility grid standard of 60 Hz. Ultimately, this plan was shelved as economically infeasible and the electrical traction infrastructure was left largely unchanged with the exception of a general traction power voltage increase to 12 kV and a corresponding transmission voltage increase to 138 kV.

During the 1970s, several of the original converter or power stations which had originally supplied power to the system were shut down. Also the end of electrified through freight service on the Main Line to Paoli allowed the original 1915 substations and their 44 kV distribution lines to be decommissioned with that 20-mile section of track being fed from 1930s-era substations on either end. In the decade between 1992 and 2002, several static converter stations were commissioned to replace stations that had or were being shut down. Jericho Park, Richmond, and Sunnyside Yard converters were all installed during this period. This replaced much of the electrical frequency conversion equipment, but the lineside transmission and distribution equipment were unchanged.

In 2003, Amtrak commenced a planned capital improvement plan that involved planned replacement of much of the lineside network including 138/12 kV transformers, circuit breakers, and catenary wire. Statistically, this capital improvement has resulted in significantly fewer delays, although dramatic system shutdowns have still occurred.

Specifications and statistics



West Philadelphia Substation 1915

The 25 Hz system was originally built by the Pennsylvania Railroad with a nominal voltage of 11.0 kV. The nominal operating voltages were raised in 1948 and are now:

- Catenary (Traction) Voltage : 12.0 kV
- Transmission Voltage: 138 kV
- Signal Power:
 - 2.2 kV 91 2/3 Hz - NY Penn Area. 60 Hz used 1910-1931. 100 Hz installed but quickly changed to avoid interference caused by simultaneous AC and DC electrification.
 - 3.3 kV 100 Hz - Paoli/Chestnut Hill. 60 Hz used 1915/18-1930.
 - 6.9 kV 91 2/3 Hz - all electrification work from 1930 onward.

As of 1997, the system included:

- 951 miles of 138 kV transmission line,
- 55 substations,
- 147 transformers, and
- 1104 miles of 12 kV catenary.

Over 550 GWhr of energy are consumed annually by locomotives on the system. If this was consumed at a constant rate over the entire year (although it is not in practice), the average system load would be approximately 63 MW.

The system power factor varies between 0.75 and around 0.85.

Power sources

Electrical power originates at seven generation or conversion facilities. The nameplate capacity of all the power sources in the system is about 354 MW. The instantaneous peak loading on the system is between 210-220 MW (as of c. 2009) during the morning rush hour, and up to 225 MW during afternoon. Peak load has risen significantly in the last decade - in 1997 the peak load was 148 MW. As a point of comparison, an HHP-8 electric locomotive is rated for a 6 MW (equivalent to 8,000 hp) mechanical output, after conversion and Head End Power losses.

Regardless of the source, all converter and generator plants supply power to the transmission system at 138 kV, 25 Hz, single phase, using two wires. Typically at least two separate 138 kV circuits follow each right of way to supply the lineside substations.

Currently, the following converter and generating plants are operable, although all are rarely in operation simultaneously due to maintenance shutdowns and overhaul:

Location	Capacity (MW)	In-service	Comments
Sunnyside Yard (Long Island)	30	c. 1996	Static Inverter
Metuchen	25	1933	Motor Generator
Richmond	180	2002	Static Inverter
Lamokin	48	1928	(3) Motor Generators
Safe Harbor	81	1938	(2) Water turbines; (1) Motor Generator
Jericho Park	20	1992	Static Cycloconverter
System Total Capacity	354		

Three types of equipment are currently in operation: hydroelectric generators, motor generators (sometimes called rotary frequency converters), and static frequency converters.

Hydroelectric generators



The Safe Harbor Dam generates 25 Hz railroad power via two turbines in the east end of the turbine hall and an M-G set outside against the Dam face.

- Safe Harbor Dam, PA - The Safe Harbor Dam has two 28 MW, single phase, turbines dedicated to 25 Hz power generation. A 25 MW bi-directional motor generator type frequency converter is also installed. The total 25 Hz capacity of the dam is 81 MW. Power from Safe Harbor is transmitted via the Conestoga substation to Royalton, PA, Parkesburg, PA (two circuits), and Perryville, MD (four circuits) where it is fed into the lineside 138 kV network.

The 25 Hz machines at the dam are scheduled by Amtrak but owned and operated by Safe Harbor Water Power Company. Amtrak typically uses this source as a peaking power source, similarly to most hydroelectric plants in the US. Like other hydroelectric plants, it also has excellent black start capability. This was most recently demonstrated during the 2006 blackout. After a cascade shutdown of converters had left the network de-energized, it was recovered using Safe Harbor's generators, and the other converters subsequently brought back online.

During the twelve month period that ended in August 2009, Safe Harbor supplied about 133 GWh of energy to the Amtrak substation at Perryville. Typically, two thirds of the

Safe Harbor output is routed through Perryville (the remainder being sent through Harrisburg or Parkesburg). This suggests that Safe Harbor supplies around 200 GWh of energy annually into the 25 Hz network. 39°55'36"N 76°23'6"W / 39.92667°N 76.385°W

Motor generators (rotary frequency converters)

Motor generators and steam driven turbine generators were the original power sources on the PRR traction power network. The last steam turbine shutdown in 1954, but some of the original motor generators remain. Although the converting machines are frequently called 'rotary converters' or 'rotary frequency converters', they are not the rotary converter used frequently by subways to convert low frequency alternating current to DC power. The converters used are more precisely described as motor generators and consist of two synchronous AC machines on a common shaft with different ratios of poles; they are not electrically connected as in a true rotary converter.

Principal advantages of motor generators include very high fault current ratings and clean output current. Solid state electronics can be damaged very quickly, so the microprocessor control systems react very quickly to overcorrect conditions to place the converter in a safe, idle mode; or to trip the output circuit breaker. Motor generators are (being of 1930s design) heavily overbuilt. The machines can absorb large load transients and demanding fault conditions and continue to remain online. Their output waveform is also perfectly sinusoidal without noise or higher harmonic output. They can actually absorb harmonic noise produced by solid state devices, effectively serving as a filter. This, combined with their high fault current capability make them desirable in a stabilizing role within the power system. Amtrak has retained two of the original converter plants and plans to overhaul them and continue their operation indefinitely.

Disadvantages of motor generators include lower efficiency, generally between 83% (lightly loaded machine) and 92% (fully loaded machine). A cycloconverter efficiency can exceed 95%. They also require more maintenance due their nature as rotating machines. Their replacement would also be difficult today due to high cost and limited demand for these large 25 Hz machines.

- Metuchen, NJ - 25 MW Motor Generator. Upgrades to transmission lines and circuit breakers are planned for 2010. 40°31'51"N 74°20'50"W / 40.530743°N 74.347281°W
- Lamokin (Chester), PA - The Lamokin plant was built in the 1920s and has a net capacity of 48 MW and consists of three 16 MW motor generators. All three units will be overhauled including re-winding of rotors and stators, and replacement of slip ring assemblies. Associated breakers and cables are also planned for replacement.

Static frequency converters

The static converters in the system were commissioned during the decade between 1992 and around 2002. Chief advantages of static converters over motor generators include lower capital cost, lower operating costs, and higher conversion efficiency. The Jericho Park converter exceeds its efficiency design criteria of 95%. Major disadvantages of solid state converters include harmonic frequency generation on both the 25 Hz and 60 Hz sides, and lower overload capability.

- Sunnyside Yard (Long Island City), NY - Static Inverter rated at 30 MW ordered from ABB in 1993 for 27 million dollars. This converter is operated by Amtrak and generally run at low continuous loading to provide peaking and reactive power support to the New York area.
- Richmond (Philadelphia), PA - The Richmond Static Converter plant consists of five 36 MW modules and has a net capacity of 180 MW. It was ordered from Siemens in 1999 for 60 million dollars and installation was completed around 2002. The plant receives 69 kV, three phase, 60 Hz power from the electric utility (PECO). Although the exact electrical architecture of the converter modules is unknown, they are presumably of the DC link variety (Rectifier, filtering capacity, and inverter placed back to back) based on other Siemens traction power converters. The 2006 traction network shutdown originated in one of the converter modules at this plant. Richmond output power is scheduled with PECO, although the units themselves are operated by Amtrak remotely from Philadelphia. Generally, the three PECO supplied converters (Richmond, Metuchen, and Lamokin) are scheduled as a block with PECO.
- Jericho Park, MD - 20 MW Static Converter. Jericho Park was constructed to replace the capacity lost when BG&E declined to renew the Benning rotary converter contract. BG&E proposed a static converter to replace Benning and Jericho Park came on service six years later. It consists of two 10 MW cycloconverter modules supplied by GE.

Jericho Park was the first solid-state power supply introduced on the Amtrak network. It suffered from some filtering network problems caused by the highly distorted voltage present on the catenary and was ultimately downgraded from its original design capacity of 25 MW to 22 MVA. Amtrak has requested funding to rehabilitate portions of the converter in an ARRA request. During the twelve month period that ended in August 2009, the Jericho Park converter used about 70 GWhr of energy. Note that SEPTA's static converter plant at Wayne Junction is also based on this technology, although it was supplied by a different company.

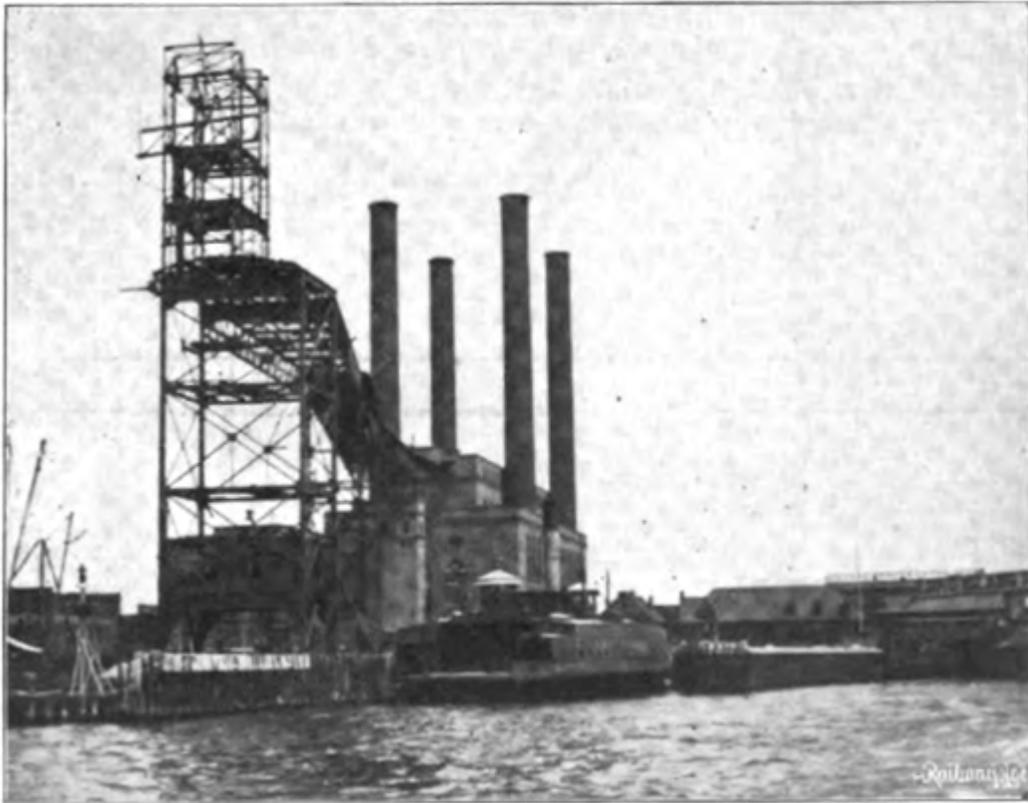
Former converter and power stations



Waterside Power Station in Manhattan, New York, NY

The majority of power sources in the original Pennsylvania Railroad electrification were built prior to 1940. Some have been retired out-right, others have been replaced with co-located static frequency converters, and others remain in service and will be refurbished and operated indefinitely. The following tables lists sources which are no longer in service.

Location	Type (Number)	Capacity (MW)	Dates in Service	Comments
Long Island City	Steam Turbines (5)	18 / 32	1910–1954	Three turbines originally; Five from c. 1910. 32.5 MW total capacity.
Waterside	Steam Turbines (3)	24	c. 1910 - 1978	
Richmond	Motor-Generators (2)	60	1932–1996	Replaced with co-located 180 MW Static Frequency Converter
Schuylkill	Motor Generator	18	1914–1971	
Somerset	Motor Generator	18	c. 1933 - c. 1990s	Power at 13 kV, single phase, 25 Hz, ran from four switches at NE corner of building NE along Trenton Ave and connecting rail line to Frankford Junction, where they ran along Delair Branch to Richmond Sub 31. Also supplied Reading via Wayne Junction. Transmission lines have been removed. 39°59'11"N 75°07'04"W / 39.98639°N 75.11778°W
Benning	Frequency Changer	25	1934–1986	Operating contract expired.
Radnor	Synchronous Condensers	N/A	1917 - c. 1930	Power factor correction and voltage regulation

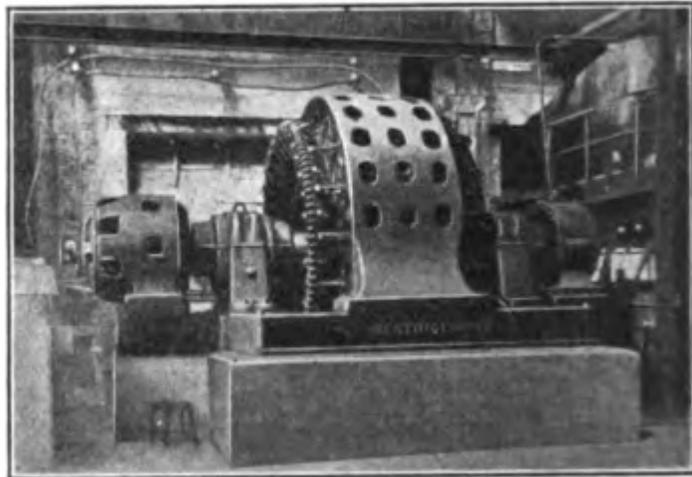


PENNSYLVANIA TERMINAL WORK—POWER HOUSE, LONG ISLAND CITY.

Long Island City Power Plant under construction in 1905



The Pepco Benning Road power station supplied 25 MVA of 25 Hz power via a rotary frequency changer in the hall nearest the Metro tracks from 1935 until 1986.



A picture of one of the 1916 Radnor Synchronous Condensers from *Electrical World*

Declining need for 25 Hz power

During the beginning of the 20th century, 25 Hz power was much more readily available from commercial electrical utilities. The vast majority of urban subway systems used 25 Hz power to supply their lineside rotary converters used to generate the DC voltage supplied to the trains. Since rotary converters work more efficiently with lower frequency supplies, 25 Hz was a common supply frequency for these machines. Rotary converters have been steadily replaced over the past 70 years with, at first, mercury arc rectifiers and more lately solid-state rectifiers. Thus, the need for special frequency power for urban traction has disappeared, along with the financial motivation for utilities to operate generators at these frequencies.

Long Island City Generating Station

Long Island City Power Station in Hunter's Point, NY was built by the Pennsylvania Railroad in 1906 in preparation for the Hudson River Tunnels and opening of Pennsylvania Station in Manhattan. The station consisted of 64 coal-fired boilers and three steam turbine generators with a total capacity of 16 MW. In 1910, the station was expanded with two additional turbine generators for a total capacity of 32.5 MW. Power was transmitted to rotary converters (AC to DC machines) for use in the PRR's original third-rail electrification scheme. Like most DC electric distribution systems of the time (Edison's being the most famous), 25 Hz power was used to drive rotary converters at substations along the line. Some sources state that the station was largely dormant by the 1920s. When AC overhead electrification was extended in the 1930s, Long Island City connected to the 11 kV catenary distribution system. Operation of the station was transferred to Consolidated Edison in 1938, although ConEd began supplying power from the adjacent Waterside Generating Station, most likely due to declining overall demand for 25 Hz power. The station was disused and sold in the mid 1950s.

Waterside Generating Station

Originally constructed by Consolidated Edison to supply power to their DC distribution system in Manhattan, Waterside began supplying power to the PRR's AC system around 1938 when ConEd assumed operation of the Long Island City Station. The single-phase turbine generators were retired in the mid-1970s due to safety concerns. Two transformers were installed to supply catenary power from remaining (three-phase) portions of ConEd's still relatively extensive 25 Hz system. Power flow management problems prevented usage of this source under other than emergency conditions.

Benning Frequency Changer

In 1986, Baltimore Gas and Electric elected to not renew the contract under which it had operated the Benning Power Station frequency changer on behalf of Amtrak. They proposed a static frequency changer which was built at Jericho Park (Bowie, MD) and placed on service in the spring of 1992.

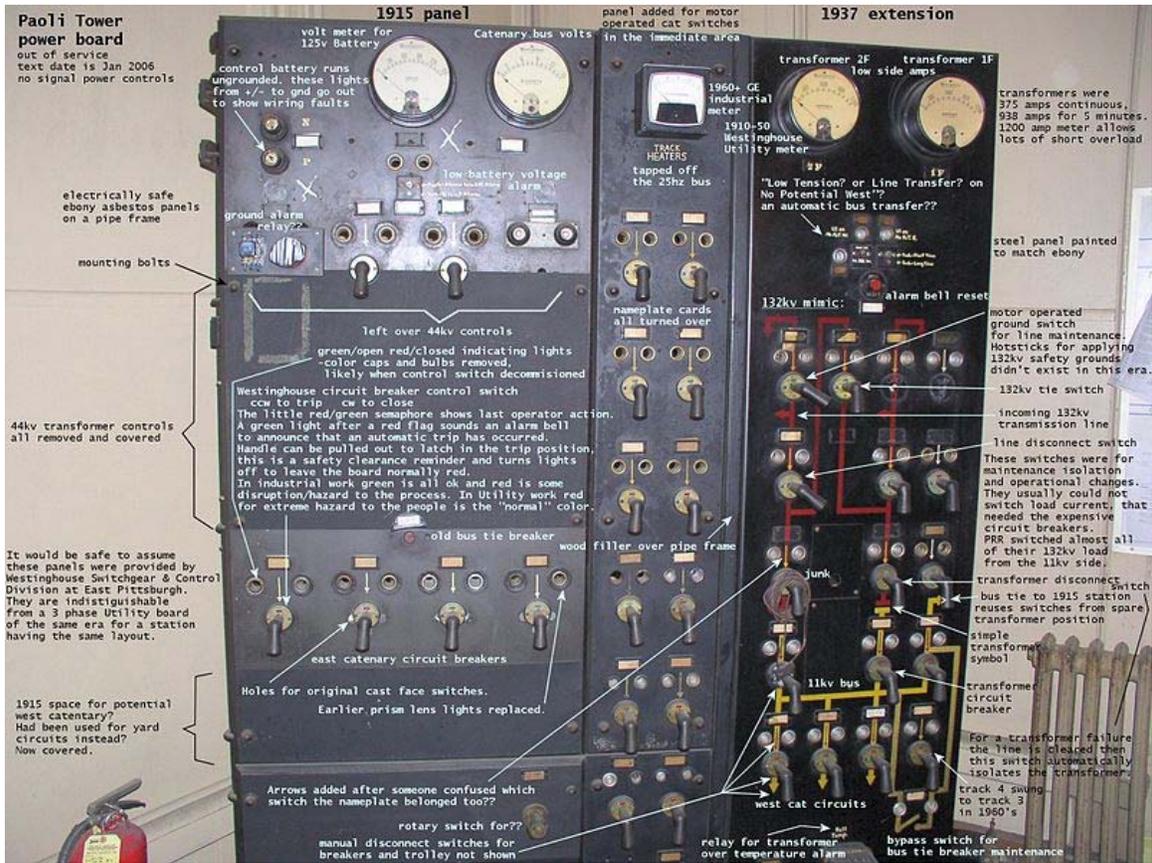
Radnor Synchronous Condenser

Although reactive power has primarily been supplied along with real power by the steam turbines and motor generators of the system, the PRR briefly used two synchronous condensers. Shortly after commissioning the 1915 electrification, the railroad discovered that the 44 kV feeders and large inductive loads on the system were causing significant voltage sag. The supplying electric utility (Philadelphia Electric) also discovered that power factor correction was needed. In 1917, the PRR installed two 11 kV, 4.5 MVA synchronous converters at Radnor, the approximate center point of the system load. This substation was located at the site of water tanks used to supply water to track pans which supplied water to conventional locomotives. At some later time, the converters were shutdown and removed. Dedicated machines for reactive power support have not been used subsequently by either the PRR or Amtrak.

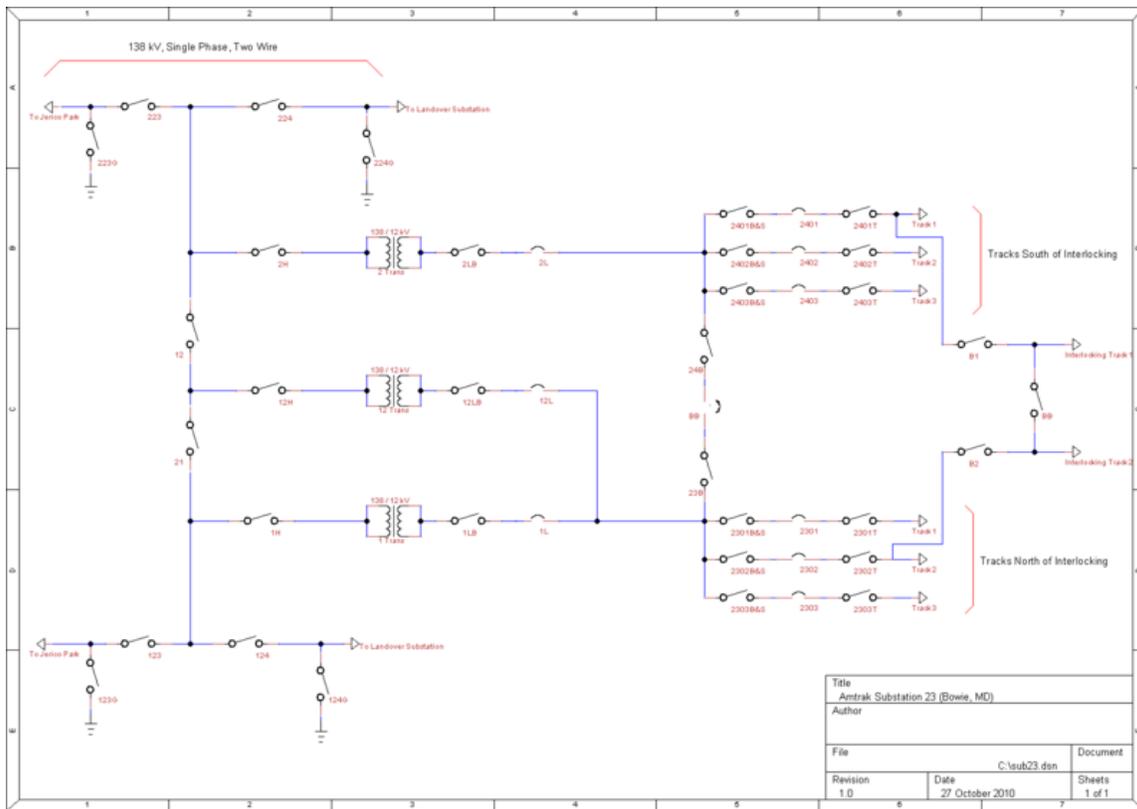
Substations



Frazer substation on the Philadelphia to Harrisburg Main Line



Old substation remote control panel at Paoli interlocking tower



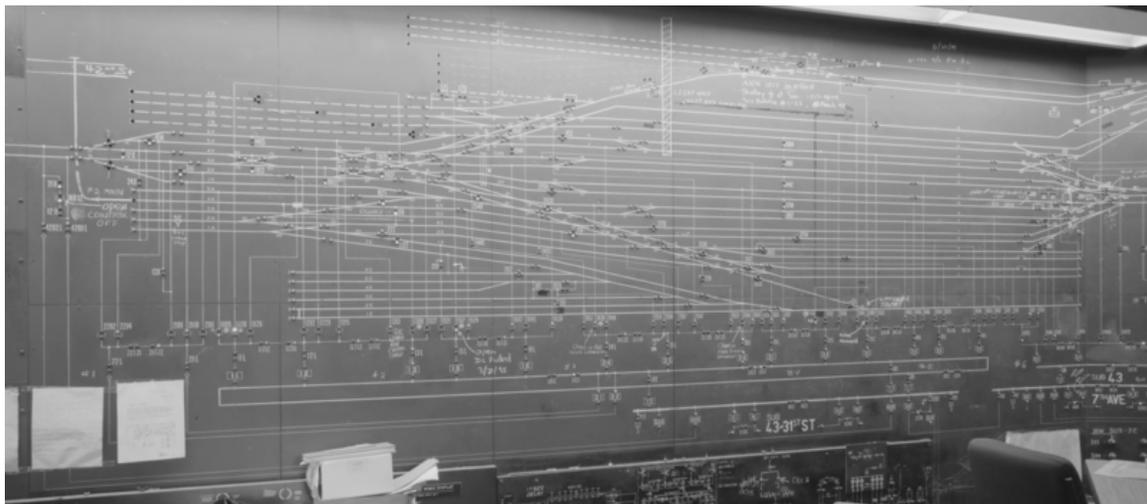
A one-line diagram of the 1930 era substation at Bowie, MD



The large substation at the Safe Harbor dam is one of the minority that steps-up 25 Hz power to 138 kV for long distance transmission.



One-line diagram of Zoo Sub 9, circa 1997, on the Load Dispatcher mimic board in Philadelphia, PA



The Power Dispatcher's view of substation 43 (New York City Penn Station)

The PRR's original 1915 electrification made use of four substations located at Arsenal Bridge, West Philadelphia, Bryn Mawr, and Paoli. The Arsenal Bridge substation stepped-up 13.2 kV, 25 Hz power supplied from PECO's Schuylkill power station on

Christian Street to 44 kV for distribution. The remaining three substations reduced the 44 kV distribution voltage to 11 kV trolley voltage. The substations were operated from adjacent signal towers. They used typical period concrete buildings to house the transformers and switchgear while the line terminals were on the roof. From 1918 onwards outdoor stations were used and when the main line electrification began in 1928 the stations became large open air structures using lattice steel frameworks to mount the 132 kV terminations and switchgear. By 1935 new stations were connected to remote supervision systems allowing power directors to open and close switches and breakers from central offices without having to go through the tower operators.

Today about 55 substations are part of Amtrak's network. Substations are spaced on average 8 miles apart and feed 12 kV catenary circuits in both directions along the line. Thus the catenary is segmented (via section breaks, also called 'sectionalizations' by the PRR) at each substation, and each substation feeds both sides of a catenary's section break. A train traveling between two substations draws power through both transformers.

A typical substation includes two to four 138 / 12 kV transformers, 138 kV air switches that permit isolation of individual transformers, shutdown one of the two 138 kV feeders, or cross-connection from one feeder to another. The output of the transformers is routed to track catenary via 12 kV circuit breakers and air disconnect switches. Cross-connect switches allow one transformer to feed all catenary lines.

The PRR substation architecture was based on a long distance, high speed railway. The substation spacing ensures that any train is never more than 4 or 5 miles from the nearest substation, which minimized voltage drop. One disadvantage to the substation design as originally built by the PRR concerns its lack of 138 kV circuit breakers. Essentially all segmentation of the 138 kV system must be done by hand. This makes rapid isolation of a fault on the 138 kV line very slow. Faults in one part of the line also affect the entire distribution system since it is impossible for the 138 kV transmission to protect or reconfigure itself during a fault condition. High voltage faults generally are cleared by opening converter output breakers, which causes a concurrent loss of the converter. The system does not degrade gracefully under high voltage faults. Rather than isolating, for example, the south 138 kV feeder between Washington and Perryville, the system would require opening converter output breakers at Jericho Park and Safe Harbor. This results in loss of much more of the network than is required to simply isolate the fault.

Former Pennsylvania Railroad Substations				
Station Name	Coordinates	Sta. No.	Yr. Blt.	Comments
Early Philadelphia Lines				
West Philadelphia (44 kV)	39°57'24"N 75°11'08"W / 39.95667°N 75.18556°W	1	1915	Removed c. 1930
Arsenal (44 kV)	39°56'46"N	2	1915	44 kV portions abandoned c.

	75°11'30"W / 39.94611°N 75.19167°W			1930
Bryn Mawr	40°01'17"N 75°18'51"W / 40.02139°N 75.31417°W	3	1915	Switching Station only since c. 1960
Radnor SC	40°02'37"N 75°22'07"W / 40.04361°N 75.36861°W	5	1916	Two 4.5 MVA Synchronous Condensers. Removed c. 1960
Paoli	40°02'36"N 75°29'22"W / 40.04333°N 75.48944°W	4	1915	Station expanded 1938. 44 kV disconnected c. 1960
Greentree Switching	40°02'27"N 75°30'04"W / 40.04083°N 75.50111°W	--	1938	
North Philadelphia	39°59'49"N 75°09'27"W / 39.99694°N 75.1575°W	6	1918	
Allen Lane	40°03'46"N 75°11'55"W / 40.062643°N 75.198652°W	7	1918	Switching Station only since c. 19??
Arsenal (138 kV) Step up	39°56'45"N 75°11'31"W / 39.94583°N 75.19194°W	2A	1928	Step-up capability removed c. 1971
Morton	39°54'26"N 75°19'56"W / 39.9073°N 75.3321°W	01	1928	
Lenni	39°53'38"N 75°26'33"W / 39.89389°N 75.4425°W	02	1928	
Cheyney	39°55'45"N	03	1928	Reduced to switching-only

	75°31'21"W / 39.92915°N 75.5225°W			station then removed outright
West Chester	39°57'26"N 75°35'37"W / 39.95722°N 75.59361°W	04	1928	Reduced to Switching station only then Removed
New York - Philadelphia Main Line				
New Rochelle	40°54'25"N 73°47'24"W / 40.9069°N 73.7900°W	47		Originally 25 Hz; switched to 60 Hz coincident with Metro North. No longer supplies Amtrak power.
Van Nest	40°50'31"N 73°51'48"W / 40.8420°N 73.8633°W	46		Originally 25 Hz; switched to 60 Hz coincident with Metro North. Now the supply substation for Amtrak's 60 Hz system between Gate Interlocking and New Rochelle.
Bowery Bay	40°45'51"N 73°54'19"W / 40.7643°N 73.9054°W	45		Originally 25 Hz; switched to 60 Hz coincident with Metro North. Switching only. Section break between 25 Hz and 60 Hz systems.
Sunnyside	40°44'50"N 73°55'53"W / 40.747341°N 73.931370°W	44	1931	Switching only
Penn Station	40°45'06"N 73°59'52"W / 40.7518°N 73.9979°W	43A, 43B	1931	Switching only; two sections: 31st St., and 7th Ave.
Hackensack (Union City)	40°46'18"N 74°2'38"W / 40.77167°N 74.04389°W	42	1931/32	
Kearney	40°44'41"N 74°07'06"W / 40.74472°N 74.11833°W	41	1931/32	

Waverly	40°41'24"N 74°11'54"W / 40.69°N 74.19833°W	40	1932/33	
Rahway	40°36'01"N 74°16'58"W / 40.60028°N 74.28278°W	39	1932/33	
Metuchen	40°32'21"N 74°21'49"W / 40.53917°N 74.36361°W	38	1932/33	
Millstone	40°28'45"N 74°27'56"W / 40.47917°N 74.46556°W	37	1932/33	
Monmouth	40°22'36"N 74°32'54"W / 40.37667°N 74.54833°W	36	1933	
Princeton	40°19'03"N 74°37'17"W / 40.317459°N 74.62145°W	35	1933	
Morrisville	40°12'04"N 74°46'38"W / 40.20111°N 74.77722°W	34	1930	
Edgely	40°07'07"N 74°50'23"W / 40.11861°N 74.83972°W	33	1930	
Cornwells (Cornwells Heights, PA)	40°04'19"N 74°57'02"W / 40.07194°N 74.95056°W	32	1930	
Richmond FC	39°59'10"N 75°04'26"W / 39.986241°N 75.073939°W	31	1933	

Frankford	40°00'07"N 75°5'52"W / 40.00194°N 75.09778°W	30	1930	Also supplied 44 kV to Allen Lane c. 1930 to c. 19??.
Zoo (138 kV)	39°58'14"N 75°11'57"W / 39.97056°N 75.19917°W	9	1930	Contains 138 kV circuit breakers.
Zoo (44 kV)	39°58'13"N 75°12'00"W / 39.97028°N 75.2°W	8	1930	Removed c. 1960
West Philadelphia Switching	39°57'27"N 75°11'06"W / 39.9575°N 75.185°W	1A	1930	Supplied from Arsenal & Zoo
New Jersey Branches				
Journal Square	40°44'00"N 74°03'53"W / 40.733284°N 74.064806°W	50	1932/33	Catenary disused c. 1980. Remained for a while to supply signal power for PATH and freight on Jersey City Branch.
South Amboy	40°29'25"N 74°17'15"W / 40.49028°N 74.2875°W	48	1932/33	
Helmetta (Outcalt)	40°23'05"N 74°24'16"W / 40.3848°N 74.4044°W	47	1938	Disused c. 1980
Greenville Switching	40°41'12"N 74°05'46"W / 40.68667°N 74.09611°W	--	1935	Supplied from Waverly. Removed c. 1980
Philadelphia - Washington Main Line				
Arsenal	39°56'44"N 75°11'32"W / 39.94556°N 75.19222°W	2A	1928	138 kV step-down
Brill	39°55'45"N	10A	1981	Added for SEPTA Airport

	75°13'26"W / 39.92917°N 75.22389°W			Line
Glenolden	39°53'58"N 75°16'54"W / 39.899444°N 75.281603°W	10	1928	
Lamokin (Chester, PA)	39°50'34"N 75°22'33"W / 39.8429°N 75.3759°W	11	1928	Adjacent to Rotary Converter
Bellevue	39°46'03"N 75°29'02"W / 39.7675°N 75.48389°W	12	1928	
West Yard (Wilmington, DE)	39°43'43"N 75°34'13"W / 39.72861°N 75.57028°W	13	1928	
Davis (Newark, DE)	39°40'21"N 75°44'36"W / 39.6725°N 75.74333°W	14	1935	
Bacon Hill (North East, MD)	39°36'13"N 75°53'37"W / 39.6035°N 75.8937°W	15	1935	
Perryville, MD	39°33'23"N 76°04'36"W / 39.55639°N 76.07667°W	16	1935	Phase Break Indicator. 138 kV circuit breakers segment transmission lines North from West.
Perryman, MD	39°27'45"N 76°12'12"W / 39.462501°N 76.203256°W	17	1935	
Gunpow (Chase, MD)	39°22'40"N 76°21'19"W / 39.377844°N 76.355243°W	18	1935	
North Point	39°18'10"N	19	1935	

	76°31'02"W / 39.30278°N 76.51722°W			
Baltimore	39°18'33"N 76°37'08"W / 39.30916°N 76.618955°W	20	1935	
Loudon Park	39°16'23"N 76°40'37"W / 39.273084°N 76.67689°W	21	1935	
Severn	39°08'20"N 76°41'49"W / 39.13889°N 76.69694°W	22	1935	
Bowie	39°00'21"N 76°46'52"W / 39.00583°N 76.78111°W	23	1935	
Landover	38°55'44"N 76°53'51"W / 38.92889°N 76.8975°W	24	1935	
Ivy City	38°55'6"N 76°58'57"W / 38.91833°N 76.9825°W	2nd 25	2010	
Union Switching	38°54'08"N 77°00'14"W / 38.9021°N 77.0038°W	25A	1935	12 kV switching station supplied from Capitol 1935, then Landover c. 1990, then Ivy City 2010.
Capitol	38°52'50"N 77°0'30"W / 38.88056°N 77.00833°W	Formerly 25	1935	Demolished; footings still visible
Potomac Switching	38°50'24"N 77°03'03"W / 38.84°N 77.05083°W	26	1935	Supplied from Capitol. Disused c. 1980 and demolished c. 2000, New Utility Sub built.
Trenton Cutoff Freight Route				

Langhorne	40°10'30"N 74°58'08"W / 40.175°N 74.96889°W	61	1938	Removed
Horsham	40°08'55"N 75°08'53"W / 40.14861°N 75.14806°W	62	1938	Removed
Earnest	40°06'24"N 75°19'34"W / 40.10667°N 75.32611°W	63	1930	Supplied PRR Schuylkill Branch as well as Trenton Cutoff. Removed.
Philadelphia - Harrisburg Main Line				
Frazer, PA	40°01'52"N 75°34'27"W / 40.03111°N 75.57417°W	64	1938	
Thorndale, PA	39°59'48"N 75°44'3"W / 39.99667°N 75.73417°W	65	1938	Phase Break Indicators Holds one of the three sets of 138 kV circuit breakers in the system.
Parkesburg, PA	39°57'37"N 75°54'58"W / 39.96028°N 75.91611°W	66	1938	
Kinzer	39°59'55"N 76°4'8"W / 39.99861°N 76.06889°W	67	1938	
Witmer (Smoketown, PA)	40°2'35"N 76°12'51"W / 40.04306°N 76.21417°W	68	1938	
Dillersville Switching	40°3'25"N 76°19'16"W / 40.05694°N 76.32111°W	--	1938	Supplied Columbia Branch from Mainline catenary (12 kV). Disused c. 1980?
Landisville, PA	40°5'23"N 76°23'0"W / 40.08972°N	69	1938	

	76.383333°W			
Rheems, PA	40°07'51"N 76°34'01"W / 40.130704°N 76.566996°W	70	1938	
Royalton, PA	40°11'02"N 76°43'33"W / 40.18389°N 76.72583°W	71	1938	
Harrisburg, PA	40°15'17"N 76°52'25"W / 40.25472°N 76.87361°W	72	1938	
Low-grade Freight Routes (now only used for transmission lines)				
Bart	39°55'03"N 76°04'40"W / 39.9175°N 76.07778°W	51	1938	Removed
Providence	39°55'42"N 76°13'51"W / 39.92833°N 76.23083°W	52	1938	Removed
Conowingo	39°40'7"N 76°10'15"W / 39.66861°N 76.17083°W	53	1938	Removed c. 1981. Separate from Conowingo generating station, never connected.
Fishing Creek	39°47'23"N 76°15'46"W / 39.78972°N 76.26278°W	54	1938	Removed. Separate from Holtwood generating station, never connected.
Safe Harbor (PRR) Conestoga Sub (SHWP)	39°55'36"N 76°23'6"W / 39.92667°N 76.385°W	55	1934	Step-up station for Safe Harbor supply. Catenary facilities added 1938 then disused c. 1980.
Columbia	40°01'58"N 76°30'31"W / 40.03278°N 76.50861°W	56	1938	Removed - site paved over
Rowenna (Marietta, PA)	40°03'43"N 76°36'43"W /	57	1938	Abandoned; concrete footings visible. Single transmission

	40.06194°N 76.61194°W			line between Safe Harbor Sub 55 and Royalton Sub 71 runs past site, but no longer terminates.
Goldsboro	40°07'18"N 76°43'54"W / 40.1217°N 76.7317°W	58	1938	Removed
Enola, PA	40°16'40"N 76°55'13"W / 40.27778°N 76.92028°W	59, 73	1938	Abandoned

Transmission lines



The Load Dispatcher's Mimic Board at 30th Street Station in Philadelphia, PA, circa 1996. The entire 138 kV transmission system is represented on this panel.



The four 138 kV circuits from Safe Harbor to Perryville are utility-owned.



Catenary support with 6.9 kV, 100 Hz transformer for signal power



Catenary supports near Odenton, MD. Three-conductor 60 Hz utility lines enter from the left and are carried in either direction along the line. The remainder of the high voltages lines are 25 Hz.

All transmission lines within the 25 Hz system are two-wire, single-phase, 138 kV. The center tap of each 138 kV/12 kV transformer is connected to ground, thus the two transmission lines are tied to ± 69 kV with respect to ground and 138 kV relative to each other.

Generally two separate two-wire circuits travel along the rail line between substations. One circuit is mounted at the top of the catenary poles on one side of the track; the second circuit runs along the other side.

The arrangement of catenary supports and transmission wires gives the overhead structure along former Pennsylvania Railroad lines its characteristic 80-foot-tall 'H'-shaped structure. They are much taller than the overhead electrification structures on other electrified American railroads due to the 138 kV transmission lines. Catenary towers and transmission lines along former NYC lines and Amtrak's New England division are much shorter, and are recognizable due to different design and construction.

While a majority of the transmission infrastructure is located directly above the rail lines on the same structure that supports the catenary system, some lines are either located above lines that have been de-electrified or abandoned or in a few cases on completely independent rights of way.

The following is a list of all major segments of the 25 Hz 138 kV transmission infrastructure listing substations (SS or Sub) or high-tension switching stations (HT Sw'g) as termini. For clarity, positions of substations are not repeated in this table. A listing of the high-tension switching stations follows.

Terminus	Terminus	# 138 kV circuits	Right of way	Notes
Union City Sub 42	Cornwell Heights Sub 32	4	Main Line Philadelphia to New York	
Kearney Sub 41	Journal Square Sub 50	2	Jersey City Branch	Out of service, line used by PATH.
Rahway Sub 39	South Amboy 48	2	New York and Long Branch	Used for NJTRO NJCL power
Monmouth Jct 36	South Amboy 48	1	Jamesburg Branch	Via Helmetta Sub 47; Out of service
Morrisville Sub 34	Earnest HT Sw'g	1	Trenton Cutoff	Out of service and almost completely removed. Some portions near Earnest Junction HT Switching Station remain.
Cornwell Heights Sub 32	Richmond Sub 31	2	Industrial RoW	Splits from Main Line south of Holmesburg and follows alignment along Delaware River.
Cornwell Heights Sub 32	Richmond Sub 31	2	Along Main Line to Frankford Junction, then Delair Branch	

Frankford Sub 30	Richmond Sub 31	2	Delair Branch	De-electrified and catenary removed.
Cornwell Heights Sub 32	Frankford Sub 30	1	Along Main Line ROW Phil to NY	
Franford Sub 30	Ivy City Sub 25	2	Main Line from north of Phil to Washington	
Zoo Sub 9	Earnest HT Sw'g	2	Schuylkill Branch	Tracks removed past Cynwyd Station.
Arsenal Sub 2A	Lenni Sub 02	1	West Chester Branch	Power for SEPTA Media/Elwyn Line line.
Lamokin Sub 11	Lenni Sub 02	1 (2)	Private RoW	Feeds West end of SEPTA Media/Elwyn Line line. Built as two (c. 1935) circuits.
Earnest HT Sw'g	Frazer Sub 64	2	Runs along Trenton Cutoff	Powers Main Line via Frazer Sub
Paoli Sub 4	Landisville Sub 69	2	Main Line Philadelphia to Harrisburg	Frazer SS to Paoli SS dead end line.
Parkesburg Sub 66	Safe Harbor Sub 55	2	Atglen and Susquehanna	Rails removed. Replacement of transmission lines in progress.
Landisville Sub 69	Royalton Sub 71	1	Main Line Philadelphia to Harrisburg	
Safe Harbor Sub 55	Rowenna Sub 57	2	Enola Branch	After Rowenna Sub decommissioned, one circuit logically split to run direct to Royalton Sub.
Rowenna Sub 57	Royalton Sub 71	1	Royalton Branch	Line now continuous from Safe Harbor to Royalton.
Rowenna Sub 57	Lemo HT Sw'g	1	Enola Branch	Line now continuous from Safe Harbor. Out of Service, wires cut at Columbia.
Lemo HT Sw'g	Enola Sub 59	2	Enola Branch	Served Enola Yard, out of service.
Royalton Sub 71	Harrisburg Sub 72	2	Main Line Philadelphia to Harrisburg	
Lemo HT Sw'g	Harrisburg Sub 72	2	Runs across Susquehanna River on	Out of service

			Cumberland Valley RR Bridge	
Safe Harbor Sub 55	Perryville Sub 16	4	Private RoW	Utility-style transmission towers. P5 and P6 lines were tapped south to serve Fishing Creek Sub 54 and Conowingo Sub 53. These taps were removed concurrently with their associated substations.
Landover Sub 24	Ivy City Sub 25	2	Main Line Philadelphia to Washington	Portion from Landover (24) to Ivy City (25) is under construction as of 2010.
Landover Sub 24	Capitol (Former Sub 25)	2	Landover Line	Former route to Capitol Sub 25. Removed.

High-tension switching stations - located outside substations, i.e. in the field

Name	Location	Designation	Comments
Metuchen HT Sw'g	 40°32'56"N 74°20'47"W / 40.548998°N 74.346318°W	138M through 438M	Disconnects each of main line circuits (4) from two spurs that runs via private ROW to Metuchen Frequency Changer.
Lemo HT Sw'g	 40°14'54"N 76°53'19"W / 40.248454°N 76.888483°W		West of Susquehanna River near Harrisburg; disconnects circuits running between Enola, Harrisburg, and Rowenna substations
Earnest HT Sw'g	 40°6'15"N 75°19'15"W / 40.10417°N 75.32083°W	163,263 (Trenton Cutoff E); 164, 264 (Trenton Cutoff W); 1ED,2ED (to Zoo)	Located at junction between Trenton Cutoff and Schuylkill Branch. Manually operated disconnect switches, these are now redundant with the abandonment of Trenton Cutoff transmission line and removal of Earnest Sub 63.
Frankford HT Sw'g	 40°00'05"N 75°05'39"W / 40.0013°N 75.0943°W	22	Disconnects the feeder (42H) from Richmond from transmission line running between Frankford (22HT) and Cornwells (230E) in event of damage to catenary supports on Delair Branch. Allow limited feeding between Cornwells and

Frankford to bypass Richmond.

Ongoing construction



Ivy City Substation 25 under construction in 2010

Amtrak's capital improvement program which began in 2003 has continued to the present day and has since 2009 received added support from economic stimulus funding sources (ARRA).

Major improvements in 2009 included:

- Replacement of the final 138 kV cable in the Baltimore tunnel.
- Renewal of 33 miles of catenary.
- Replacement of 14 traction power transformers (138/12 kV).

- Installation of twenty 12 kV traction circuit breakers.
- Commencing Ivy City substation construction.
- Catenary renewal along Hell Gate line.

Planned 2010 projects:

- Completion of the Ivy City substation and 138 kV transmission line.
- Replace five traction power transformers.
- Renew 40 miles of catenary in Maryland.
- Renew 18 miles of catenary in Pennsylvania.
- Continue catenary renewal along Hell Gate line in New York.
- Replace the 138 kV transmission line between Safe Harbor (Conestoga Substation) and Atglen, PA (just west of Parkesburg, PA).
- Upgrade the Metuchen frequency converter.

Conestoga to Atglen transmission line

Amtrak will replace the transmission lines that tie the Conestoga Substation to Parkesburg via Atglen. These lines were originally installed over the Atglen and Susquehanna Branch. The line was subsequently abandoned by Conrail and the tracks removed, but Amtrak has retained an easement to operate its 138 kV transmission lines over the roadbed. Towers and conductors over 24 miles of the route are to be replaced. Work is scheduled to be complete by September 2011. The scope of work includes:

- Original Portal and Cantelever catenary support (~450 structures) removal.
- Installation of 257 new monopole structures.
- 96 miles of ACSR transmission conductor installation (two circuits, two wires each).
- 24 miles of fiberoptic ground line.

Funding for this project is included under the ARRA program. The specified number of poles will result in a spacing of approximately 500 feet per tower. This is approximately twice as far apart the 1930s structures were placed; 270 ft was the average span length.

Ivy City Substation

The Ivy City substation is the first extension of 138 kV transmission line since Safe Harbor Dam was constructed in 1938. In the original PRR electrification scheme, the 138 kV transmission lines went south from Landover to the Capital South substation rather than following the line through Ivy City to the northern approach to Union Station. The two tracks between Landover and Union Station had no high voltage transmission line above them; Union Station catenary was fed at 12 kV from the Landover and Capitol substations (the latter via the capitol tunnels). When the Capitol substation was abandoned, coincident with the de-electrification of the track between Landover and Potomac Yard, Union Station and its approaches became a single-end fed section of

track. This combined with rising traffic levels resulted in low voltage conditions on the approaches to Union Station and decreased system reliability.

The Ivy City project will construct a two transformer (4.5 MVA each), 138/12 kV substation on the northeast edge of the Ivy City yard complex and 5.2 miles of 138 kV transmission line. Since the original catenary supports along this section of track are only high enough for the 12 kV catenary wire, the 138 kV lines are being installed on new steel monopod poles installed along the right-of-way. Except for the fact that the new poles will only carry four conductors rather than the typical six for a utility line, the new line will appear as a typical medium voltage power line rather than the typical PRR style H-shaped structure.

Zoo to Paoli Transmission Line

In late 2010, Amtrak solicited design services for new transmission lines between Paoli and Zoo Substations. Primary objectives of this expansion include improving reliability of transmission between Safe Harbor and Philadelphia, and reducing maintenance costs. This project dovetails with the Safe Harbor to Atglen transmission line replacement, which is already underway.

If built the Zoo to Paoli transmission line will replace the current supply scheme which uses 138 kV lines which run circuitously along the SEPTA Cynwyd Line, Schuylkill Secondary and Trenton Cut-off between the Zoo and Frazer substations. The new routing will reduce maintenance costs, as Amtrak must now maintain vegetation along right-of-way which it neither owns or uses for revenue service. The conceptual line will run from the existing Paoli substation to the junction of the Harrisburg to Philadelphia main line and SEPTA's Cynwyd line at the 52nd street bridge. 39°58'43"N 75°13'41"W / 39.9785°N 75.2280°W.

The new lines would connect to the existing 1ED and 2ED circuits, which will be abandoned between the junction and their current terminus at the Earnest Junction HT Switch. The plan also includes construction of a 138/12 kV substation at Bryn Mawr to replace the existing switching station. The existing 1905 era catenary structures are planned for replacement, and new transmission supports will be compatible with catenary replacement.

However a similar plan by the Pennsylvania Railroad was defeated by opposition from the wealthy Main Line communities due to the impact of tall transmission lines on the local scenery.