Handbook of

Electric Power

Transmission and Distribution Systems

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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 CO_2 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.

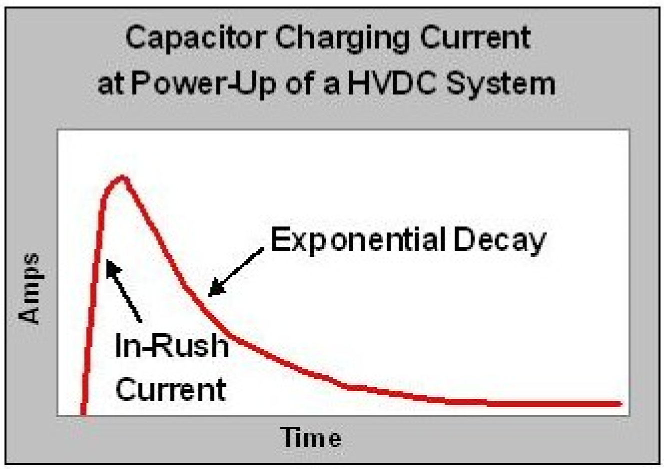
General economics developments

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 µF Powerline Capacitor	**Peak In-rush Current at Power-Up of a 15 A Feed**			
	1 ms	10 ms	100 ms	1 s
***v* = 28 V**	310 A	31 A	3.1 A	0.31 A
***v* = 610 V**	6710 A	671A	67A	7A

Color Key:

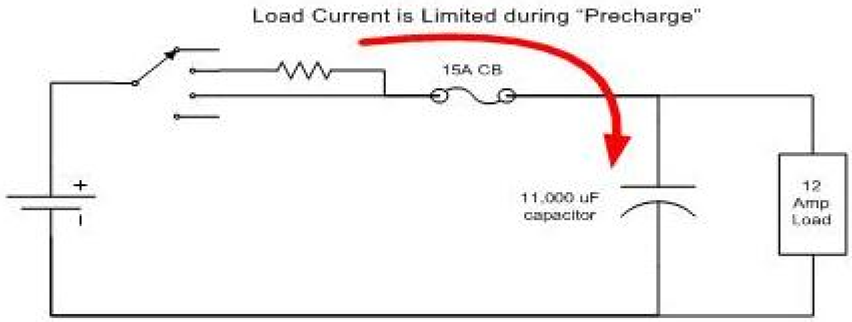
= High Risk of Tripping the Breaker

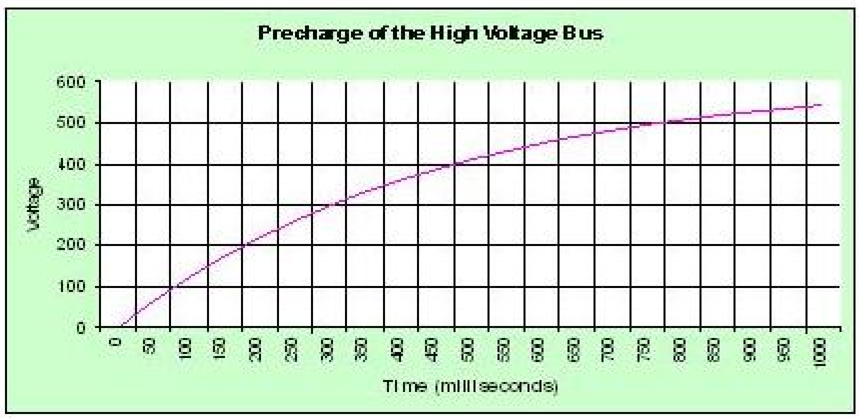
= Careful Selecting the Breaker Rating

= Good

Consider an example where a high voltage source powers up a typical electronics control unit which has an internal power supply with 11000 µF 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 EPAct 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 EPAct 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.

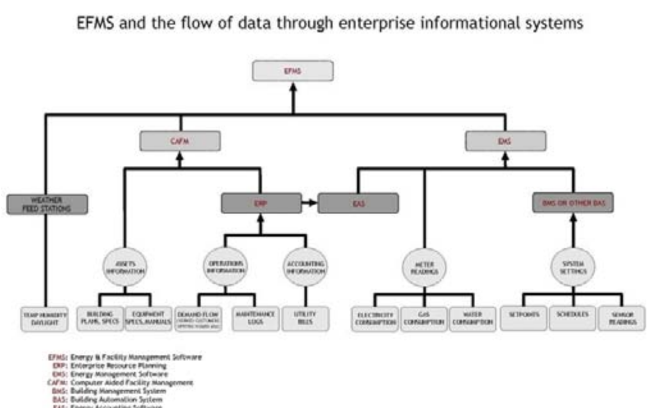
Chapter-4

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 or 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 / Dashboad 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 syncronization 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

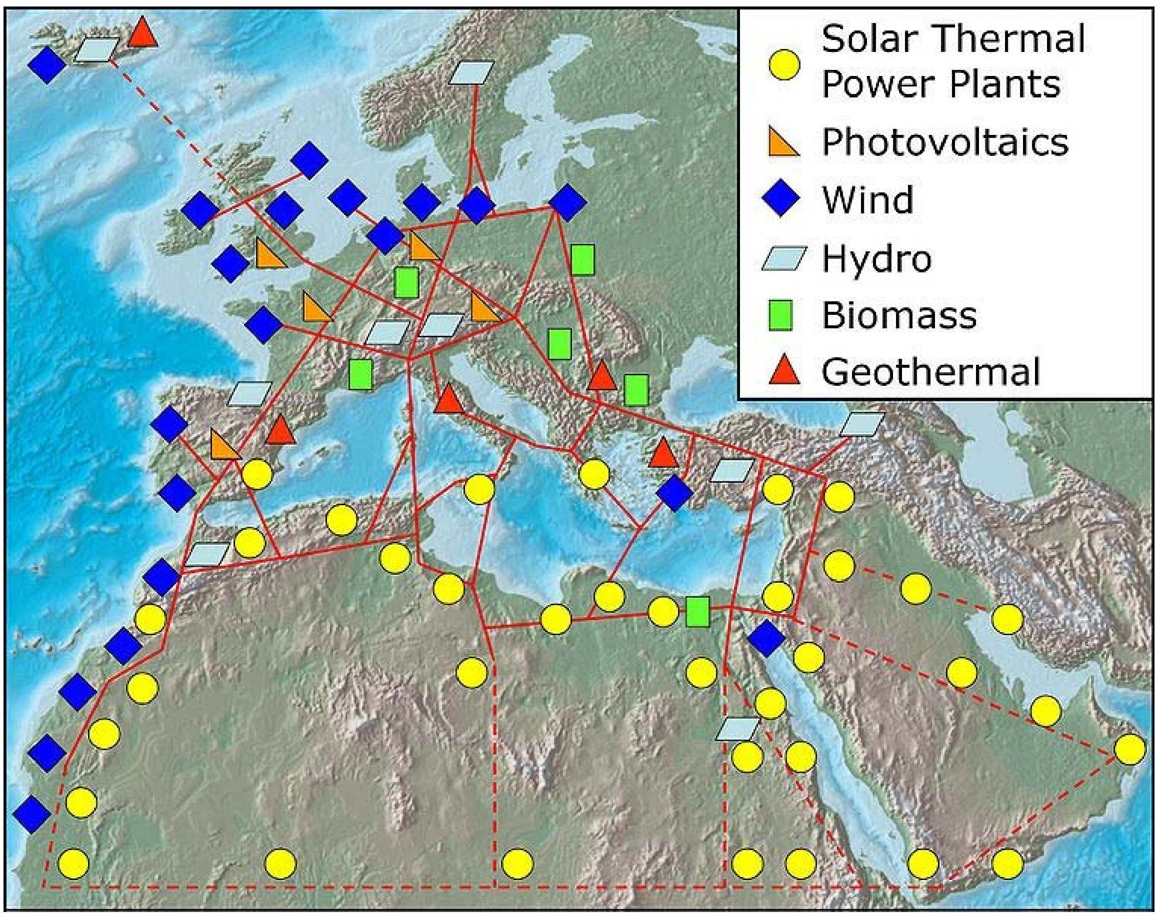
Distribution lines of 33 kV, 22 kV, 11 kv, 6.6 kV and 415/240 volt in the Malaysia distribution network connect to the National Grid via transmission substations where voltages are stepped down by transformers.

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

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.

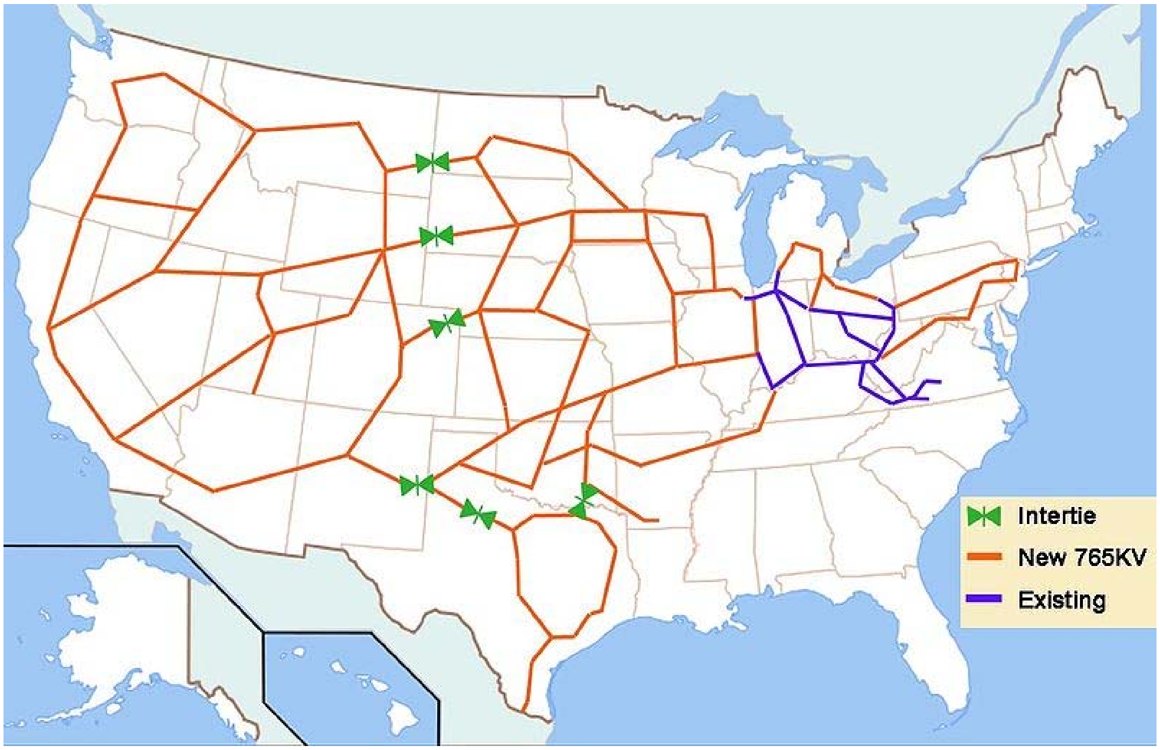
Mega grid

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 Czisch, 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.

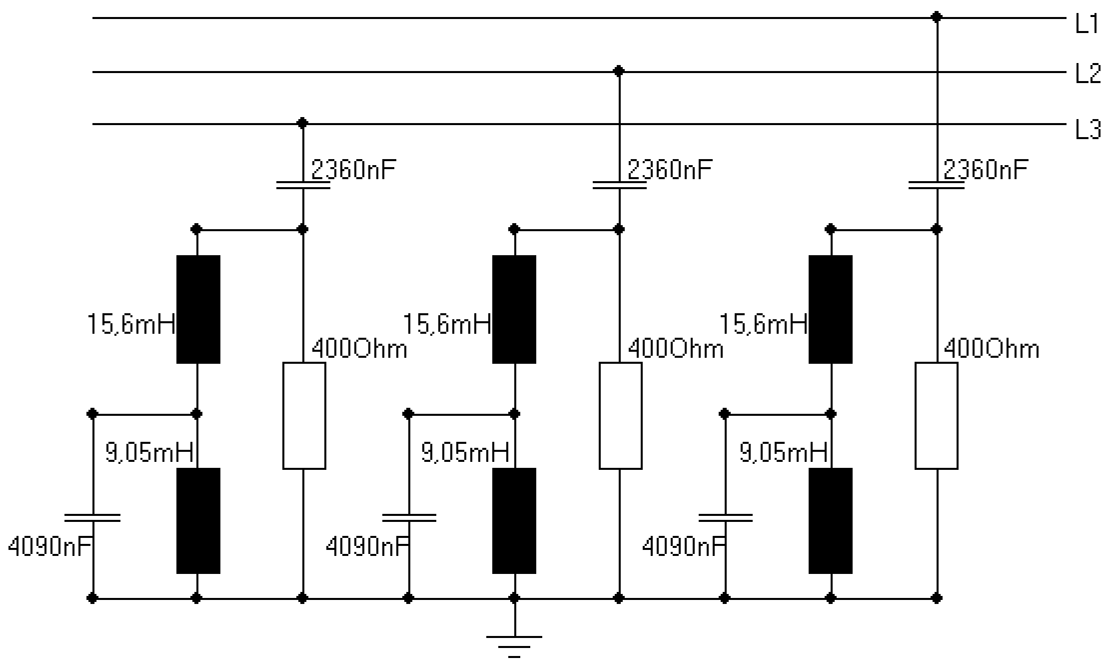
Competition

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.

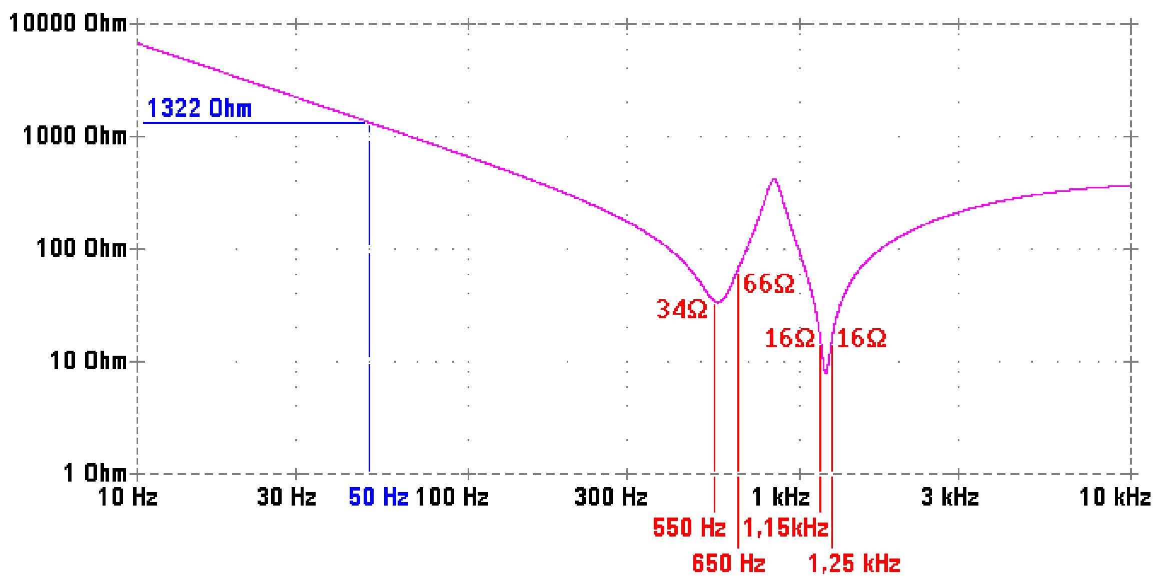
Chapter-6

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

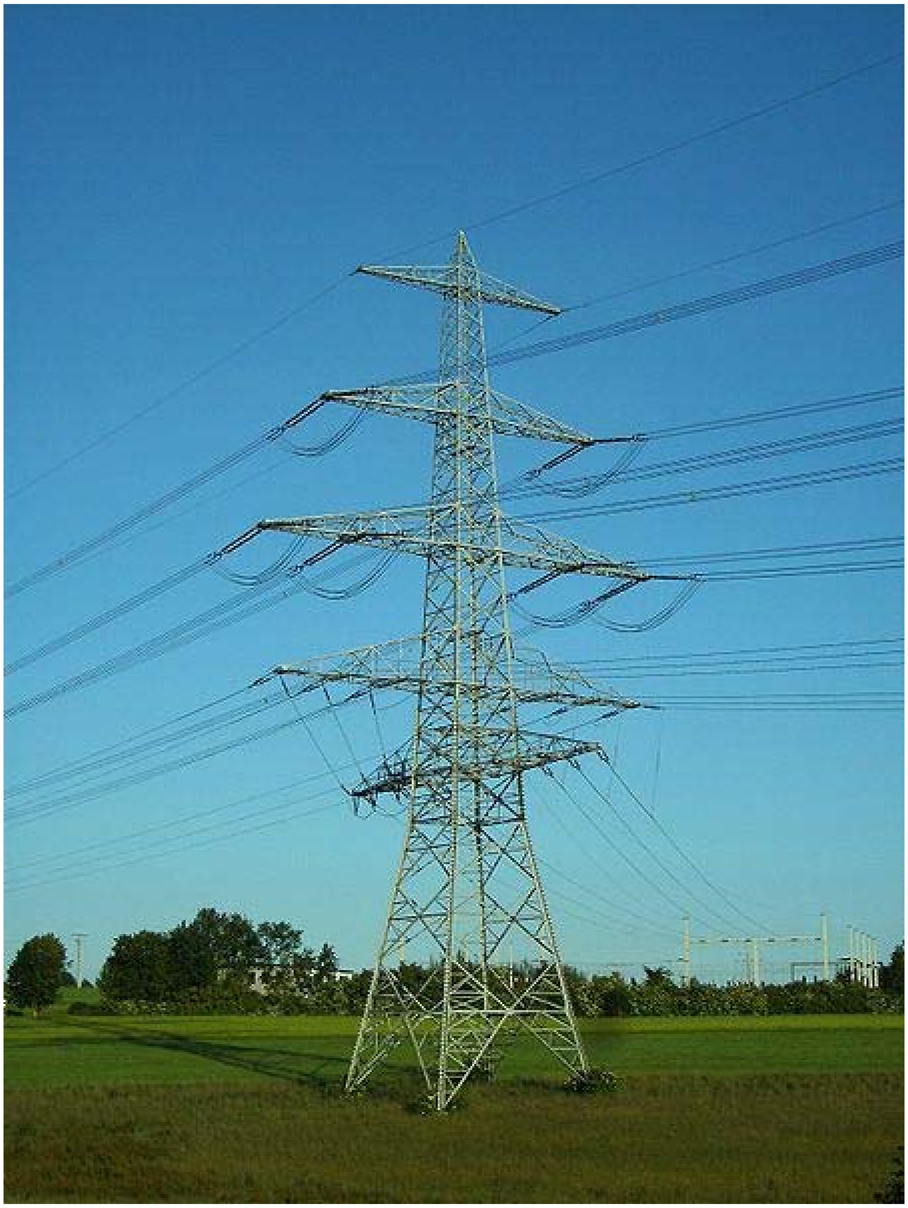
Close view at valve hall with empty transformer bays. Also the smoothing reactors are gone

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

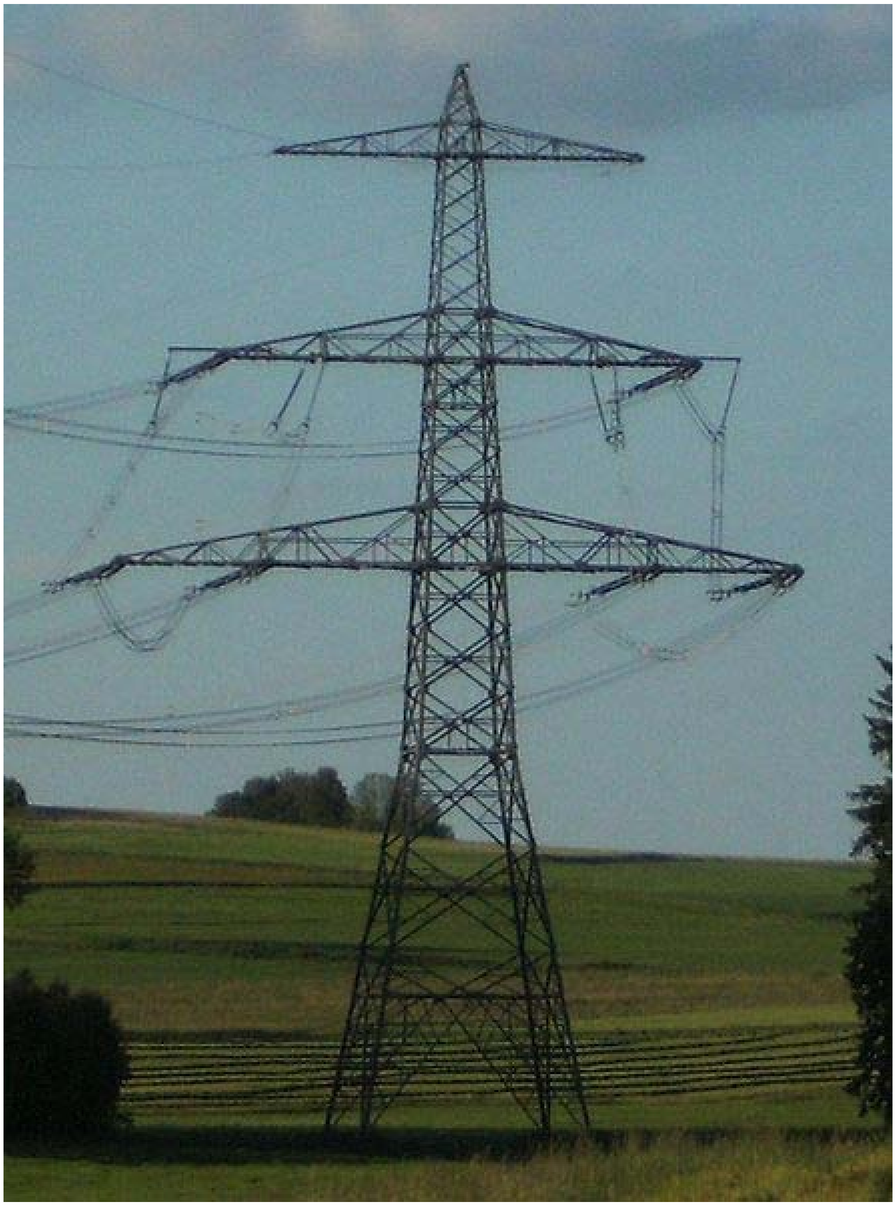
Power transmission line to the Czech Republic

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

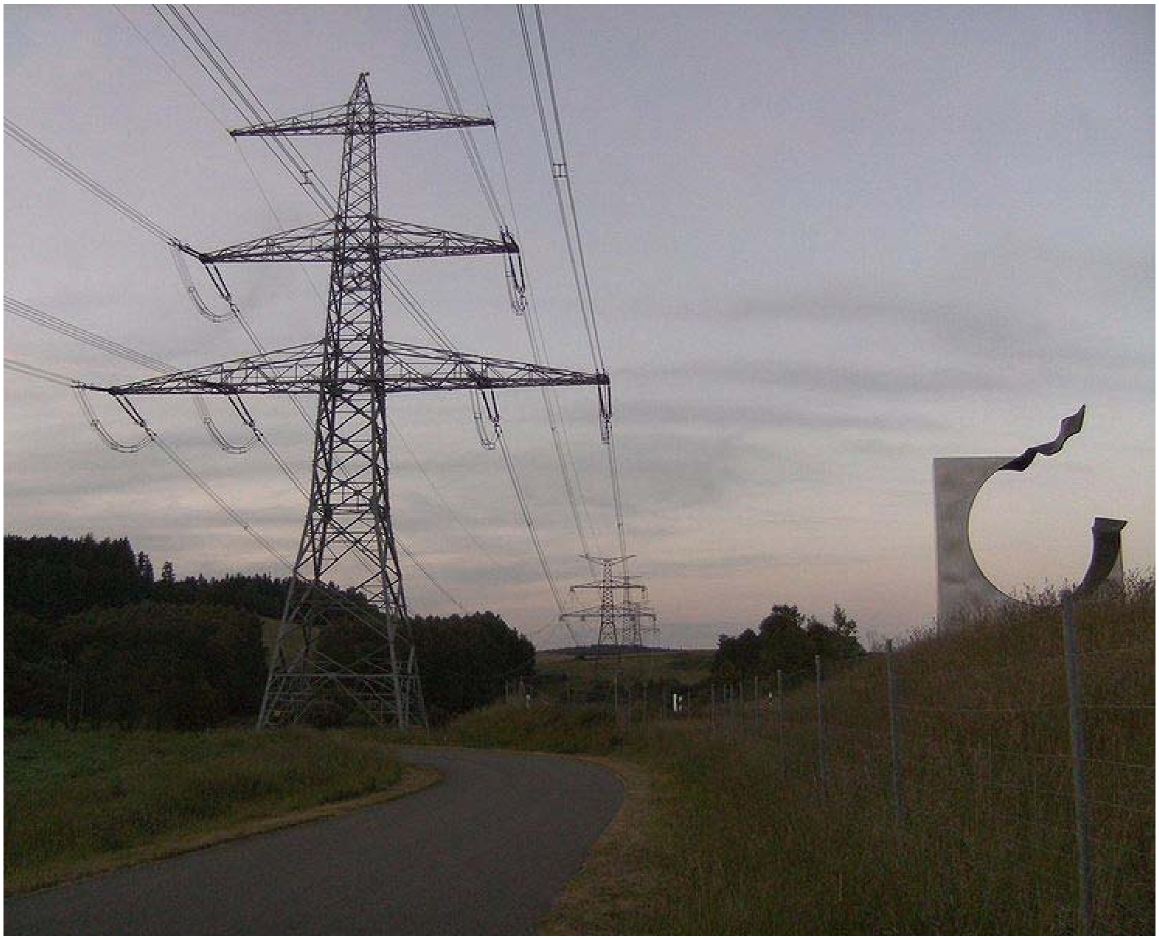


Branch pylon Vohenstrauss

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°37'28" N and 12°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-7

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

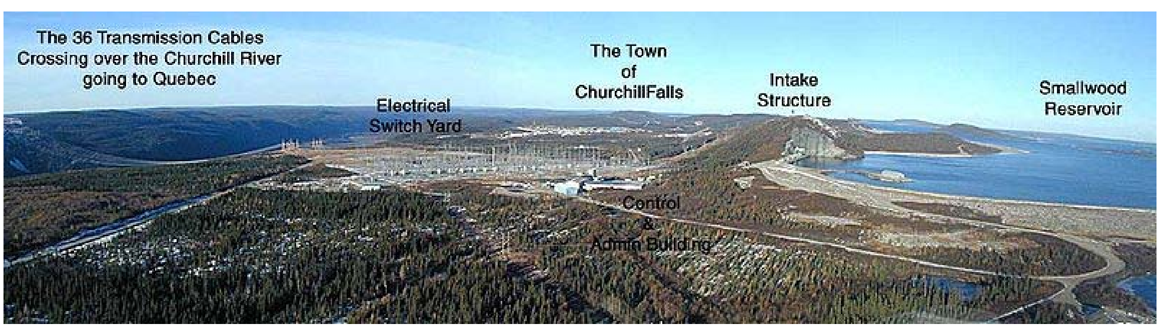
1973 to 1985 and the second phase lasted from 1985 to present time. In all, the nine hydroelectric dams there produce over 16,500 MW of electric power, with the Robert-Bourassa or La Grande-2 station generating over 5,600 MW alone. In total, the project cost over C$20 billion to construct.

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 crosses 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.

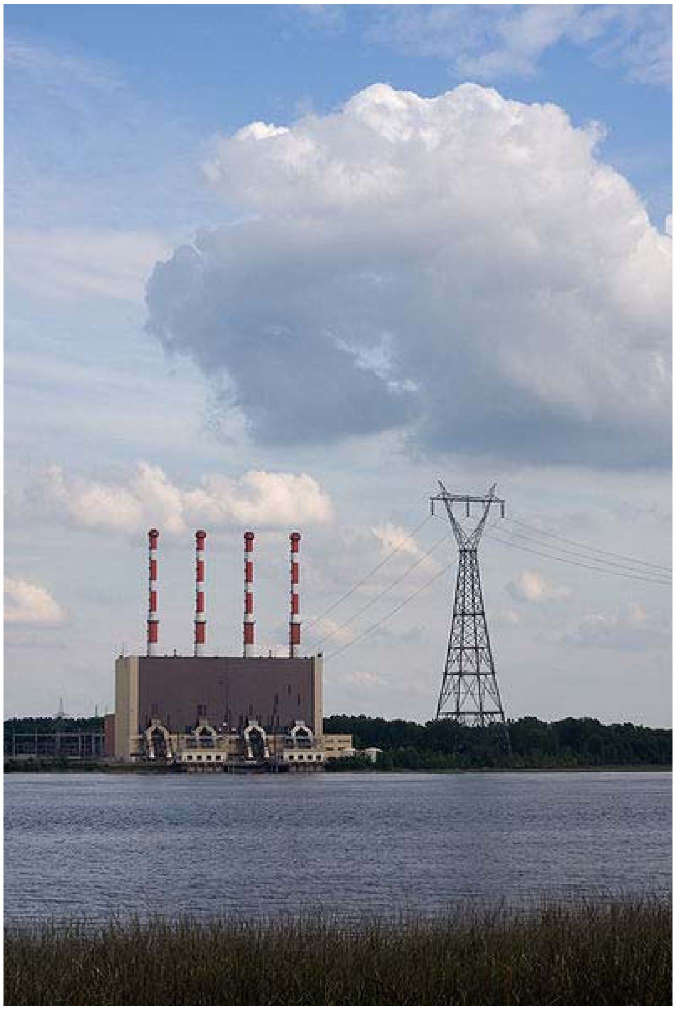
During the construction of the James Bay transmission system, the cross-rope suspension tower was invented. This type of tower features two guyed-tower legs similar to the V-guyed tower, but the two legs don't converge at the tower base. In the case of the cross-rope suspension tower, the tower legs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

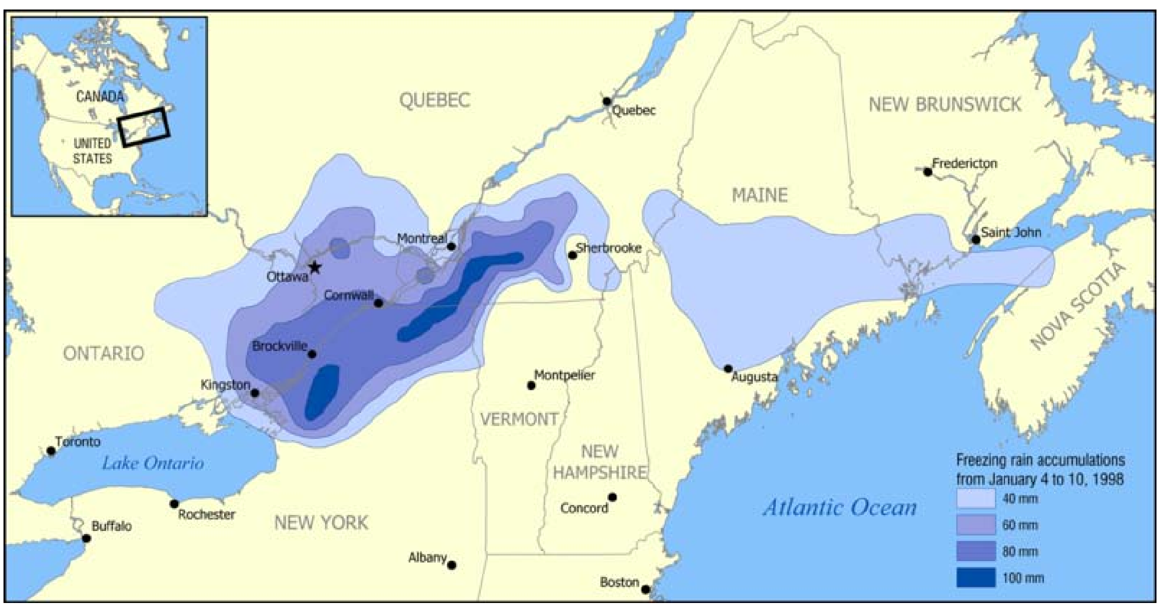
In spite of the transmission system's reputation and the fact Quebec escaped unscathed from the Northeast Blackout of 2003, the system has experienced damage and service interruptions from severe storms in the past. Examples include the 1982 and 1988 Quebec blackouts prior to the large 1989 and 1998 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-8

Electric Power Distribution

Electricity distribution is the final stage in the delivery (before retail) of electricity to end users. A distribution system's network carries electricity from the transmission system and delivers it to consumers. Typically, the network would include medium-voltage (less than 50 kV) power lines, electrical substations and pole-mounted transformers, low-voltage (less than 1 kV) distribution wiring and sometimes electricity meters.

Modern distribution systems

Electric distribution substations transform power from transmission voltage to the lower voltage used for local distribution to homes and businesses

The modern distribution system begins as the primary circuit leaves the sub-station and ends as the secondary service enters the customer's meter socket. A variety of methods, materials, and equipment are used among the various utility companies, but the end result is similar. First, the energy leaves the sub-station in a primary circuit, usually with all three phases.

The actual attachment to a building varies in different parts of the world.

Most areas provide three phase industrial service. There is no substitute for three-phase service to run heavy industrial equipment. A ground is normally provided, connected to conductive cases and other safety equipment, to keep current away from equipment and people. Distribution voltages vary depending on customer need, equipment and availability. Delivered voltage is usually constructed using stock transformers, and either the voltage difference between phase and neutral or the voltage difference from phase to phase.

In many areas, "delta" three phase service is common. Delta service has no distributed neutral wire and is therefore less expensive. The three coils in the generator rotor are in series, in a loop, with the connections made at the three joints between the coils. Ground is provided as a low resistance earth ground, sometimes attached to a synthetic ground made by a transformer in a substation. High frequency noise (like that made by arc furnaces) can sometimes cause transients on a synthetic ground.

In North America and Latin America, three phase service is often a Y (wye) in which the neutral is directly connected to the center of the generator rotor. Wye service resists transients better than delta, since the distributed neutral provides a low-resistance metallic return to the generator. Wye service is recognizable when a grid has four wires, one of which is lightly insulated.

Many areas in the world use single phase 220 V or 230 V residential and light industrial service. In this system, a high voltage distribution network supplies a few substations per city, and the 230V power from each substation is directly distributed. A hot wire and neutral are connected to the building from one phase of three phase service.

In the U.S. and parts of Canada and Latin America, split phase service is the most common. Split phase provides both 120 V and 240 V service with only three wires. Split phase has substations that provide intermediate voltage. The house voltages are provided by neighborhood transformers that lower the voltage of a phase of the distributed three-phase. The neutral is directly connected to the three-phase neutral. Socket voltages are only 120 V, but 240 V is available for heavy appliances because the two two halves of a phase oppose each other.

Japan has a large number of small industrial manufacturers, and therefore supplies standard low voltage three phase service in many suburbs. Also, Japan normally supplies residential service as two phases of a three phase service, with a neutral.

Rural services normally try to minimize the number of poles and wires. Single-wire earth return (SWER) is the least expensive, with one wire. It uses high voltages, which in turn permit use of galvanized steel wire. The strong steel wire permits inexpensive wide pole spacings. Other areas use high voltage split-phase or three phase service at higher cost.

The least expensive network has the fewest transformers, poles and wires. Some experts say that this is three-phase delta for industrial, SWER for rural service, and 230 V single phase for residential and light industrial. The system of three-phase Wye feeding split phase is flexible and somewhat more resistant to geomagnetic faults, but more expensive.

Two frequencies are in wide use. Using 60 Hz permits slightly smaller transformers and is usually associated with 120 V wall sockets. Outside North America 50 Hz is more common and is associated with 230 V wall sockets. Large electrical networks tightly control the line frequencies. The short term accuracy is normally better than 0.1 Hz. The long term accuracy is controlled by making up "lost" cycles so that electric clocks maintain correct time.

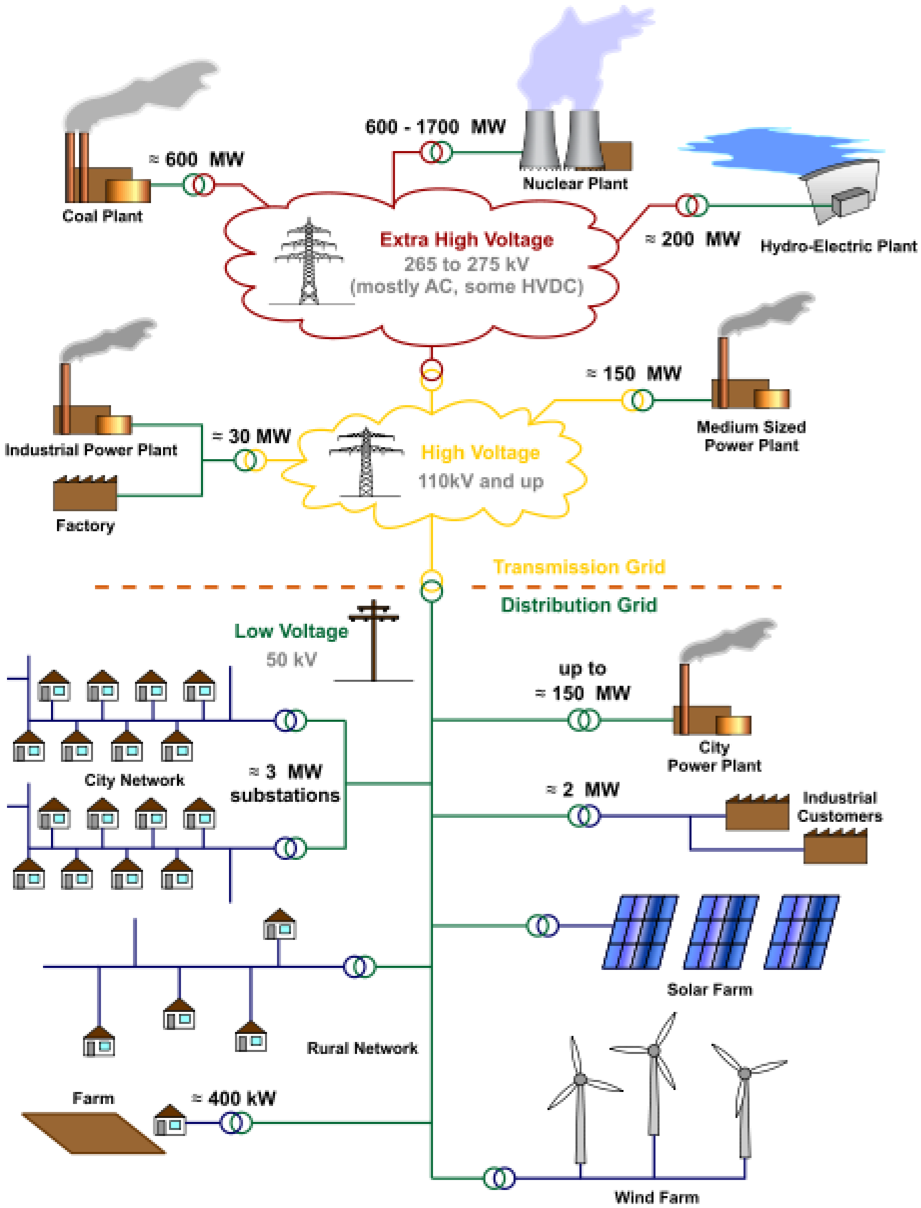
Electricity meters use different equations for each distribution system.

History

In the early days of electricity distribution, direct current (DC) generators were connected to loads at the same voltage. The generation, transmission and loads had to be of the same voltage because there was no way of changing DC voltage levels, other than inefficient motor-generator sets. Low DC voltages were used (on the order of 100 volts) since that was a practical voltage for incandescent lamps, which were the primary electrical load. Low voltage also required less insulation for safe distribution within buildings.

The losses in a cable are proportional to the square of the current, the length of the cable, and the resistivity of the material, and are inversely proportional to cross-sectional area. Early transmission networks used copper, which is one of the best economically feasible conductors for this application. To reduce the current and copper required for a given quantity of power transmitted would require a higher transmission voltage, but no efficient method existed to change the voltage of DC power circuits. To keep losses to an economically practical level the Edison DC system needed thick cables and local generators. Early DC generating plants needed to be within about 1.5 miles (2.4 km) of the farthest customer to avoid excessively large and expensive conductors.

Introduction of alternating current



General layout of electricity networks

The adoption of alternating current (AC) for electricity generation following the War of Currents dramatically changed the situation. Power transformers, installed at power stations, could be used to raise the voltage from the generators, and transformers at local substations could reduce voltage to supply loads. Increasing the voltage reduced the current in the transmission and distribution lines and hence the size of conductors and distribution losses. This made it more economical to distribute power over long distances. Generators (such as hydroelectric sites) could be located far from the loads.

In North America, early distribution systems used a voltage of 2.2 kV corner-grounded delta. Over time, this was gradually increased to 2.4 kV. As cities grew, most 2.4 kV systems were upgraded to 2.4/4.16 kV, three-phase systems. In three phase networks that permit connections between phase and neutral, both the phase-to-phase voltage (4160, in this example) and the phase-to-neutral voltage are given; if only one value is shown, the network does not serve single-phase loads connected phase-to-neutral. Some city and suburban distribution systems continue to use this range of voltages, but most have been converted to 7200/12470Y, 7620/13200Y, 14400/24940Y, and 19920/34500Y.

European systems used 3.3 kV to ground, in support of the 220/380Y volt power systems used in those countries. In the UK, urban systems progressed to 6.6 kV and then 11 kV (phase to phase), the most common distribution voltage.

North American and European power distribution systems also differ in that North American systems tend to have a greater number of low-voltage, step-down transformers located close to customers' premises. For example, in the US a pole-mounted transformer in a suburban setting may supply 1-3 houses, whereas in the UK a typical urban or suburban low-voltage substation would normally be rated between 315 kVA and 1 MVA and supply a whole neighbourhood. This is because the higher voltage used in Europe (415 V vs 230 V) may be carried over a greater distance with acceptable power loss. An advantage of the North American setup is that failure or maintenance on a single transformer will only affect a few customers. Advantages of the UK setup are that the transformers may be fewer, larger and more efficient, and due to diversity there need be less spare capacity in the transformers, reducing power wastage. In North American city areas with many customers per unit area, network distribution will be used, with multiple transformers and low-voltage buses interconnected over several city blocks.

Rural Electrification systems, in contrast to urban systems, tend to use higher voltages because of the longer distances covered by those distribution lines. 7.2, 12.47, 25, and 34.5 kV distribution is common in the United States; 11 kV and 33 kV are common in the UK, New Zealand and Australia; 11 kV and 22 kV are common in South Africa. Other voltages are occasionally used.

In New Zealand, Australia, Saskatchewan, Canada, and South Africa, single wire earth return systems (SWER) are used to electrify remote rural areas.

While power electronics now allow for conversion between DC voltage levels, AC is still used in distribution due to the economy, efficiency and reliability of transformers. High-voltage DC is used for transmission of large blocks of power over long distances, or for interconnecting adjacent AC networks, but not for distribution to customers.

Distribution network configurations

Substation near Yellowknife, in the Northwest Territories of Canada

Distribution networks are typically of two types, radial or interconnected. A radial network leaves the station and passes through the network area with no normal connection to any other supply. This is typical of long rural lines with isolated load areas. An interconnected network is generally found in more urban areas and will have multiple connections to other points of supply. These points of connection are normally open but allow various configurations by the operating utility by closing and opening switches. Operation of these switches may be by remote control from a control centre or by a lineman. The benefit of the interconnected model is that in the event of a fault or required maintenance a small area of network can be isolated and the remainder kept on supply.

Within these networks there may be a mix of overhead line construction utilizing traditional utility poles and wires and, increasingly, underground construction with cables and indoor or cabinet substations. However, underground distribution is significantly more expensive than overhead construction. In part to reduce this cost, underground power lines are sometimes co-located with other utility lines in what are called Common utility ducts. Distribution feeders emanating from a substation are generally controlled by a circuit breaker which will open when a fault is detected. Automatic Circuit Reclosers may be installed to further segregate the feeder thus minimizing the impact of faults.

Long feeders experience voltage drop requiring capacitors or voltage regulators to be installed.

Characteristics of the supply given to customers are generally mandated by contract between the supplier and customer. Variables of the supply include:

- AC or DC - Virtually all public electricity supplies are AC today. Users of large amounts of DC power such as some electric railways, telephone exchanges and industrial processes such as aluminium smelting usually either operate their own or have adjacent dedicated generating equipment, or use rectifiers to derive DC from the public AC supply
- Voltage, including tolerance (usually +10 or -15 percentage)
- Frequency, commonly 50 & 60 Hz, 16.6 Hz for some railways and, in a few older industrial and mining locations, 25 Hz.
- Phase configuration (single phase, polyphase including two phase and three phase)
- Maximum demand (usually measured as the largest amount of power delivered within a 15 or 30 minute period during a billing period)
- Load Factor, expressed as a ratio of average load to peak load over a period of time. Load factor indicates the degree of effective utilization of equipment (and capital investment) of distribution line or system.
- Power factor of connected load
- Earthing arrangements - TT, TN-S, TN-C-S or TN-C
- Prospective short circuit current
- Maximum level and frequency of occurrence of transients

Distribution industry

Traditionally the electricity industry has been a publicly owned institution but starting in the 1970s nations began the process of deregulation and privatisation, leading to electricity markets. A major focus of these was the elimination of the former so called natural monopoly of generation, transmission, and distribution. As a consequence, electricity has become more of a commodity. The separation has also led to the development of new terminology to describe the business units (e.g., line company, wires business and network company).

Chapter-9

Electric Power Transmission

400 kV high-tension transmission lines near Madrid

Electric power transmission or "high voltage electric transmission" is the bulk transfer of electrical energy, from generating power plants to substations located near to population centers. This is distinct from the local wiring between high voltage substations and customers, which is typically referred to as electricity distribution. Transmission lines, when interconnected with each other, become high voltage transmission networks. In the US, these are typically referred to as "power grids" or sometimes simply as "the grid", while in the UK the network is known as the "national grid." North America has three major grids: The Western Interconnection; The Eastern Interconnection and the Electric Reliability Council of Texas (or ERCOT) grid.

Historically, transmission and distribution lines were owned by the same company, but over the last decade or so many countries have introduced market reforms that have led to the separation of the electricity transmission business from the distribution business.

Transmission lines mostly use three phase alternating current (AC), although single phase AC is sometimes used in railway electrification systems. High-voltage direct current (HVDC) technology is used only for very long distances (typically greater than 400 miles, or 600 km); submarine power cables (typically longer than 30 miles, or 50 km); or for connecting two AC networks that are not synchronized.

Electricity is transmitted at high voltages (110 kV or above) to reduce the energy lost in long distance transmission. Power is usually transmitted through overhead power lines. Underground power transmission has a significantly higher cost and greater operational limitations but is sometimes used in urban areas or sensitive locations.

A key limitation in the distribution of electricity is that, with minor exceptions, electrical energy cannot be stored, and therefore it must be generated as it is needed. A sophisticated system of control is therefore required to ensure electric generation very closely matches the demand. If supply and demand are not in balance, generation plants and transmission equipment can shut down which, in the worst cases, can lead to a major regional blackout, such as occurred in California and the US Northwest in 1996 and in the US Northeast in 1965, 1977 and 2003. To reduce the risk of such failures, electric transmission networks are interconnected into regional, national or continental wide networks thereby providing multiple redundant alternate routes for power to flow should (weather or equipment) failures occur. Much analysis is done by transmission companies to determine the maximum reliable capacity of each line which is mostly less than its physical or thermal limit, to ensure spare capacity is available should there be any such failure in another part of the network.

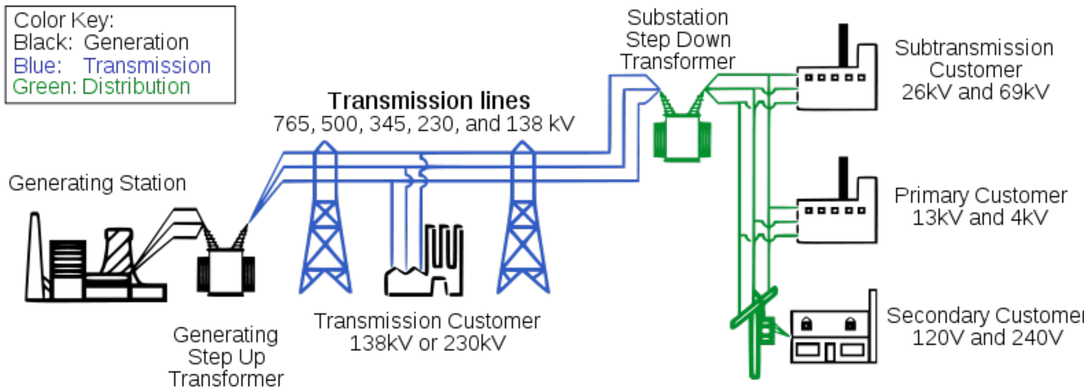
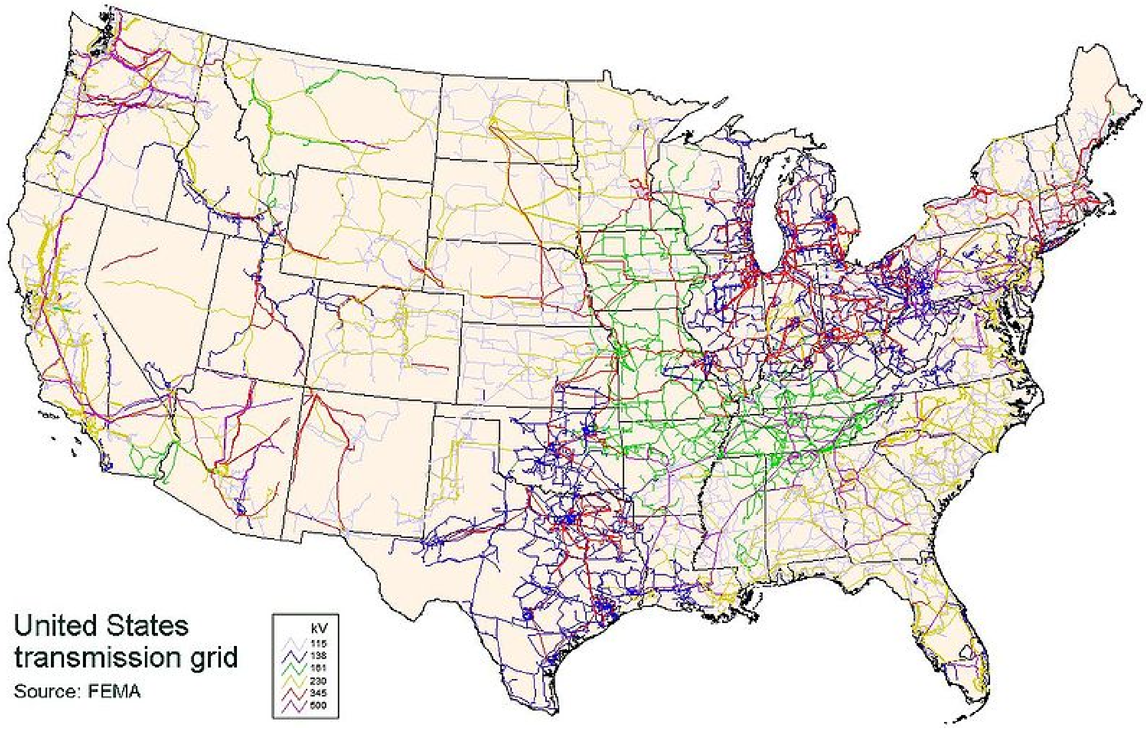


Diagram of an electrical system.

Overhead transmission

High-voltage overhead conductors are not covered by insulation. The conductor material is nearly always an aluminium alloy, made into several strands and possibly reinforced with steel strands. Copper was sometimes used for overhead transmission but aluminium is lower in weight for equivalent performance, and much lower in cost. Overhead conductors are a commodity supplied by several companies worldwide. Improved conductor material and shapes are regularly used to allow increased capacity and modernize transmission circuits. Conductor sizes range from 12 mm^2 (#6 American wire gauge) to 750 mm^2 (1,590,000 circular mils area), with varying resistance and current-carrying capacity. Thicker wires would lead to a relatively small increase in capacity due to the skin effect, that causes most of the current to flow close to the surface of the wire.



Contiguous United States power transmission grid consists of 300,000 km of lines operated by 500 companies.

Today, transmission-level voltages are usually considered to be 110 kV and above. Lower voltages such as 66 kV and 33 kV are usually considered sub-transmission voltages but are occasionally used on long lines with light loads. Voltages less than 33 kV are usually used for distribution. Voltages above 230 kV are considered extra high voltage and require different designs compared to equipment used at lower voltages.

Since overhead transmission lines are uninsulated, design of these lines requires minimum clearances to be observed to maintain safety. Adverse weather conditions of high wind and low temperatures can lead to power outages: wind speeds as low as 23 knots (43 km/h) can permit conductors to encroach operating clearances, resulting in a flashover and loss of supply. Oscillatory motion of the physical line can be termed gallop or flutter depending on the frequency and amplitude of oscillation.

Underground transmission

Electric power can also be transmitted by underground power cables instead of overhead power lines. They can assist the transmission of power across:

- Densely populated urban areas
- Areas where land is unavailable or planning consent is difficult
- Rivers and other natural obstacles
- Land with outstanding natural or environmental heritage

- Areas of significant or prestigious infrastructural development
- Land whose value must be maintained for future urban expansion and rural development

Some other advantages of underground power cables:

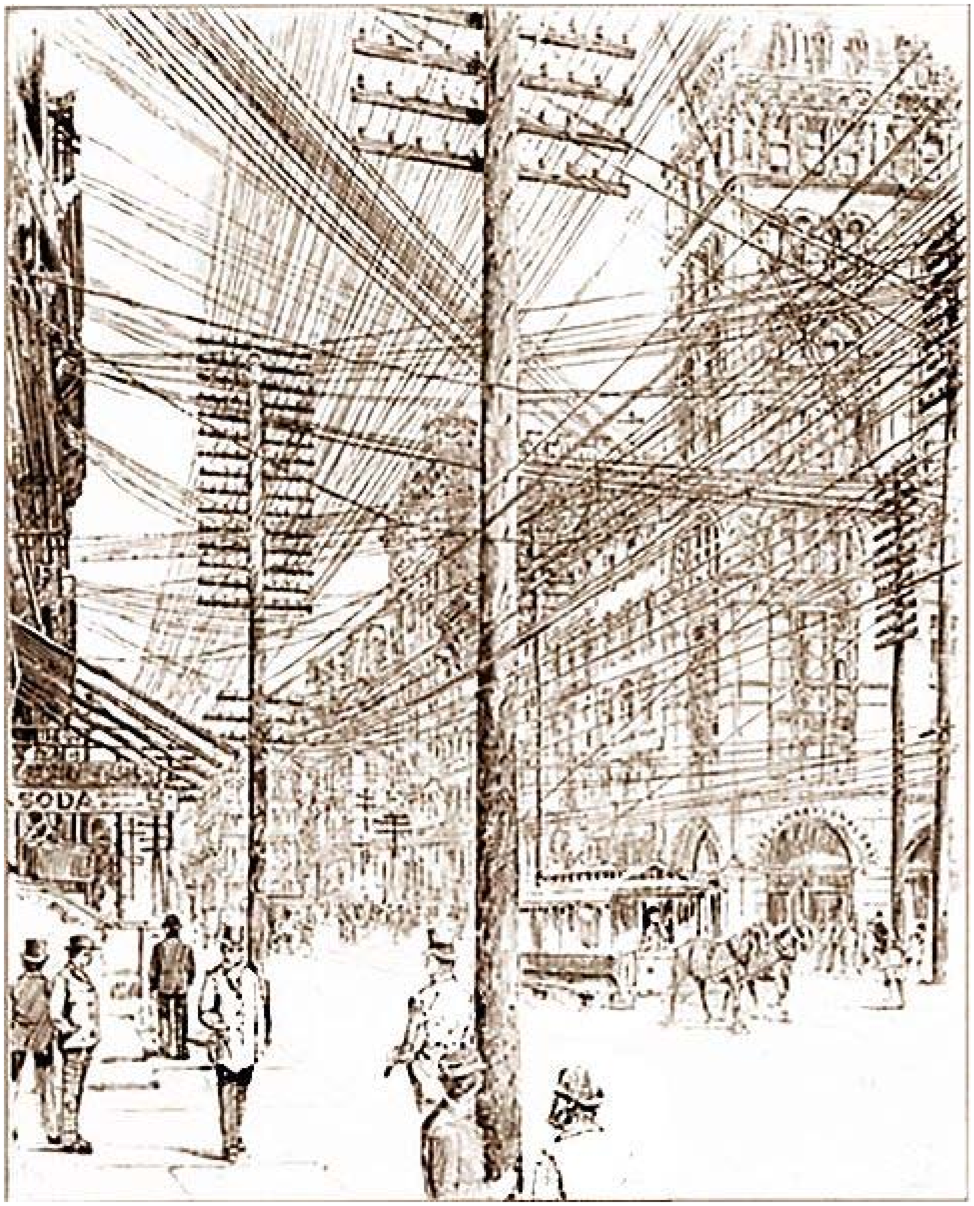
- Less subject to damage from severe weather conditions (mainly lightning, wind and freezing)
- Greatly reduced emission, into the surrounding area, of electromagnetic fields (EMF). All electric currents generate EMF, but the shielding provided by the earth surrounding underground cables restricts their range and power.
- Underground cables need a narrower surrounding strip of about 1–10 meters to install, whereas an overhead line requires a surrounding strip of about 20–200 meters wide to be kept permanently clear for safety, maintenance and repair.
- Underground cables pose no hazard to low flying aircraft or to wildlife, and are significantly safer as they pose no shock hazard (except to the unwary digger).
- Much less subject to conductor theft, illegal connections, sabotage, and damage from armed conflict.

Some disadvantages of underground power cables:

- Undergrounding is more expensive, since the cost of burying cables at transmission voltages is several times greater than overhead power lines, and the life-cycle cost of an underground power cable is two to four times the cost of an overhead power line. Above ground lines cost around $10 per foot and underground lines cost in the range of $20 to $40 per foot.
- Whereas finding and repairing overhead wire breaks can be accomplished in hours, underground repairs can take days or weeks, and for this reason redundant lines are run.
- Underground power cables, due to their proximity to earth, cannot be maintained live, whereas overhead power cables can be.
- Operations are more difficult since the high reactive power of underground cables produces large charging currents and so makes voltage control more difficult.

The advantages can in some cases outweigh the disadvantages of the higher investment cost, and more expensive maintenance and management.

History

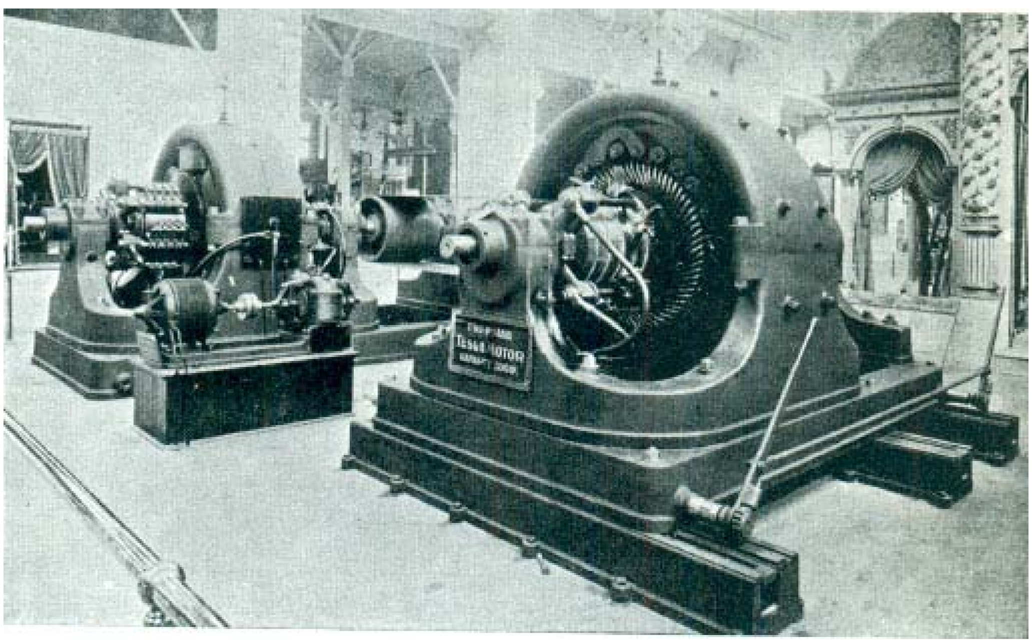


New York City streets in 1890. Besides telegraph lines, multiple electric lines were required for each class of device requiring different voltages.

In the early days of commercial electric power, transmission of electric power at the same voltage as used by lighting and mechanical loads restricted the distance between generating plant and consumers. In 1882, generation was with direct current, which could not easily be increased in voltage for long-distance transmission. Different classes of loads (for example, lighting, fixed motors, and traction/railway systems) required different voltages, and so used different generators and circuits.

Due to this specialization of lines and because transmission was so inefficient that generators needed to be near their loads, it seemed at the time that the industry would develop into what is now known as a distributed generation system with large numbers of small generators located nearby their loads.

In 1886 in Great Barrington, Massachusetts, a 1 kV AC distribution system was installed. That same year, AC power at 2 kV, transmitted 30 km, was installed at Cerchi, Italy. At an AIEE meeting on May 16, 1888, Nikola Tesla delivered a lecture entitled A New System of Alternating Current Motors and Transformers, describing the equipment which allowed efficient generation and use of polyphase alternating currents. The transformer, and Tesla's polyphase and single-phase induction motors, were essential for a combined AC distribution system for both lighting and machinery. Ownership of the rights to the Tesla patents was a key advantage to the Westinghouse Company in offering a complete alternating current power system for both lighting and power.



Nikola Tesla's Alternating current polyphase generators on display at the 1893 World's Fair in Chicago. Tesla's polyphase innovations revolutionized transmission.

Regarded as one of the most influential electrical innovations, the universal system used transformers to step-up voltage from generators to high-voltage transmission lines, and then to step-down voltage to local distribution circuits or industrial customers. By a suitable choice of utility frequency, both lighting and motor loads could be served. Rotary converters and later mercury-arc valves and other rectifier equipment allowed DC to be provided where needed. Generating stations and loads using different frequencies could be interconnected using rotary converters. By using common generating plants for every type of load, important economies of scale were achieved, lower overall capital investment was required, load factor on each plant was increased allowing for higher efficiency, a lower cost for the consumer and increased overall use of electric power.

By allowing multiple generating plants to be interconnected over a wide area, electricity production cost was reduced. The most efficient available plants could be used to supply the varying loads during the day. Reliability was improved and capital investment cost was reduced, since stand-by generating capacity could be shared over many more customers and a wider geographic area. Remote and low-cost sources of energy, such as hydroelectric power or mine-mouth coal, could be exploited to lower energy production cost.

The first transmission of three-phase alternating current using high voltage took place in 1891 during the international electricity exhibition in Frankfurt. A 25 kV transmission line, approximately 175 km long, connected Lauffen on the Neckar and Frankfurt.

Voltages used for electric power transmission increased throughout the 20th century. By 1914, fifty-five transmission systems each operating at more than 70 kV were in service. The highest voltage then used was 150 kV.

The rapid industrialization in the 20th century made electrical transmission lines and grids a critical part of the infrastructure in most industrialized nations. Interconnection of local generation plants and small distribution networks was greatly spurred by the requirements of World War I, where large electrical generating plants were built by governments to provide power to munitions factories. Later these plants were connected to supply civil loads through long-distance transmission.

Bulk power transmission

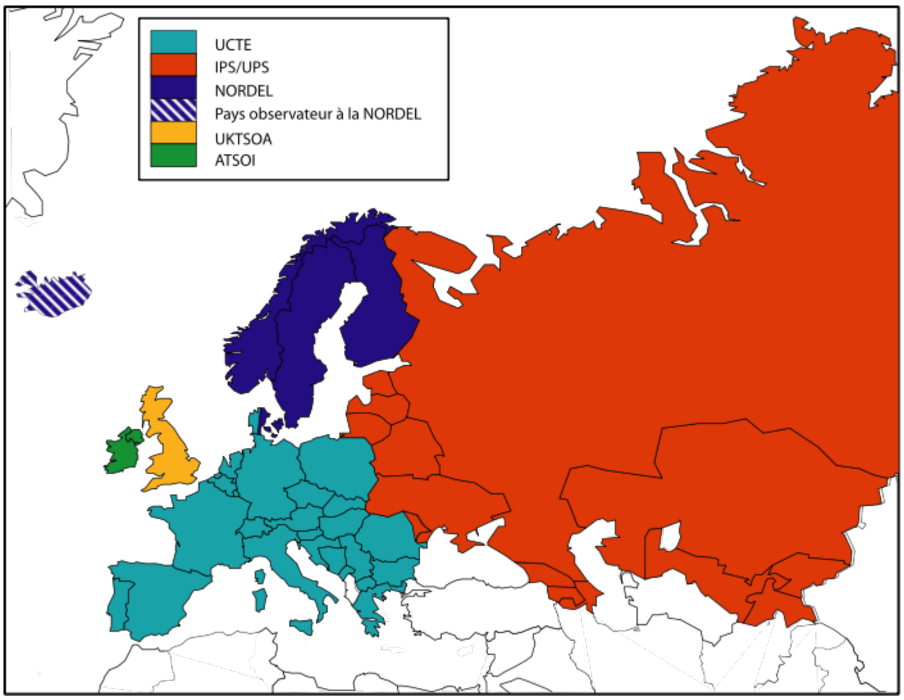
A transmission substation decreases the voltage of incoming electricity, allowing it to connect from long distance high voltage transmission, to local lower voltage distribution. It also reroutes power to other transmission lines that serve local markets. A transmission substation may include phase-shifting or voltage regulating transformers. This is the PacifiCorp Hale Substation, Orem, Utah, USA.

Engineers design transmission networks to transport the energy as efficiently as feasible, while at the same time taking into account economic factors, network safety and redundancy. These networks use components such as power lines, cables, circuit breakers, switches and transformers. The transmission network is usually administered on a regional basis by an entity such as a regional transmission organization or transmission system operator.

Transmission efficiency is hugely improved by devices that increase the voltage, and proportionately reduce the current in the conductors, thus keeping the power transmitted nearly equal to the power input. The reduced current flowing through the line reduces the losses in the conductors. According to Joule's Law, energy losses are directly proportional to the square of the current. Thus, reducing the current by a factor of 2 will lower the energy lost to conductor resistance by a factor of 4.

This change in voltage is usually achieved in AC circuits using a step-up transformer. DC systems require relatively costly conversion equipment which may be economically justified for particular projects, but are less common currently.

A transmission grid is a network of power stations, transmission circuits, and substations. Energy is usually transmitted within a grid with three-phase AC. Single phase AC is used only for distribution to end users since it is not usable for large polyphase induction motors. In the 19th century, two-phase transmission was used but required either three wires with unequal currents or four wires. Higher order phase systems require more than three wires, but deliver marginal benefits.



The synchronous grids of Eurasia.

The capital cost of electric power stations is so high, and electric demand is so variable, that it is often cheaper to import some portion of the needed power than to generate it locally. Because nearby loads are often correlated (hot weather in the Southwest portion of the US might cause many people to use air conditioners), electricity often comes from distant sources. Because of the economics of load balancing, wide area transmission grids now span across countries and even large portions of continents. The web of interconnections between power producers and consumers ensures that power can flow, even if a few links are inoperative.

The unvarying (or slowly varying over many hours) portion of the electric demand is known as the base load and is generally served best by large facilities (which are therefore efficient due to economies of scale) with low variable costs for fuel and operations. Such facilities might be nuclear or coal-fired power stations, or hydroelectric, while other renewable energy sources such as concentrated solar thermal and geothermal power have the potential to provide base load power. Renewable energy sources such as solar photovoltaics, wind, wave, and tidal are, due to their intermittency, not considered "base load" but can still add power to the grid. The remaining power demand, if any, is supplied by peaking power plants, which are typically smaller, faster-responding, and higher cost sources, such as combined cycle or combustion turbine plants fueled by natural gas.

A high-power electrical transmission tower.

Long-distance transmission of electricity (thousands of kilometers) is cheap and efficient, with costs of US$0.005–0.02/kWh (compared to annual averaged large producer costs of US$0.01–0.025/kWh, retail rates upwards of US$0.10/kWh, and multiples of retail for instantaneous suppliers at unpredicted highest demand moments). Thus distant suppliers can be cheaper than local sources (e.g., New York City buys a lot of electricity from Canada). Multiple **local sources** (even if more expensive and infrequently used) can make the transmission grid more fault tolerant to weather and other disasters that can disconnect distant suppliers.

Long distance transmission allows remote renewable energy resources to be used to displace fossil fuel consumption. Hydro and wind sources can't be moved closer to populous cities, and solar costs are lowest in remote areas where local power needs are minimal. Connection costs alone can determine whether any particular renewable alternative is economically sensible. Costs can be prohibitive for transmission lines, but various proposals for massive infrastructure investment in high capacity, very long distance super grid transmission networks could be recovered with modest usage fees.

Grid input

At the generating plants the energy is produced at a relatively low voltage between about 2.3 kV and 30 kV, depending on the size of the unit. The generator terminal voltage is then stepped up by the power station transformer to a higher voltage (115 kV to 765 kV AC, varying by country) for transmission over long distances.

Losses

Transmitting electricity at high voltage reduces the fraction of energy lost to resistance. For a given amount of power, a higher voltage reduces the current and thus the resistive losses in the conductor. For example, raising the voltage by a factor of 10 reduces the current by a corresponding factor of 10 and therefore the I^2Rlosses by a factor of 100, provided the same sized conductors are used in both cases. Even if the conductor size (cross-sectional area) is reduced 10-fold to match the lower current the I^2Rlosses are still reduced 10-fold. Long distance transmission is typically done with overhead lines at voltages of 115 to 1,200 kV. At extremely high voltages, more than 2 MV between conductor and ground, corona discharge losses are so large that they can offset the lower resistance loss in the line conductors.

Transmission and distribution losses in the USA were estimated at 6.6% in 1997 and 6.5% in 2007. In general, losses are estimated from the discrepancy between energy produced (as reported by power plants) and energy sold to end customers; the difference between what is produced and what is consumed constitute transmission and distribution losses.

As of 1980, the longest cost-effective distance for electricity was 7,000 km (4,300 mi), although all present transmission lines are considerably shorter.

In an alternating current circuit, the inductance and capacitance of the phase conductors can be significant. The currents that flow in these components of the circuit impedance constitute reactive power, which transmits no energy to the load. Reactive current causes extra losses in the transmission circuit. The ratio of real power (transmitted to the load) to apparent power is the power factor. As reactive current increases, the reactive power increases and the power factor decreases. For systems with low power factors, losses are higher than for systems with high power factors. Utilities add capacitor banks and other components (such as phase-shifting transformers; static VAR compensators; physical transposition of the phase conductors; and flexible AC transmission systems, FACTS) throughout the system to control reactive power flow for reduction of losses and stabilization of system voltage.

Transmission grid exit

At the substations, transformers reduce the voltage to a lower level for distribution to commercial and residential users. This distribution is accomplished with a combination of sub-transmission (33 kV to 132 kV) and distribution (3.3 to 25 kV). Finally, at the point of use, the energy is transformed to low voltage (varying by country and customer requirements).

High-voltage direct current

High voltage direct current (HVDC) is used to transmit large amounts of power over long distances or for interconnections between asynchronous grids. When electrical energy is required to be transmitted over very long distances, it is more economical to transmit using direct current instead of alternating current. For a long transmission line, the lower losses and reduced construction cost of a DC line can offset the additional cost of converter stations at each end. Also, at high AC voltages, significant (although economically acceptable) amounts of energy are lost due to corona discharge, the capacitance between phases or, in the case of buried cables, between phases and the soil or water in which the cable is buried.

HVDC is also used for long submarine cables because over about 30 km length AC can no longer be applied. In that case special high voltage cables for DC are built. Many submarine cable connections - up to 600 km length - are in use nowadays.

HVDC links are sometimes used to stabilize against control problems with the AC electricity flow. In other words, to transmit AC power as AC when needed in either direction between Seattle and Boston would require the (highly challenging) continuous real-time adjustment of the relative phase of the two electrical grids. With HVDC instead the interconnection would: (1) Convert AC in Seattle into HVDC. (2) Use HVDC for the three thousand miles of cross country transmission. Then (3) convert the HVDC to locally synchronized AC in Boston, and optionally in other cooperating cities along the transmission route. One prominent example of such a transmission line is the Pacific DC Intertie located in the Western United States.

Limitations

The amount of power that can be sent over a transmission line is limited. The origins of the limits vary depending on the length of the line. For a short line, the heating of conductors due to line losses sets a thermal limit. If too much current is drawn, conductors may sag too close to the ground, or conductors and equipment may be damaged by overheating. For intermediate-length lines on the order of 100 km (62 mi), the limit is set by the voltage drop in the line. For longer AC lines, system stability sets the limit to the power that can be transferred. Approximately, the power flowing over an AC line is proportional to the sine of the phase angle of the voltage at the receiving and transmitting ends. Since this angle varies depending on system loading and generation, it is undesirable for the angle to approach 90 degrees. Very approximately, the allowable product of line length and maximum load is proportional to the square of the system voltage. Series capacitors or phase-shifting transformers are used on long lines to improve stability. High-voltage direct current lines are restricted only by thermal and voltage drop limits, since the phase angle is not material to their operation.

Up to now, it has been almost impossible to foresee the temperature distribution along the cable route, so that the maximum applicable current load was usually set as a compromise between understanding of operation conditions and risk minimization. The availability of industrial Distributed Temperature Sensing (DTS) systems that measure in real time temperatures all along the cable is a first step in monitoring the transmission system capacity. This monitoring solution is based on using passive optical fibers as temperature sensors, either integrated directly inside a high voltage cable or mounted externally on the cable insulation. A solution for overhead lines is also available. In this case the optical fiber is integrated into the core of a phase wire of overhead transmission lines (OPPC). The integrated Dynamic Cable Rating (DCR) or also called Real Time Thermal Rating (RTTR) solution enables not only to continuously monitor the temperature of a high voltage cable circuit in real time, but to safely utilize the existing network capacity to its maximum. Furthermore it provides the ability to the operator to predict the behavior of the transmission system upon major changes made to its initial operating conditions.

Control

To ensure safe and predictable operation the components of the transmission system are controlled with generators, switches, circuit breakers and loads. The voltage, power, frequency, load factor, and reliability capabilities of the transmission system are designed to provide cost effective performance for the customers.

Load balancing

The transmission system provides for base load and peak load capability, with safety and fault tolerance margins. The peak load times vary by region largely due to the industry mix. In very hot and very cold climates home air conditioning and heating loads have an effect on the overall load. They are typically highest in the late afternoon in the hottest part of the year and in mid-mornings and mid-evenings in the coldest part of the year. This makes the power requirements vary by the season and the time of day. Distribution system designs always take the base load and the peak load into consideration.

The transmission system usually does not have a large buffering capability to match the loads with the generation. Thus generation has to be kept matched to the load, to prevent overloading failures of the generation equipment.

Multiple sources and loads can be connected to the transmission system and they must be controlled to provide orderly transfer of power. In centralized power generation, only local control of generation is necessary, and it involves synchronization of the generation units, to prevent large transients and overload conditions.

In distributed power generation the generators are geographically distributed and the process to bring them online and offline must be carefully controlled. The load control signals can either be sent on separate lines or on the power lines themselves. To load balance the voltage and frequency can be used as a signaling mechanism.

In voltage signaling, the variation of voltage is used to increase generation. The power added by any system increases as the line voltage decreases. This arrangement is stable in principle. Voltage based regulation is complex to use in mesh networks, since the individual components and setpoints would need to be reconfigured every time a new generator is added to the mesh.

In frequency signaling, the generating units match the frequency of the power transmission system. In droop speed control, if the frequency decreases, the power is increased. (The drop in line frequency is an indication that the increased load is causing the generators to slow down.)

Wind turbines, v2g and other distributed storage and generation systems can be connected to the power grid, and interact with it to improve system operation.

Failure protection

Under excess load conditions, the system can be designed to fail gracefully rather than all at once. Brownouts occur when the supply power drops below the demand. Blackouts occur when the supply fails completely.

Rolling blackouts, or load shedding, are intentionally engineered electrical power outages, used to distribute insufficient power when the demand for electricity exceeds the supply.

Communications

Operators of long transmission lines require reliable communications for control of the power grid and, often, associated generation and distribution facilities. Fault-sensing protective relays at each end of the line must communicate to monitor the flow of power into and out of the protected line section so that faulted conductors or equipment can be quickly de-energized and the balance of the system restored. Protection of the transmission line from short circuits and other faults is usually so critical that common carrier telecommunications are insufficiently reliable, and in remote areas a common carrier may not be available. Communication systems associated with a transmission project may use:

- Microwaves
- Power line communication
- Optical fibers

Rarely, and for short distances, a utility will use pilot-wires strung along the transmission line path. Leased circuits from common carriers are not preferred since availability is not under control of the electric power transmission organization.

Transmission lines can also be used to carry data: this is called power-line carrier, or PLC. PLC signals can be easily received with a radio for the long wave range.

Optical fibers can be included in the stranded conductors of a transmission line, in the overhead shield wires. These cables are known as optical ground wire (OPGW). Sometimes a standalone cable is used, all-dielectric self-supporting (ADSS) cable, attached to the transmission line cross arms.

Some jurisdictions, such as Minnesota, prohibit energy transmission companies from selling surplus communication bandwidth or acting as a telecommunications common carrier. Where the regulatory structure permits, the utility can sell capacity in extra dark fibers to a common carrier, providing another revenue stream.

Electricity market reform

Some regulators regard electric transmission to be a natural monopoly and there are moves in many countries to separately regulate transmission.

Spain was the first country to establish a regional transmission organization. In that country transmission operations and market operations are controlled by separate companies. The transmission system operator is Red Eléctrica de España (REE) and the wholesale electricity market operator is Operador del Mercado Ibérico de Energía - Polo Español, S.A. (OMEL). Spain's transmission system is interconnected with those of France, Portugal, and Morocco.

In the United States and parts of Canada, electrical transmission companies operate independently of generation and distribution companies.

Cost of electric power transmission

The cost of high voltage electricity transmission (as opposed to the costs of electricity distribution) is comparatively low, compared to all other costs arising in a consumer's electricity bill. In the UK transmission costs are about 0.2p/kWh compared to a delivered domestic price of around 10 p/kWh.

Merchant transmission

Merchant transmission is an arrangement where a third party constructs and operates electric transmission lines through the franchise area of an unrelated utility. Advocates of merchant transmission claim that this will create competition to construct the most efficient and lowest cost additions to the transmission grid. Merchant transmission projects typically involve DC lines because it is easier to limit flows to paying customers.

Operating merchant transmission projects in the United States include the Cross Sound Cable from Long Island, New York to New Haven, Connecticut, Neptune RTS Transmission Line from Sayreville, N.J., to Newbridge, N.Y, ITC Holdings, Inc. transmission system in the midwest, and Path 15 in California. Additional projects are in development or have been proposed throughout the United States.

There is only one unregulated or market interconnector in Australia: Basslink between Tasmania and Victoria. Two DC links originally implemented as market interconnectors Directlink and Murraylink have been converted to regulated interconnectors. NEMMCO

A major barrier to wider adoption of merchant transmission is the difficulty in identifying who benefits from the facility so that the beneficiaries will pay the toll. Also, it is difficult for a merchant transmission line to compete when the alternative transmission lines are subsidized by other utility businesses.

Health concerns

The preponderance of evidence does not suggest that the low-power, low-frequency, electromagnetic radiation associated with household current constitutes a short or long term health hazard. Some studies have found statistical correlations between various diseases and living or working near power lines, but no adverse health effects have been substantiated for people not living close to powerlines.

There are established biological effects for acute high level exposure to magnetic fields well above 100 μT. In a residential setting, there is "limited evidence of carcinogenicity in humans and less than sufficient evidence for carcinogenicity in experimental animals", in particular, childhood leukaemia, associated with average exposure to residential power-frequency magnetic field above 0.3 to 0.4 μT. These levels exceed average residential power-frequency magnetic fields in homes which are about 0.07 μT in Europe and 0.11 μT in North America.

Government policy

Historically, local governments have exercised authority over the grid and have significant disincentives to take action that would benefit states other than their own. Localities with cheap electricity have a disincentive to making interstate commerce in electricity trading easier, since other regions will be able to compete for local energy and drive up rates. Some regulators in Maine for example do not wish to address congestion problems because the congestion serves to keep Maine rates low. Further, vocal local constituencies can block or slow permitting by pointing to visual impact, environmental, and perceived health concerns. In the US, generation is growing 4 times faster than transmission, but big transmission upgrades require the coordination of multiple states, a multitude of interlocking permits, and cooperation between a significant portion of the 500 companies that own the grid. From a policy perspective, the control of the grid is balkanized, and even former energy secretary Bill Richardson refers to it as a third world grid. There have been efforts in the EU and US to confront the problem. The US national security interest in significantly growing transmission capacity drove passage of the 2005 energy act giving the Department of Energy the authority to approve transmission if states refuse to act. However, soon after using its power to designate two National Interest Electric Transmission Corridors, 14 senators signed a letter stating the DOE was being too aggressive.

Special transmission

Grids for railways

In some countries where electric trains run on low frequency AC (e.g., 16.7 Hz and 25 Hz) power, there are separate single phase traction power networks operated by the railways. These grids are fed by separate generators in some traction powerstations or by traction current converter plants from the public three phase AC network.

Superconducting cables

High-temperature superconductors promise to revolutionize power distribution by providing lossless transmission of electrical power. The development of superconductors with transition temperatures higher than the boiling point of liquid nitrogen has made the concept of superconducting power lines commercially feasible, at least for high-load applications. It has been estimated that the waste would be halved using this method, since the necessary refrigeration equipment would consume about half the power saved by the elimination of the majority of resistive losses. Some companies such as Consolidated Edison and American Superconductor have already begun commercial production of such systems. In one hypothetical future system called a SuperGrid, the cost of cooling would be eliminated by coupling the transmission line with a liquid hydrogen pipeline.

Superconducting cables are particularly suited to high load density areas such as the business district of large cities, where purchase of an easement for cables would be very costly.

Single wire earth return

Single-wire earth return (SWER) or single wire ground return is a single-wire transmission line for supplying single-phase electrical power for an electrical grid to remote areas at low cost. It is principally used for rural electrification, but also finds use for larger isolated loads such as water pumps, and light rail. Single wire earth return is also used for HVDC over submarine power cables.

Wireless power transmission

Both Nikola Tesla and Hidetsugu Yagi attempted to devise systems for large scale wireless power transmission, with no commercial success.

Wireless power transmission has been studied for transmission of power from solar power satellites to the earth. A high power array of microwave transmitters would beam power to a rectenna. Major engineering and economic challenges face any solar power satellite project.

Security of control systems

The Federal government of the United States admits that the power grid is susceptible to cyber-warfare. The United States Department of Homeland Security works with industry to identify vulnerabilities and to help industry enhance the security of control system networks, the federal government is also working to ensure that security is built in as the U.S. develops the next generation of 'smart grid' networks.

Records

- Highest capacity system: 6.3 GW HVDC Itaipu (Brazil) (±600 kV DC)
- Highest transmission voltage (AC): 1.15 MV on Powerline Ekibastuz-Kokshetau (Kazakhstan)
- Largest double-circuit transmission, Kita-Iwaki Powerline.
- Highest pylons: Yangtze River Crossing (height: 345 m/1,132 ft)
- Longest power line: Inga-Shaba (length: 1,700 kilometres / 1,056 miles)
- Longest span of power line: 5,376 m (17,638 ft) at Ameralik Span
- Longest submarine cables:
    - NorNed, North Sea - (length of submarine cable: 580 kilometres / 360 miles)
    - Basslink, Bass Strait - (length of submarine cable: 290 kilometres / 180 miles, total length: 370.1 kilometres / 230 miles)
    - Baltic-Cable, Baltic Sea - (length of submarine cable: 238 kilometres / 148 miles, HVDC length: 250 kilometres / 155 miles, total length: 262 kilometres / 163 miles)
- Longest underground cables:
    - Murraylink, Riverland/Sunraysia - (length of underground cable: 180 kilometres / 112 miles)

Chapter-10

Electrical Substation

A 50 Hz electrical substation in Melbourne, Australia. This is showing 3 of the 5 220 kV/66 kV transformers each with a capacity of 185 MVA.

A 115 kV to 41.6/12.47 kV 5 MVA 60 Hz substation with circuit switcher, regulators, reclosers and control building at Warren, Minnesota

An **electrical substation** is a subsidiary station of an electricity generation, transmission and distribution system where voltage is transformed from high to low or the reverse using transformers. Electric power may flow through several substations between generating plant and consumer, and may be changed in voltage in several steps.

A substation that has a step-up transformer increases the voltage while decreasing the current, while a step-down transformer decreases the voltage while increasing the current for domestic and commercial distribution. The word substation comes from the days before the distribution system became a grid. The first substations were connected to only one power station where the generator was housed, and were subsidiaries of that power station.

Elements of a substation

Substations generally have switching, protection and control equipment and one or more transformers. In a large substation, circuit breakers are used to interrupt any short-circuits or overload currents that may occur on the network. Smaller distribution stations may use recloser circuit breakers or fuses for protection of distribution circuits. Substations do not usually have generators, although a power plant may have a substation nearby. Other devices such as capacitors and voltage regulators may also be located at a substation.

Substations may be on the surface in fenced enclosures, underground, or located in special-purpose buildings. High-rise buildings may have several indoor substations. Indoor substations are usually found in urban areas to reduce the noise from the transformers, for reasons of appearance, or to protect switchgear from extreme climate or pollution conditions.

Where a substation has a metallic fence, it must be properly grounded (UK: earthed) to protect people from high voltages that may occur during a fault in the network. Earth faults at a substation can cause a ground potential rise. Currents flowing in the Earth's surface during a fault can cause metal objects to have a significantly different voltage than the ground under a person's feet; this touch potential presents a hazard of electrocution.

Transmission substation

A **transmission substation** connects two or more transmission lines. The simplest case is where all transmission lines have the same voltage. In such cases, the substation contains high-voltage switches that allow lines to be connected or isolated for fault clearance or maintenance. A transmission station may have transformers to convert between two transmission voltages, voltage control/power factor correction devices such as capacitors, reactors or static VAr compensators and equipment such as phase shifting transformers to control power flow between two adjacent power systems.

Transmission substations can range from simple to complex. A small "switching station" may be little more than a bus plus some circuit breakers. The largest transmission substations can cover a large area (several acres/hectares) with multiple voltage levels, many circuit breakers and a large amount of protection and control equipment (voltage and current transformers, relays and SCADA systems). Modern substations may be implemented using International Standards such as IEC61850.

Distribution substation

A distribution substation in Scarborough, Ontario, Canada disguised as a house, complete with a driveway, front walk and a mown lawn and shrubs in the front yard. A warning notice can be clearly seen on the "front door".

A **distribution substation** transfers power from the transmission system to the distribution system of an area. It is uneconomical to directly connect electricity consumers to the high-voltage main transmission network, unless they use large amounts of power, so the distribution station reduces voltage to a value suitable for local distribution.

The input for a distribution substation is typically at least two transmission or subtransmission lines. Input voltage may be, for example, 115 kV, or whatever is common in the area. The output is a number of feeders. Distribution voltages are typically medium voltage, between 2.4 and 33 kV depending on the size of the area served and the practices of the local utility.

The feeders will then run overhead, along streets (or under streets, in a city) and eventually power the distribution transformers at or near the customer premises.

Besides changing the voltage, the job of the distribution substation is to isolate faults in either the transmission or distribution systems. Distribution substations may also be the points of voltage regulation, although on long distribution circuits (several km/miles), voltage regulation equipment may also be installed along the line.

Complicated distribution substations can be found in the downtown areas of large cities, with high-voltage switching, and switching and backup systems on the low-voltage side. More typical distribution substations have a switch, one transformer, and minimal facilities on the low-voltage side.

Collector substation

In distributed generation projects such as a wind farm, a collector substation may be required. It somewhat resembles a distribution substation although power flow is in the opposite direction, from many wind turbines up into the transmission grid. Usually for economy of construction the collector system operates around 35 kV, and the collector substation steps up voltage to a transmission voltage for the grid. The collector substation can also provide power factor correction if it is needed, metering and control of the wind farm. In some special cases a collector substation can also contain an HVDC static inverter plant.

Collector substations also exist where multiple thermal or hydroelectric power plants of comparable output power are in proximity. Examples for such substations are Brauweiler in Germany and Hradec in the Czech Republic, where power of lignite fired power plants nearby is collected. if no transformers are installed for increase of voltage to transmission level, the substation is a switching station.

Stations with change of current type

Substations may be found in association with HVDC converter plants or, formerly, where rotary converters changed frequency or interconnected non-synchronous networks.

Switching substation

A switching substation is a substation which does not contain transformers and operates only at a single voltage level. Switching substations are sometimes used as collector and distribution stations. Sometimes they are used for switching the current to back-up lines or for paralellizing circuits in case of failure. Example herefore are the switching stations at HVDC Inga-Shaba.

Design

The main issues facing a power engineer are reliability and cost. A good design attempts to strike a balance between these two, to achieve sufficient reliability without excessive cost. The design should also allow easy expansion of the station, if required.

Selection of the location of a substation must consider many factors. Sufficient land area is required for installation of equipment with necessary clearances for electrical safety, and for access to maintain large apparatus such as transformers. Where land is costly, such as in urban areas, gas insulated switchgear may save money overall. The site must have room for expansion due to load growth or planned transmission additions. Environmental effects of the substation must be considered, such as drainage, noise and road traffic effects. Grounding (earthing) and ground potential rise must be calculated to protect passers-by during a short-circuit in the transmission system. And of course, the substation site must be reasonably central to the distribution area to be served.

Layout

Tottenham Substation, set in wild parkland in North London, United Kingdom

The first step in planning a substation layout is the preparation of a one-line diagram which shows in simplified form the switching and protection arrangement required, as well as the incoming supply lines and outgoing feeders or transmission lines. It is a usual practice by many electrical utilities to prepare one-line diagrams with principal elements (lines, switches, circuit breakers, transformers) arranged on the page similarly to the way the apparatus would be laid out in the actual station.

Incoming lines will almost always have a disconnect switch and a circuit breaker. In some cases, the lines will not have both; with either a switch or a circuit breaker being all that is considered necessary. A disconnect switch is used to provide isolation, since it cannot interrupt load current. A circuit breaker is used as a protection device to interrupt fault currents automatically, and may be used to switch loads on and off. When a large fault current flows through the circuit breaker, this may be detected through the use of current transformers. The magnitude of the current transformer outputs may be used to 'trip' the circuit breaker resulting in a disconnection of the load supplied by the circuit break from the feeding point. This seeks to isolate the fault point from the rest of the system, and allow the rest of the system to continue operating with minimal impact. Both switches and circuit breakers may be operated locally (within the substation) or remotely from a supervisory control center.

Once past the switching components, the lines of a given voltage connect to one or more buses. These are sets of bus bars, usually in multiples of three, since three-phase electrical power distribution is largely universal around the world.

The arrangement of switches, circuit breakers and buses used affects the cost and reliability of the substation. For important substations a ring bus, double bus, or so-called "breaker and a half" setup can be used, so that the failure of any one circuit breaker does not interrupt power to branch circuits for more than a brief time, and so that parts of the substation may be de-energized for maintenance and repairs. Substations feeding only a single industrial load may have minimal switching provisions, especially for small installations.

Once having established buses for the various voltage levels, transformers may be connected between the voltage levels. These will again have a circuit breaker, much like transmission lines, in case a transformer has a fault (commonly called a 'short circuit').

Along with this, a substation always has control circuitry needed to command the various breakers to open in case of the failure of some component.

Switching function

An important function performed by a substation is switching, which is the connecting and disconnecting of transmission lines or other components to and from the system. Switching events may be "planned" or "unplanned".

A transmission line or other component may need to be deenergized for maintenance or for new construction; for example, adding or removing a transmission line or a transformer.

To maintain reliability of supply, no company ever brings down its whole system for maintenance. All work to be performed, from routine testing to adding entirely new substations, must be done while keeping the whole system running.

Perhaps more importantly, a fault may develop in a transmission line or any other component. Some examples of this: a line is hit by lightning and develops an arc, or a tower is blown down by a high wind. The function of the substation is to isolate the faulted portion of the system in the shortest possible time.

There are two main reasons: a fault tends to cause equipment damage; and it tends to destabilize the whole system. For example, a transmission line left in a faulted condition will eventually burn down, and similarly, a transformer left in a faulted condition will eventually blow up. While these are happening, the power drain makes the system more unstable. Disconnecting the faulted component, quickly, tends to minimize both of these problems.

Railways

Electrified railways also use substations, often distribution substations. In some cases a conversion of the current type takes place, commonly with rectifiers for DC trains, or rotary converters for trains using AC other than that of the public grid. Sometimes they are also transmission substations or collector substations if the railway network also operates its own grid and generators.

Chapter-11

Transformer

Pole-mounted "split-phase" transformer with center-tapped secondary winding (note use of grounded conductor, right, as one leg of the primary feeder)

A **transformer** is a device that transfers electrical energy from one circuit to another through inductively coupled conductors—the transformer's coils. A varying current in the first or primary winding creates a varying magnetic flux in the transformer's core and thus a varying magnetic field through the secondary winding. This varying magnetic field induces a varying electromotive force (EMF) or "voltage" in the secondary winding. This effect is called mutual induction.

If a load is connected to the secondary, an electric current will flow in the secondary winding and electrical energy will be transferred from the primary circuit through the transformer to the load. In an ideal transformer, the induced voltage in the secondary winding (V_s) is in proportion to the primary voltage (V_p), and is given by the ratio of the number of turns in the secondary (N_s) to the number of turns in the primary (N_p) as follows:

$$\frac{V_s}{V_p} = \frac{N_s}{N_p}$$

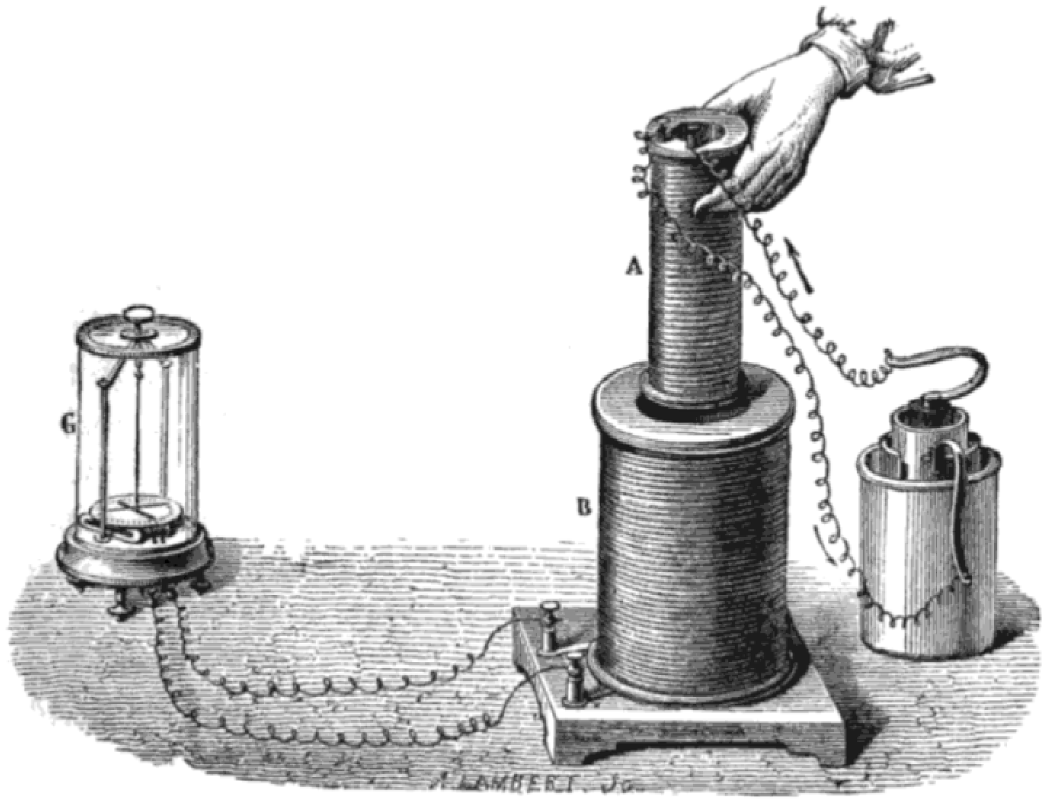
By appropriate selection of the ratio of turns, a transformer thus allows an alternating current (AC) voltage to be "stepped up" by making N_s greater than N_p, or "stepped down" by making N_s less than N_p.

In the vast majority of transformers, the windings are coils wound around a ferromagnetic core, air-core transformers being a notable exception.

Transformers range in size from a thumbnail-sized coupling transformer hidden inside a stage microphone to huge units weighing hundreds of tons used to interconnect portions of power grids. All operate with the same basic principles, although the range of designs is wide. While new technologies have eliminated the need for transformers in some electronic circuits, transformers are still found in nearly all electronic devices designed for household ("mains") voltage. Transformers are essential for high voltage power transmission, which makes long distance transmission economically practical.

History

Discovery



Faraday's experiment with induction between coils of wire

The phenomenon of electromagnetic induction was discovered independently by Michael Faraday and Joseph Henry in 1831. However, Faraday was the first to publish the results of his experiments and thus receive credit for the discovery. The relationship between electromotive force (EMF) or "voltage" and magnetic flux was formalized in an equation now referred to as "Faraday's law of induction":

$$|\mathcal{E}| = \left|\frac{d\Phi_B}{dt}\right|.$$

where $|\mathcal{E}|$ is the magnitude of the EMF in volts and Φ_B is the magnetic flux through the circuit (in webers).

Faraday performed the first experiments on induction between coils of wire, including winding a pair of coils around an iron ring, thus creating the first toroidal closed-core transformer.

Induction coils

The first type of transformer to see wide use was the induction coil, invented by Rev. Nicholas Callan of Maynooth College, Ireland in 1836. He was one of the first researchers to realize that the more turns the secondary winding has in relation to the primary winding, the larger is the increase in EMF. Induction coils evolved from scientists' and inventors' efforts to get higher voltages from batteries. Since batteries produce direct current (DC) rather than alternating current (AC), induction coils relied upon vibrating electrical contacts that regularly interrupted the current in the primary to create the flux changes necessary for induction. Between the 1830s and the 1870s, efforts to build better induction coils, mostly by trial and error, slowly revealed the basic principles of transformers.

In 1876, Russian engineer Pavel Yablochkov invented a lighting system based on a set of induction coils where the primary windings were connected to a source of alternating current and the secondary windings could be connected to several "electric candles" (arc lamps) of his own design. The coils Yablochkov employed functioned essentially as transformers.

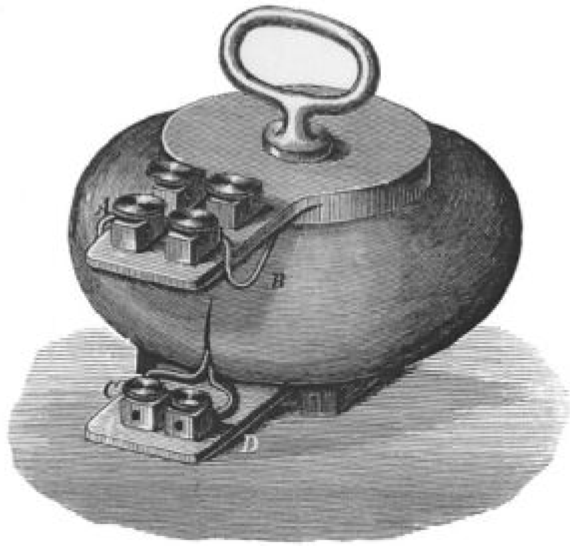
In 1878, the Ganz Company in Hungary began manufacturing equipment for electric lighting and, by 1883, had installed over fifty systems in Austria-Hungary. Their systems used alternating current exclusively and included those comprising both arc and incandescent lamps, along with generators and other equipment.

Lucien Gaulard and John Dixon Gibbs first exhibited a device with an open iron core called a "secondary generator" in London in 1882, then sold the idea to the Westinghouse company in the United States. They also exhibited the invention in Turin, Italy in 1884, where it was adopted for an electric lighting system. However, the efficiency of their open-core bipolar apparatus remained very low.

Induction coils with open magnetic circuits are inefficient for transfer of power to loads. Until about 1880, the paradigm for AC power transmission from a high voltage supply to a low voltage load was a series circuit. Open-core transformers with a ratio near 1:1 were connected with their primaries in series to allow use of a high voltage for transmission while presenting a low voltage to the lamps. The inherent flaw in this method was that turning off a single lamp affected the voltage supplied to all others on the same circuit. Many adjustable transformer designs were introduced to compensate for this problematic characteristic of the series circuit, including those employing methods of adjusting the core or bypassing the magnetic flux around part of a coil.

Efficient, practical transformer designs did not appear until the 1880s, but within a decade the transformer would be instrumental in the "War of Currents", and in seeing AC distribution systems triumph over their DC counterparts, a position in which they have remained dominant ever since.

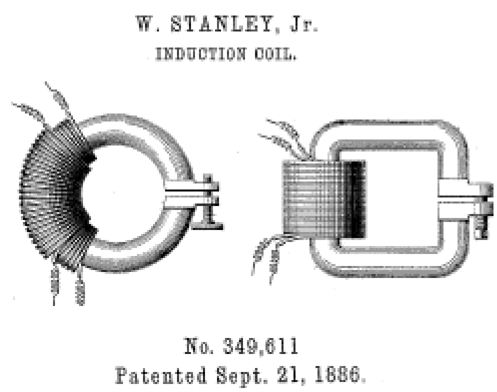
Closed-core lighting transformers



Drawing of Ganz Company's 1885 prototype. Capacity: 1400 VA, frequency: 40 Hz, voltage ratio: 120/72 V

Prototypes of the world's first high-efficiency transformers. They were built by the Z.B.D. team on 16th September 1884.

In the autumn of 1884 , Ganz Company engineers Károly Zipernowsky, Ottó Bláthy and Miksa Déri had determined that open-core devices were impracticable, as they were incapable of reliably regulating voltage. In their joint patent application for the "Z.B.D." transformers, they described two designs with closed magnetic circuits: the "closed-core" and "shell-core" transformers. In the closed-core, the primary and secondary windings were wound around a closed iron ring; in the shell-core, the windings were passed through the iron core. In both designs, the magnetic flux linking the primary and secondary windings traveled almost entirely within the iron core, with no intentional path through air. The new Z.B.D. transformers reached 98 percent efficiency, which was 3.4 times higher than the open core bipolar devices of Gaulard and Gibs. When employed in parallel connected electric distribution systems, closed-core transformers finally made it technically and economically feasible to provide electric power for lighting in homes, businesses and public spaces. Bláthy had suggested the use of closed-cores, Zipernowsky the use of shunt connections, and Déri had performed the experiments; Bláthy also discovered the transformer formula, $V_s/V_p = N_s/N_p$. The vast majority of transformers in use today rely on the basic principles discovered by the three engineers. They also reportedly popularized the word "transformer" to describe a device for altering the EMF of an electric current, although the term had already been in use by 1882. In 1886, the Ganz Company installed the world's first power station that used AC generators to power a parallel-connected common electrical network, the steam-powered Rome-Cerchi power plant.



Stanley's 1886 design for adjustable gap open-core induction coils

Although George Westinghouse had bought Gaulard and Gibbs' patents in 1885, the Edison Electric Light Company held an option on the U.S. rights for the Z.B.D. transformers, requiring Westinghouse to pursue alternative designs on the same principles. He assigned to William Stanley the task of developing a device for commercial use in United States. Stanley's first patented design was for induction coils with single cores of soft iron and adjustable gaps to regulate the EMF present in the secondary winding. This design was first used commercially in the U.S. in 1886. But Westinghouse soon had his team working on a design whose core comprised a stack of thin "E-shaped" iron plates, separated individually or in pairs by thin sheets of paper or other insulating material. Prewound copper coils could then be slid into place, and straight iron plates laid in to create a closed magnetic circuit. Westinghouse applied for a patent for the new design in December 1886; it was granted in July 1887.

Other early transformers

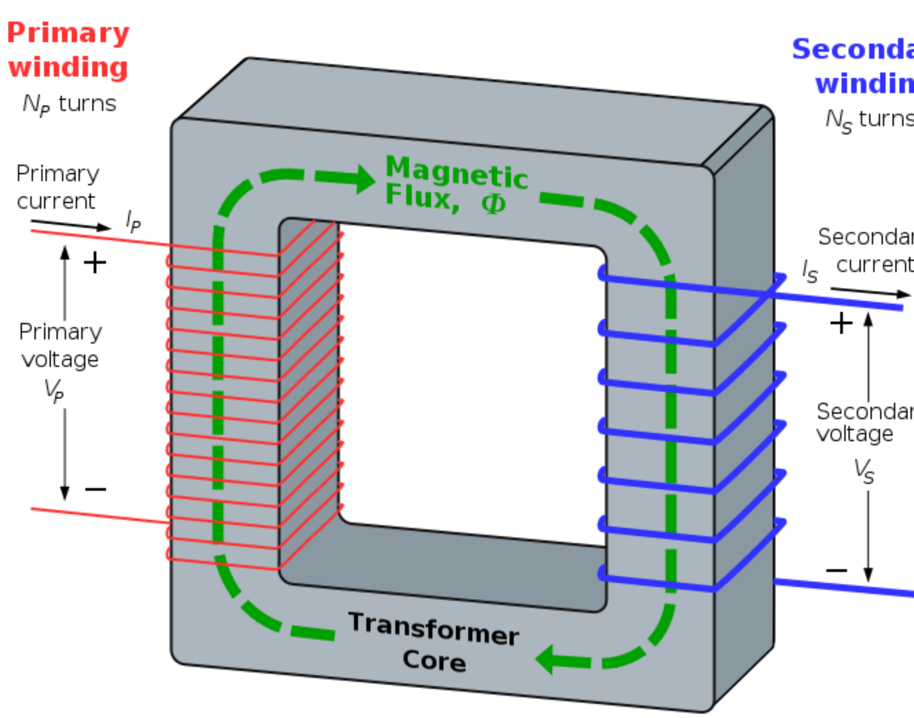
In 1889, Russian-born engineer Mikhail Dolivo-Dobrovolsky developed the first three-phase transformer at the Allgemeine Elektricitäts-Gesellschaft ("General Electricity Company") in Germany.

In 1891, Nikola Tesla invented the Tesla coil, an air-cored, dual-tuned resonant transformer for generating very high voltages at high frequency.

Audio frequency transformers ("repeating coils") were used by early experimenters in the development of the telephone.

Basic principles

The transformer is based on two principles: first, that an electric current can produce a magnetic field (electromagnetism), and, second that a changing magnetic field within a coil of wire induces a voltage across the ends of the coil (electromagnetic induction). Changing the current in the primary coil changes the magnetic flux that is developed. The changing magnetic flux induces a voltage in the secondary coil.



An ideal transformer

An ideal transformer is shown in the adjacent figure. Current passing through the primary coil creates a magnetic field. The primary and secondary coils are wrapped around a core of very high magnetic permeability, such as iron, so that most of the magnetic flux passes through both the primary and secondary coils.

Induction law

The voltage induced across the secondary coil may be calculated from Faraday's law of induction, which states that:

$$V_s = N_s \frac{d\Phi}{dt},$$

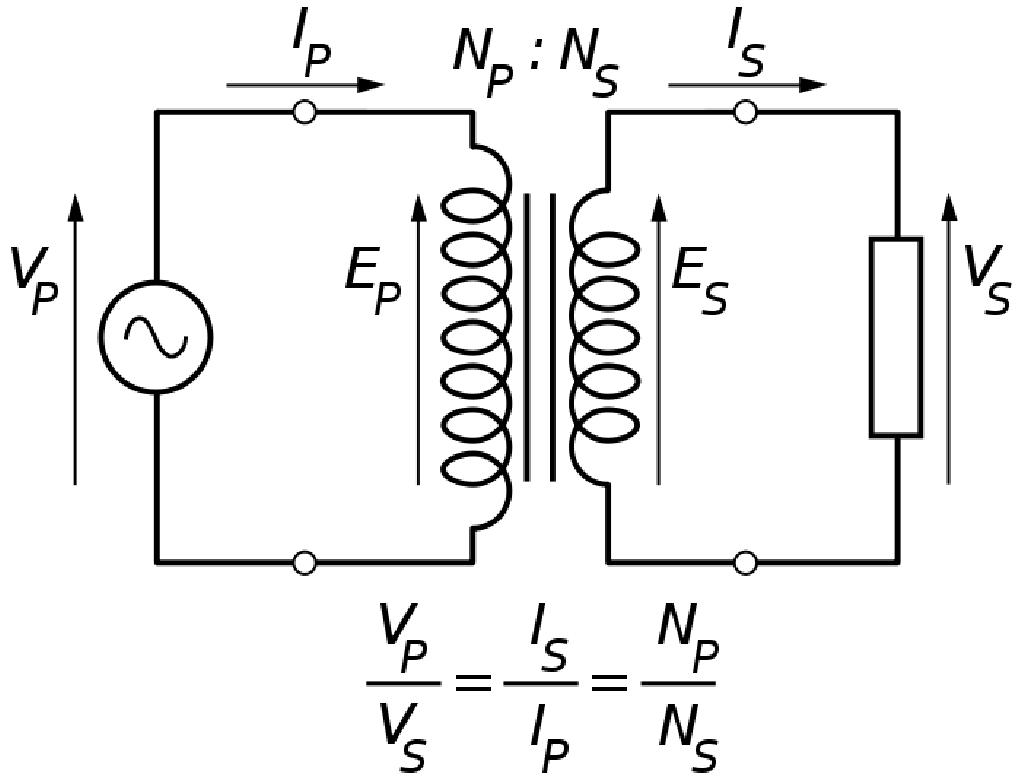
where V_s is the instantaneous voltage, N_s is the number of turns in the secondary coil and Φ is the magnetic flux through one turn of the coil. If the turns of the coil are oriented perpendicular to the magnetic field lines, the flux is the product of the magnetic flux density B and the area A through which it cuts. The area is constant, being equal to the cross-sectional area of the transformer core, whereas the magnetic field varies with time according to the excitation of the primary. Since the same magnetic flux passes through both the primary and secondary coils in an ideal transformer, the instantaneous voltage across the primary winding equals

$$V_p = N_p \frac{d\Phi}{dt}.$$

Taking the ratio of the two equations for V_s and V_p gives the basic equation for stepping up or stepping down the voltage

$$\frac{V_s}{V_p} = \frac{N_s}{N_p}.$$

Ideal power equation



The ideal transformer as a circuit element

If the secondary coil is attached to a load that allows current to flow, electrical power is transmitted from the primary circuit to the secondary circuit. Ideally, the transformer is perfectly efficient; all the incoming energy is transformed from the primary circuit to the magnetic field and into the secondary circuit. If this condition is met, the incoming electric power must equal the outgoing power:

$$P_{\mathrm{incoming}} = I_{\mathrm{p}} V_{\mathrm{p}} = P_{\mathrm{outgoing}} = I_{\mathrm{s}} V_{\mathrm{s}},$$

giving the ideal transformer equation

$$\frac{V_{\mathrm{s}}}{V_{\mathrm{p}}} = \frac{N_{\mathrm{s}}}{N_{\mathrm{p}}} = \frac{I_{\mathrm{p}}}{I_{\mathrm{s}}}.$$

Transformers normally have high efficiency, so this formula is a reasonable approximation.

If the voltage is increased, then the current is decreased by the same factor. The impedance in one circuit is transformed by the square of the turns ratio. For example, if an impedance Z_s is attached across the terminals of the secondary coil, it appears to the primary circuit to have an impedance of $(N_p/N_s)^2Z_s$. This relationship is reciprocal, so that the impedance Z_p of the primary circuit appears to the secondary to be $(N_s/N_p)^2Z_p$.

Detailed operation

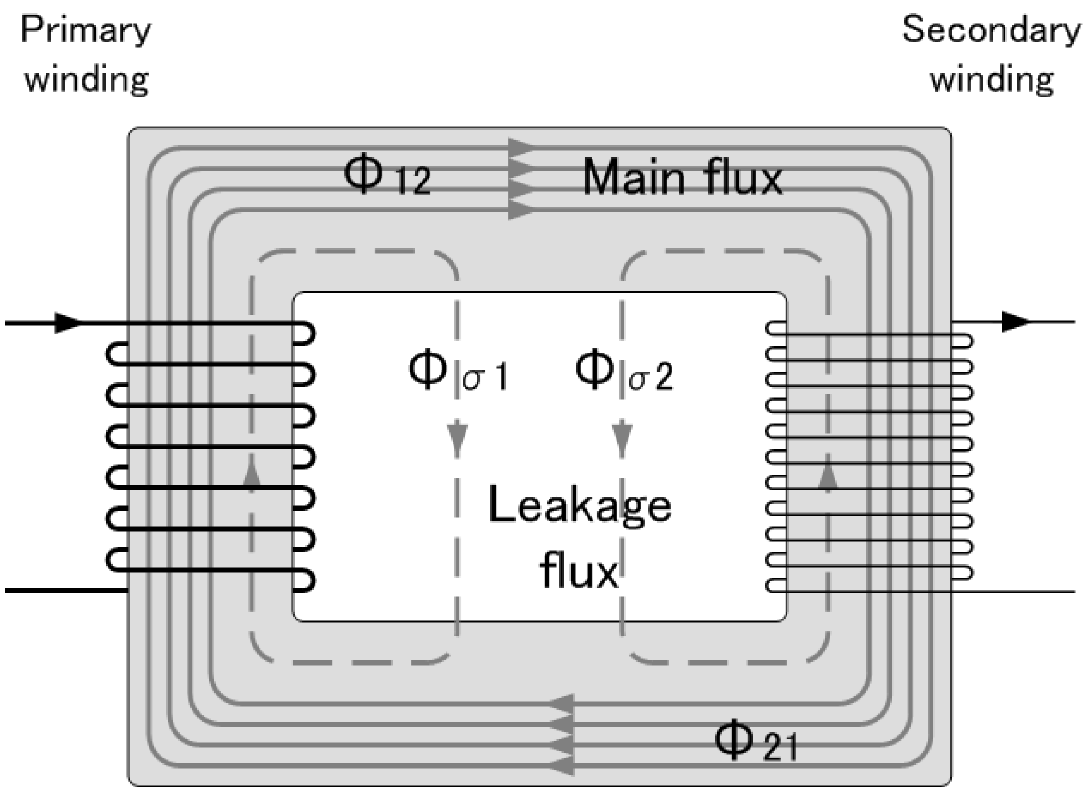
The simplified description above neglects several practical factors, in particular the primary current required to establish a magnetic field in the core, and the contribution to the field due to current in the secondary circuit.

Models of an ideal transformer typically assume a core of negligible reluctance with two windings of zero resistance. When a voltage is applied to the primary winding, a small current flows, driving flux around the magnetic circuit of the core. The current required to create the flux is termed the magnetizing current; since the ideal core has been assumed to have near-zero reluctance, the magnetizing current is negligible, although still required to create the magnetic field.

The changing magnetic field induces an electromotive force (EMF) across each winding. Since the ideal windings have no impedance, they have no associated voltage drop, and so the voltages V_P and V_S measured at the terminals of the transformer, are equal to the corresponding EMFs. The primary EMF, acting as it does in opposition to the primary voltage, is sometimes termed the "back EMF". This is due to Lenz's law which states that the induction of EMF would always be such that it will oppose development of any such change in magnetic field.

Practical considerations

Leakage flux



Leakage flux of a transformer

The ideal transformer model assumes that all flux generated by the primary winding links all the turns of every winding, including itself. In practice, some flux traverses paths that take it outside the windings. Such flux is termed leakage flux, and results in leakage inductance in series with the mutually coupled transformer windings. Leakage results in energy being alternately stored in and discharged from the magnetic fields with each cycle of the power supply. It is not directly a power loss, but results in inferior voltage regulation, causing the secondary voltage to fail to be directly proportional to the primary, particularly under heavy load. Transformers are therefore normally designed to have very low leakage inductance.

However, in some applications, leakage can be a desirable property, and long magnetic paths, air gaps, or magnetic bypass shunts may be deliberately introduced to a transformer's design to limit the short-circuit current it will supply. Leaky transformers may be used to supply loads that exhibit negative resistance, such as electric arcs, mercury vapor lamps, and neon signs; or for safely handling loads that become periodically short-circuited such as electric arc welders.

Air gaps are also used to keep a transformer from saturating, especially audio-frequency transformers in circuits that have a direct current flowing through the windings.

Leakage inductance is also helpful when transformers are operated in parallel. It can be shown that if the "per-unit" inductance of two transformers is the same (a typical value is 5%), they will automatically split power "correctly" (e.g. 500 kVA unit in parallel with 1,000 kVA unit, the larger one will carry twice the current).

Effect of frequency

Transformer universal EMF equation

If the flux in the core is purely sinusoidal, the relationship for either winding between its **rms voltage** E_{rms} of the winding , and the supply frequency f, number of turns N, core cross-sectional area a and peak magnetic flux density B is given by the universal EMF equation:

$$E_{\text{rms}} = \frac{2\pi f N a B_{\text{peak}}}{\sqrt{2}} \approx 4.44 f N a B$$

If the flux does not contain even harmonics the following equation can be used for **half-cycle average voltage** E_{avg} of any waveshape:

$$E_{\text{avg}} = 4 f N a B_{\text{peak}}$$

The time-derivative term in Faraday's Law shows that the flux in the core is the integral with respect to time of the applied voltage. Hypothetically an ideal transformer would work with direct-current excitation, with the core flux increasing linearly with time. In practice, the flux would rise to the point where magnetic saturation of the core occurs, causing a huge increase in the magnetizing current and overheating the transformer. All practical transformers must therefore operate with alternating (or pulsed) current.

The EMF of a transformer at a given flux density increases with frequency. By operating at higher frequencies, transformers can be physically more compact because a given core is able to transfer more power without reaching saturation and fewer turns are needed to achieve the same impedance. However, properties such as core loss and conductor skin effect also increase with frequency. Aircraft and military equipment employ 400 Hz power supplies which reduce core and winding weight. Conversely, frequencies used for some railway electrification systems were much lower (e.g. 16.7 Hz and 25 Hz) than normal utility frequencies (50 – 60 Hz) for historical reasons concerned mainly with the limitations of early electric traction motors. As such, the transformers used to step down the high over-head line voltages (e.g. 15 kV) are much heavier for the same power rating than those designed only for the higher frequencies.

Operation of a transformer at its designed voltage but at a higher frequency than intended will lead to reduced magnetizing current; at lower frequency, the magnetizing current will increase. Operation of a transformer at other than its design frequency may require assessment of voltages, losses, and cooling to establish if safe operation is practical. For example, transformers may need to be equipped with "volts per hertz" over-excitation relays to protect the transformer from overvoltage at higher than rated frequency.

One example of state-of-the-art design is those transformers used for electric multiple unit high speed trains, particularly those required to operate across the borders of countries using different standards of electrification. The position of such transformers is restricted to being hung below the passenger compartment. They have to function at different frequencies (down to 16.7 Hz) and voltages (up to 25 kV) whilst handling the enhanced power requirements needed for operating the trains at high speed.

Knowledge of natural frequencies of transformer windings is of importance for the determination of the transient response of the windings to impulse and switching surge voltages.

Energy losses

An ideal transformer would have no energy losses, and would be 100% efficient. In practical transformers energy is dissipated in the windings, core, and surrounding structures. Larger transformers are generally more efficient, and those rated for electricity distribution usually perform better than 98%.

Experimental transformers using superconducting windings achieve efficiencies of 99.85%. The increase in efficiency from about 98 to 99.85% can save considerable energy, and hence money, in a large heavily-loaded transformer; the trade-off is in the additional initial and running cost of the superconducting design.

Losses in transformers (excluding associated circuitry) vary with load current, and may be expressed as "no-load" or "full-load" loss. Winding resistance dominates load losses, whereas hysteresis and eddy currents losses contribute to over 99% of the no-load loss. The no-load loss can be significant, so that even an idle transformer constitutes a drain on the electrical supply and a running cost; designing transformers for lower loss requires a larger core, good-quality silicon steel, or even amorphous steel, for the core, and thicker wire, increasing initial cost, so that there is a trade-off between initial cost and running cost.

Transformer losses are divided into losses in the windings, termed copper loss, and those in the magnetic circuit, termed iron loss. Losses in the transformer arise from:

Winding resistance

Current flowing through the windings causes resistive heating of the conductors. At higher frequencies, skin effect and proximity effect create additional winding resistance and losses.

Hysteresis losses

Each time the magnetic field is reversed, a small amount of energy is lost due to hysteresis within the core. For a given core material, the loss is proportional to the frequency, and is a function of the peak flux density to which it is subjected.

Eddy currents

Ferromagnetic materials are also good conductors, and a core made from such a material also constitutes a single short-circuited turn throughout its entire length. Eddy currents therefore circulate within the core in a plane normal to the flux, and are responsible for resistive heating of the core material. The eddy current loss is a complex function of the square of supply frequency and inverse square of the material thickness. Eddy current losses can be reduced by making the core of a stack of plates electrically insulated from each other, rather than a solid block; all transformers operating at low frequencies use laminated or similar cores.

Magnetostriction

Magnetic flux in a ferromagnetic material, such as the core, causes it to physically expand and contract slightly with each cycle of the magnetic field, an effect known as magnetostriction. This produces the buzzing sound commonly associated with transformers, and can cause losses due to frictional heating.

Mechanical losses

In addition to magnetostriction, the alternating magnetic field causes fluctuating forces between the primary and secondary windings. These incite vibrations within nearby metalwork, adding to the buzzing noise, and consuming a small amount of power.

Stray losses

Leakage inductance is by itself largely lossless, since energy supplied to its magnetic fields is returned to the supply with the next half-cycle. However, any leakage flux that intercepts nearby conductive materials such as the transformer's support structure will give rise to eddy currents and be converted to heat. There are also radiative losses due to the oscillating magnetic field, but these are usually small.

Dot convention

It is common in transformer schematic symbols for there to be a dot at the end of each coil within a transformer, particularly for transformers with multiple primary and secondary windings. The dots indicate the direction of each winding relative to the others. Voltages at the dot end of each winding are in phase; current flowing into the dot end of a primary coil will result in current flowing out of the dot end of a secondary coil.

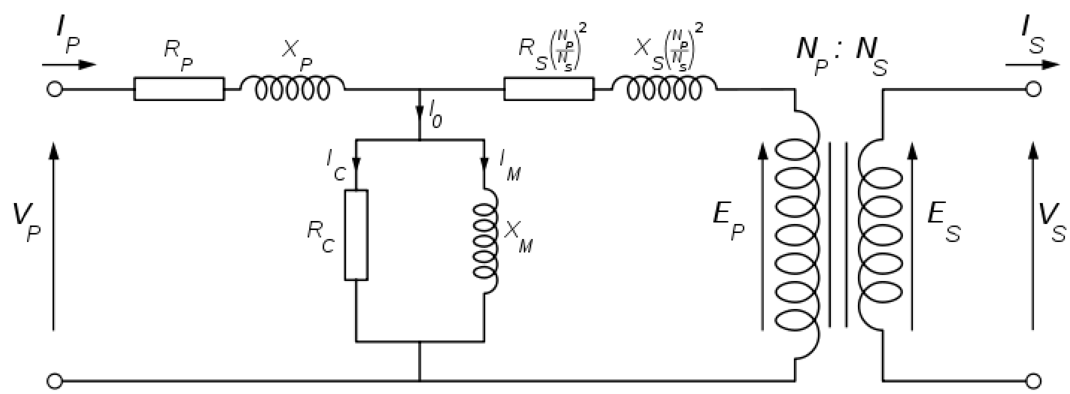
Equivalent circuit

The physical limitations of the practical transformer may be brought together as an equivalent circuit model (shown below) built around an ideal lossless transformer. Power loss in the windings is current-dependent and is represented as in-series resistances R_p and R_s. Flux leakage results in a fraction of the applied voltage dropped without contributing to the mutual coupling, and thus can be modeled as reactances of each leakage inductance X_p and X_s in series with the perfectly coupled region.

Iron losses are caused mostly by hysteresis and eddy current effects in the core, and are proportional to the square of the core flux for operation at a given frequency. Since the core flux is proportional to the applied voltage, the iron loss can be represented by a resistance R_C in parallel with the ideal transformer.

A core with finite permeability requires a magnetizing current I_m to maintain the mutual flux in the core. The magnetizing current is in phase with the flux; saturation effects cause the relationship between the two to be non-linear, but for simplicity this effect tends to be ignored in most circuit equivalents. With a sinusoidal supply, the core flux lags the induced EMF by 90° and this effect can be modeled as a magnetizing reactance (reactance of an effective inductance) X_m in parallel with the core loss component. R_c and X_m are sometimes together termed the magnetizing branch of the model. If the secondary winding is made open-circuit, the current I_0 taken by the magnetizing branch represents the transformer's no-load current.

The secondary impedance R_s and X_s is frequently moved (or "referred") to the primary side after multiplying the components by the impedance scaling factor $(N_p/N_s)^2$.



Transformer equivalent circuit, with secondary impedances referred to the primary side

The resulting model is sometimes termed the "exact equivalent circuit", though it retains a number of approximations, such as an assumption of linearity. Analysis may be simplified by moving the magnetizing branch to the left of the primary impedance, an implicit assumption that the magnetizing current is low, and then summing primary and referred secondary impedances, resulting in so-called equivalent impedance.

The parameters of equivalent circuit of a transformer can be calculated from the results of two transformer tests: open-circuit test and short-circuit test.

Types

A wide variety of transformer designs are used for different applications, though they share several common features. Important common transformer types include:

Autotransformer

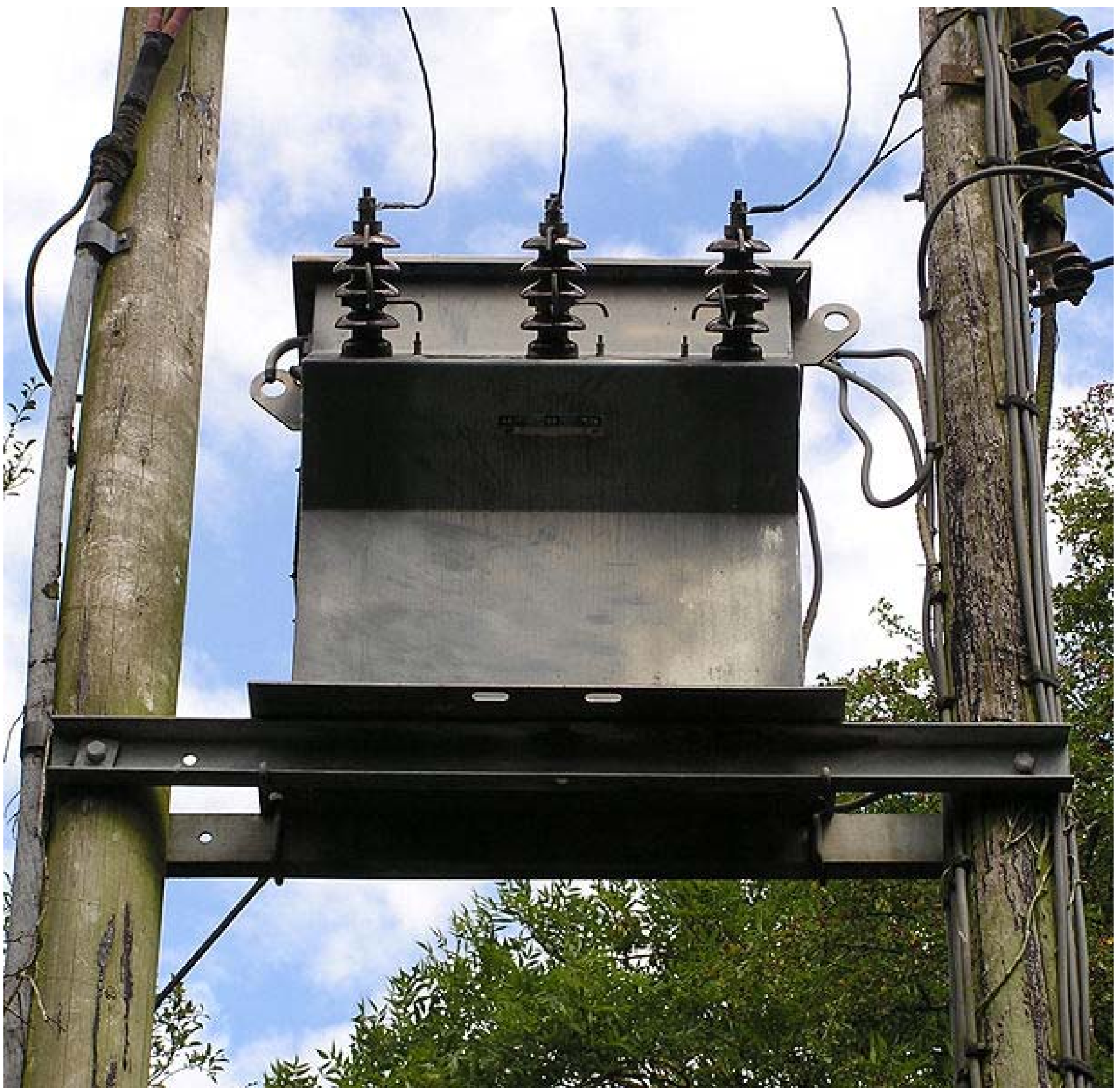
An autotransformer with a sliding brush contact

An autotransformer has a single winding with two end terminals, and one or more terminals at intermediate tap points. The primary voltage is applied across two of the terminals, and the secondary voltage taken from two terminals, almost always having one terminal in common with the primary voltage. The primary and secondary circuits therefore have a number of windings turns in common. Since the volts-per-turn is the same in both windings, each develops a voltage in proportion to its number of turns. In an autotransformer part of the current flows directly from the input to the output, and only part is transferred inductively, allowing a smaller, lighter, cheaper core to be used as well as requiring only a single winding. However, a transformer with separate windings isolates the primary from the secondary, which is safer when using mains voltages.

An adjustable autotransformer is made by exposing part of the winding coils and making the secondary connection through a sliding brush, giving a variable turns ratio. Such a device is often referred to as a variac.

Autotransformers are often used to step up or down between voltages in the 110-117-120 volt range and voltages in the 220-230-240 volt range, e.g., to output either 110 or 120V (with taps) from 230V input, allowing equipment from a 100 or 120V region to be used in a 230V region.

Polyphase transformers



Three-phase step-down transformer mounted between two utility poles

For three-phase supplies, a bank of three individual single-phase transformers can be used, or all three phases can be incorporated as a single three-phase transformer. In this case, the magnetic circuits are connected together, the core thus containing a three-phase flow of flux. A number of winding configurations are possible, giving rise to different attributes and phase shifts. One particular polyphase configuration is the zigzag transformer, used for grounding and in the suppression of harmonic currents.

Leakage transformers

Leakage transformer

A leakage transformer, also called a stray-field transformer, has a significantly higher leakage inductance than other transformers, sometimes increased by a magnetic bypass or shunt in its core between primary and secondary, which is sometimes adjustable with a set screw. This provides a transformer with an inherent current limitation due to the loose coupling between its primary and the secondary windings. The output and input currents are low enough to prevent thermal overload under all load conditions—even if the secondary is shorted.

Leakage transformers are used for arc welding and high voltage discharge lamps (neon lights and cold cathode fluorescent lamps, which are series-connected up to 7.5 kV AC). It acts then both as a voltage transformer and as a magnetic ballast.

Other applications are short-circuit-proof extra-low voltage transformers for toys or doorbell installations.

Resonant transformers

A resonant transformer is a kind of leakage transformer. It uses the leakage inductance of its secondary windings in combination with external capacitors, to create one or more resonant circuits. Resonant transformers such as the Tesla coil can generate very high voltages, and are able to provide much higher current than electrostatic high-voltage generation machines such as the Van de Graaff generator. One of the applications of the resonant transformer is for the CCFL inverter. Another application of the resonant transformer is to couple between stages of a superheterodyne receiver, where the selectivity of the receiver is provided by tuned transformers in the intermediate-frequency amplifiers.

Audio transformers

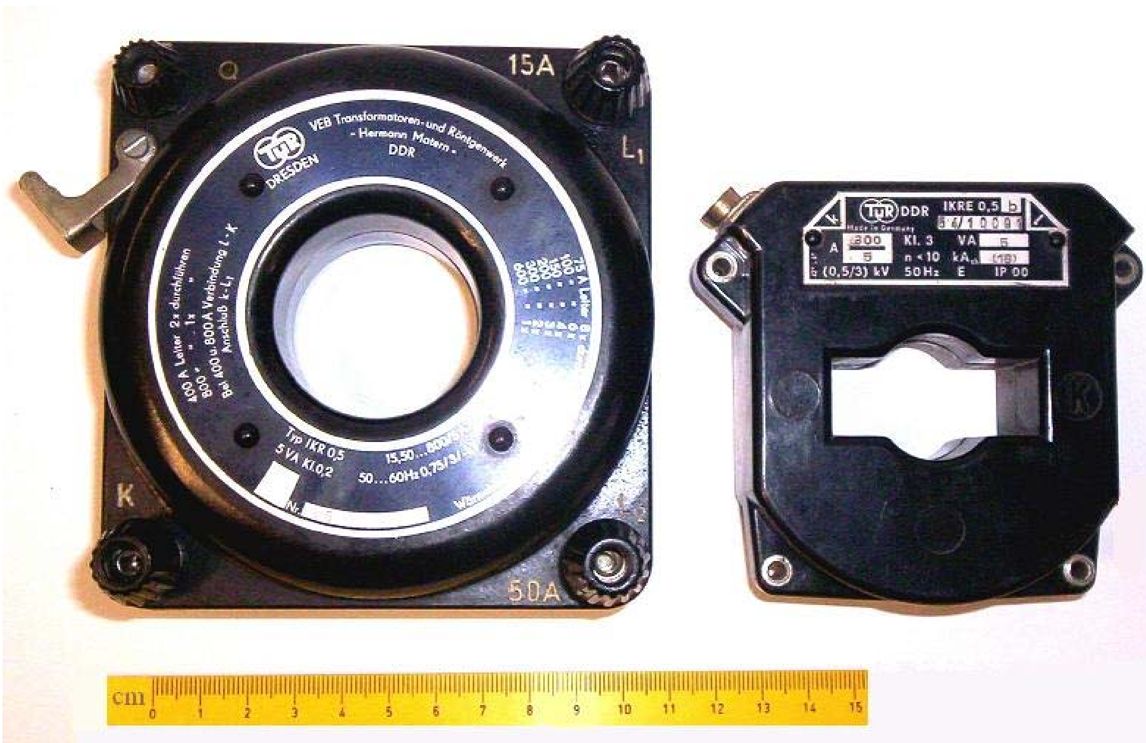
Audio transformers are those specifically designed for use in audio circuits. They can be used to block radio frequency interference or the DC component of an audio signal, to split or combine audio signals, or to provide impedance matching between high and low impedance circuits, such as between a high impedance tube (valve) amplifier output and a low impedance loudspeaker, or between a high impedance instrument output and the low impedance input of a mixing console.

Such transformers were originally designed to connect different telephone systems to one another while keeping their respective power supplies isolated, and are still commonly used to interconnect professional audio systems or system components.

Being magnetic devices, audio transformers are susceptible to external magnetic fields such as those generated by AC current-carrying conductors. "Hum" is a term commonly used to describe unwanted signals originating from the "mains" power supply (typically 50 or 60 Hz). Audio transformers used for low-level signals, such as those from microphones, often include shielding to protect against extraneous magnetically coupled signals.

Instrument transformers

Instrument transformers are used for measuring voltage and current in electrical power systems, and for power system protection and control. Where a voltage or current is too large to be conveniently used by an instrument, it can be scaled down to a standardized, low value. Instrument transformers isolate measurement, protection and control circuitry from the high currents or voltages present on the circuits being measured or controlled.



Current transformers, designed for placing around conductors

A current transformer is a transformer designed to provide a current in its secondary coil proportional to the current flowing in its primary coil.

Voltage transformers (VTs), also referred to as "potential transformers" (PTs), are designed to have an accurately known transformation ratio in both magnitude and phase, over a range of measuring circuit impedances. A voltage transformer is intended to present a negligible load to the supply being measured. The low secondary voltage allows protective relay equipment and measuring instruments to be operated at a lower voltages.

Both current and voltage instrument transformers are designed to have predictable characteristics on overloads. Proper operation of over-current protective relays requires that current transformers provide a predictable transformation ratio even during a short-circuit.

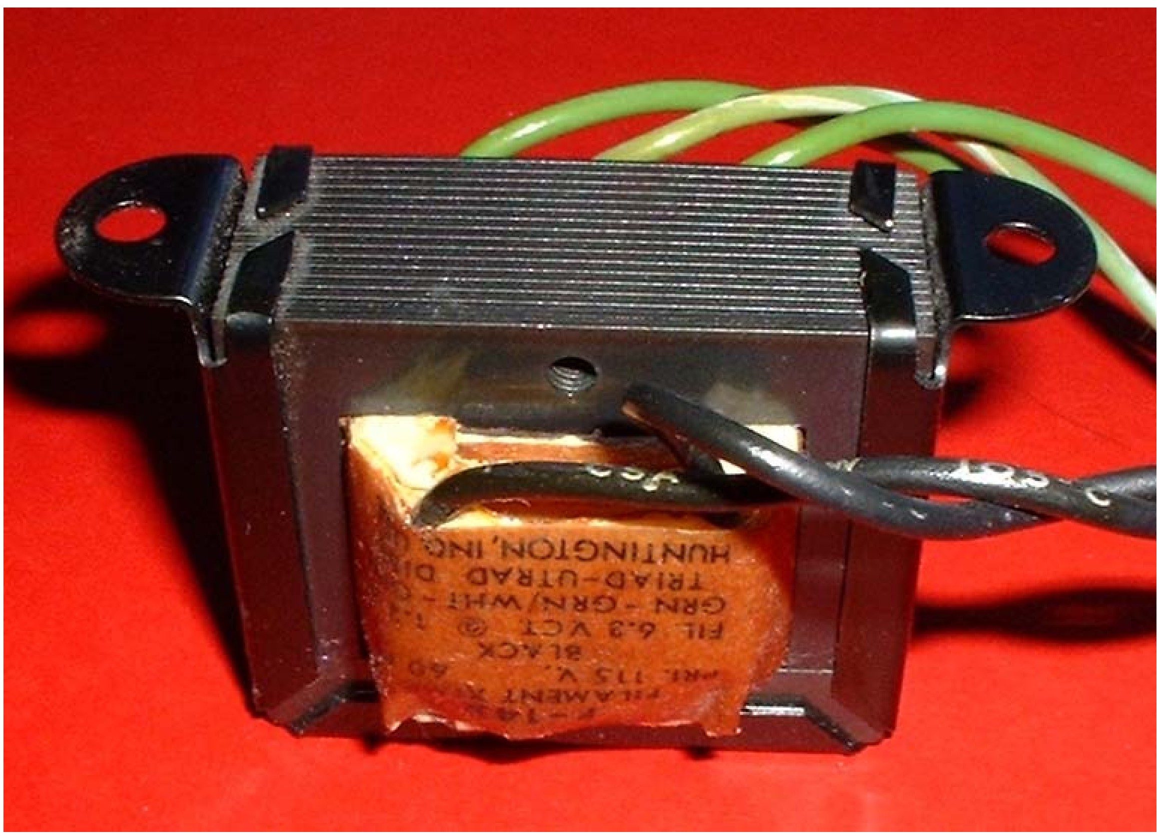
Classification

Transformers can be classified in many different ways; an incomplete list is:

- By power capacity: from a fraction of a volt-ampere (VA) to over a thousand MVA;
- By frequency range: power-, audio-, or radio frequency;
- By voltage class: from a few volts to hundreds of kilovolts;
- By cooling type: air-cooled, oil-filled, fan-cooled, or water-cooled;
- By application: such as power supply, impedance matching, output voltage and current stabilizer, or circuit isolation;
- By purpose: distribution, rectifier, arc furnace, amplifier output, etc.;
- By winding turns ratio: step-up, step-down, isolating with equal or near-equal ratio, variable, multiple windings.

Construction

Cores

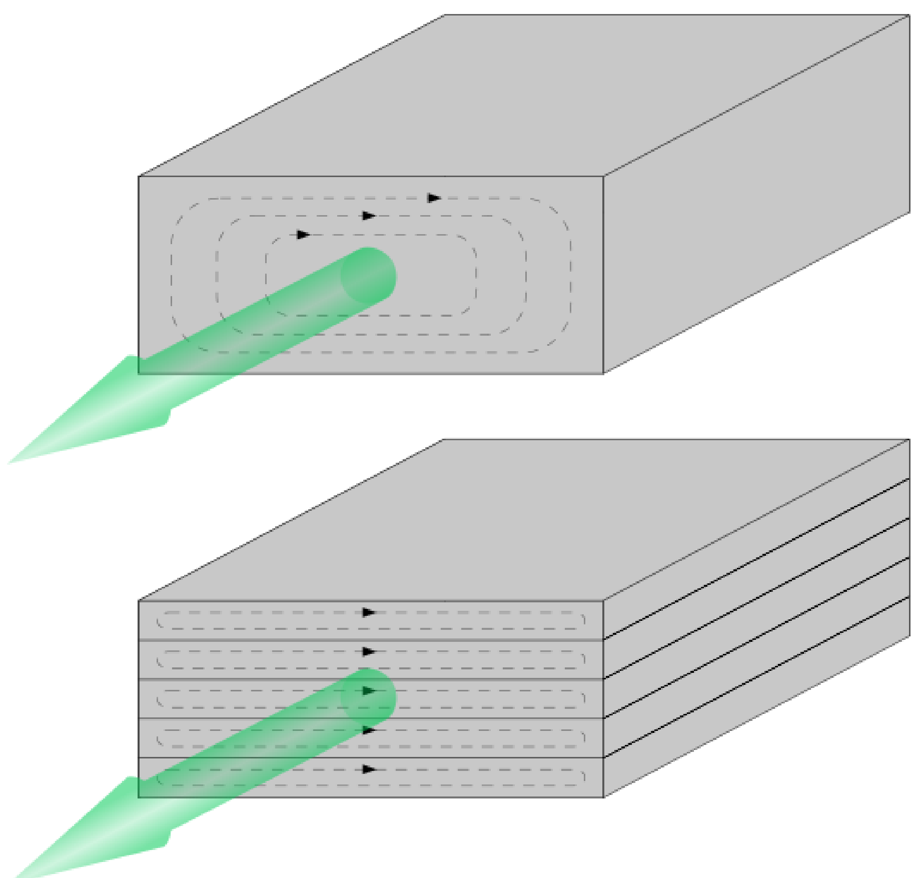


Laminated core transformer showing edge of laminations at top of photo

Laminated steel cores

Transformers for use at power or audio frequencies typically have cores made of high permeability silicon steel. The steel has a permeability many times that of free space, and the core thus serves to greatly reduce the magnetizing current, and confine the flux to a path which closely couples the windings. Early transformer developers soon realized that cores constructed from solid iron resulted in prohibitive eddy-current losses, and their designs mitigated this effect with cores consisting of bundles of insulated iron wires. Later designs constructed the core by stacking layers of thin steel laminations, a principle that has remained in use. Each lamination is insulated from its neighbors by a thin non-conducting layer of insulation. The universal transformer equation indicates a minimum cross-sectional area for the core to avoid saturation.

The effect of laminations is to confine eddy currents to highly elliptical paths that enclose little flux, and so reduce their magnitude. Thinner laminations reduce losses, but are more laborious and expensive to construct. Thin laminations are generally used on high frequency transformers, with some types of very thin steel laminations able to operate up to 10 kHz.



Laminating the core greatly reduces eddy-current losses

One common design of laminated core is made from interleaved stacks of E-shaped steel sheets capped with I-shaped pieces, leading to its name of "E-I transformer". Such a design tends to exhibit more losses, but is very economical to manufacture. The cut-core or C-core type is made by winding a steel strip around a rectangular form and then bonding the layers together. It is then cut in two, forming two C shapes, and the core assembled by binding the two C halves together with a steel strap. They have the advantage that the flux is always oriented parallel to the metal grains, reducing reluctance.

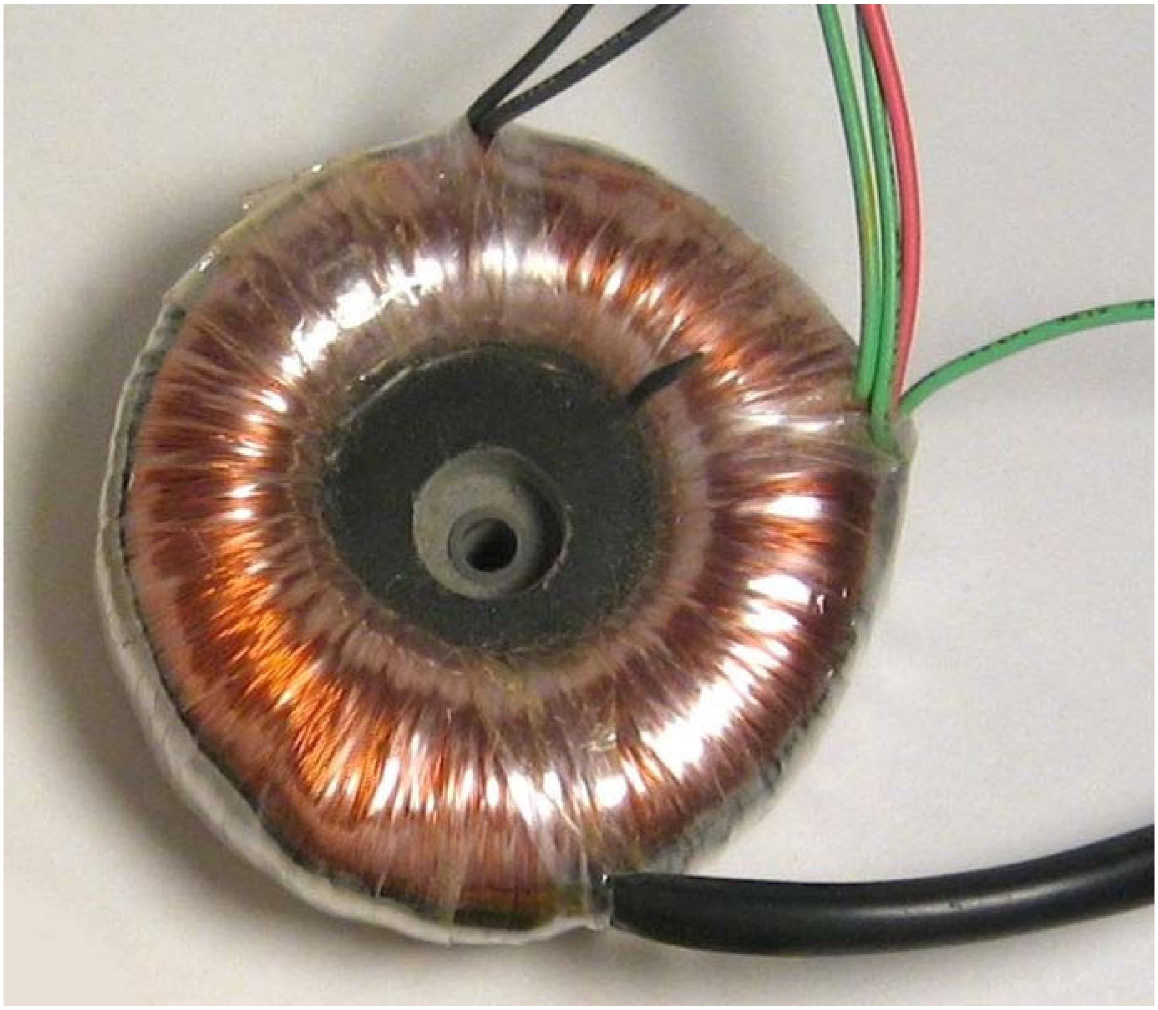
A steel core's remanence means that it retains a static magnetic field when power is removed. When power is then reapplied, the residual field will cause a high inrush current until the effect of the remaining magnetism is reduced, usually after a few cycles of the applied alternating current. Overcurrent protection devices such as fuses must be selected to allow this harmless inrush to pass. On transformers connected to long, overhead power transmission lines, induced currents due to geomagnetic disturbances during solar storms can cause saturation of the core and operation of transformer protection devices.

Distribution transformers can achieve low no-load losses by using cores made with low-loss high-permeability silicon steel or amorphous (non-crystalline) metal alloy. The higher initial cost of the core material is offset over the life of the transformer by its lower losses at light load.

Solid cores

Powdered iron cores are used in circuits (such as switch-mode power supplies) that operate above main frequencies and up to a few tens of kilohertz. These materials combine high magnetic permeability with high bulk electrical resistivity. For frequencies extending beyond the VHF band, cores made from non-conductive magnetic ceramic materials called ferrites are common. Some radio-frequency transformers also have movable cores (sometimes called 'slugs') which allow adjustment of the coupling coefficient (and bandwidth) of tuned radio-frequency circuits.

Toroidal cores



Small toroidal core transformer

Toroidal transformers are built around a ring-shaped core, which, depending on operating frequency, is made from a long strip of silicon steel or permalloy wound into a coil, powdered iron, or ferrite. A strip construction ensures that the grain boundaries are optimally aligned, improving the transformer's efficiency by reducing the core's reluctance. The closed ring shape eliminates air gaps inherent in the construction of an E-I core. The cross-section of the ring is usually square or rectangular, but more expensive cores with circular cross-sections are also available. The primary and secondary coils are often wound concentrically to cover the entire surface of the core. This minimizes the length of wire needed, and also provides screening to minimize the core's magnetic field from generating electromagnetic interference.

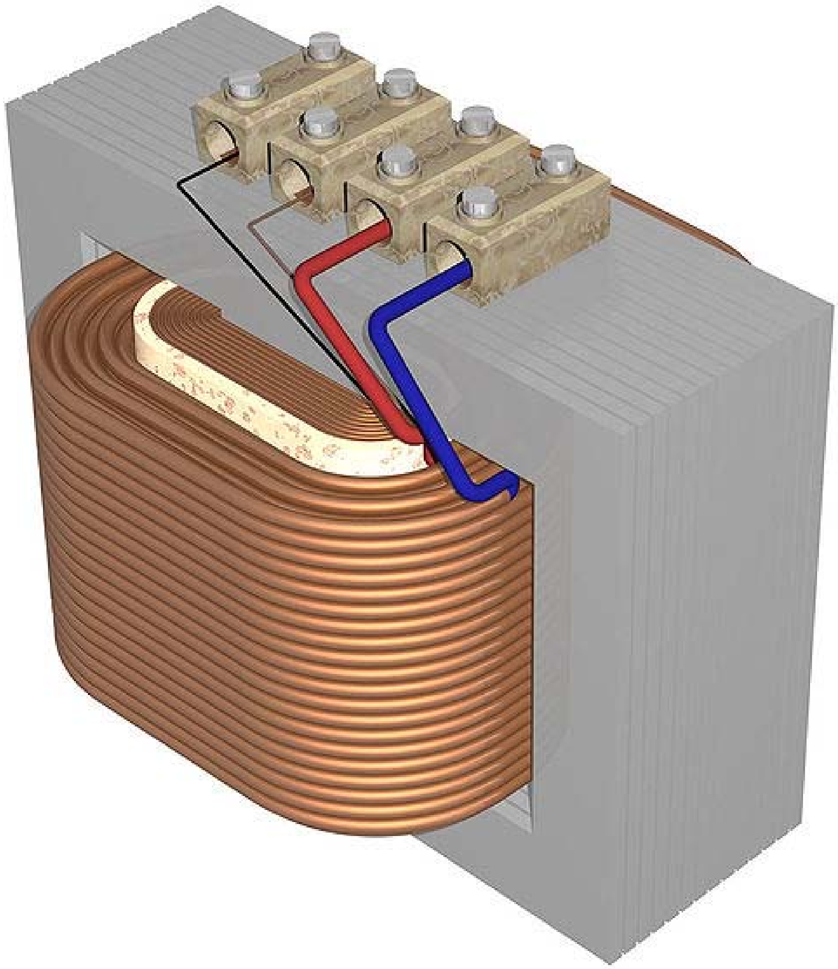
Toroidal transformers are more efficient than the cheaper laminated E-I types for a similar power level. Other advantages compared to E-I types, include smaller size (about half), lower weight (about half), less mechanical hum (making them superior in audio amplifiers), lower exterior magnetic field (about one tenth), low off-load losses (making them more efficient in standby circuits), single-bolt mounting, and greater choice of shapes. The main disadvantages are higher cost and limited power capacity. Because of the lack of a residual gap in the magnetic path, toroidal transformers also tend to exhibit higher inrush current, compared to laminated E-I types.

Ferrite toroidal cores are used at higher frequencies, typically between a few tens of kilohertz to hundreds of megahertz, to reduce losses, physical size, and weight of switch-mode power supplies. A drawback of toroidal transformer construction is the higher labor cost of winding. This is because it is necessary to pass the entire length of a coil winding through the core aperture each time a single turn is added to the coil. As a consequence, toroidal transformers are uncommon above ratings of a few kVA. Small distribution transformers may achieve some of the benefits of a toroidal core by splitting it and forcing it open, then inserting a bobbin containing primary and secondary windings.

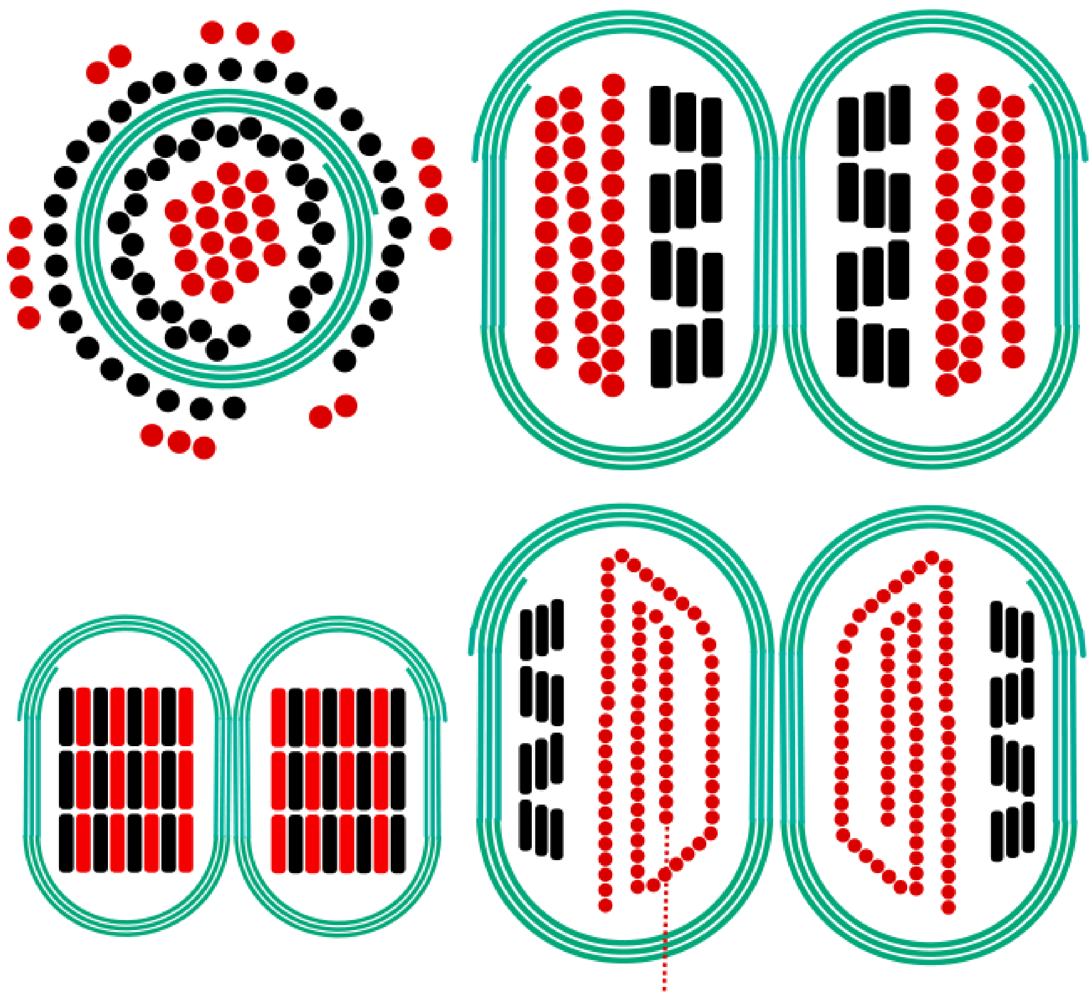
Air cores

A physical core is not an absolute requisite and a functioning transformer can be produced simply by placing the windings near each other, an arrangement termed an "air-core" transformer. The air which comprises the magnetic circuit is essentially lossless, and so an air-core transformer eliminates loss due to hysteresis in the core material. The leakage inductance is inevitably high, resulting in very poor regulation, and so such designs are unsuitable for use in power distribution. They have however very high bandwidth, and are frequently employed in radio-frequency applications, for which a satisfactory coupling coefficient is maintained by carefully overlapping the primary and secondary windings. They're also used for resonant transformers such as Tesla coils where they can achieve reasonably low loss in spite of the high leakage inductance.

Windings



Windings are usually arranged concentrically to minimize flux leakage.



Cut view through transformer windings. White: insulator. Green spiral: Grain oriented silicon steel. Black: Primary winding made of oxygen-free copper. Red: Secondary winding. Top left: Toroidal transformer. Right: C-core, but E-core would be similar. The black windings are made of film. Top: Equally low capacitance between all ends of both windings. Since most cores are at least moderately conductive they also need insulation. Bottom: Lowest capacitance for one end of the secondary winding needed for low-power high-voltage transformers. Bottom left: Reduction of leakage inductance would lead to increase of capacitance.

The conducting material used for the windings depends upon the application, but in all cases the individual turns must be electrically insulated from each other to ensure that the current travels throughout every turn. For small power and signal transformers, in which currents are low and the potential difference between adjacent turns is small, the coils are often wound from enamelled magnet wire, such as Formvar wire. Larger power transformers operating at high voltages may be wound with copper rectangular strip conductors insulated by oil-impregnated paper and blocks of pressboard.

High-frequency transformers operating in the tens to hundreds of kilohertz often have windings made of braided Litz wire to minimize the skin-effect and proximity effect losses. Large power transformers use multiple-stranded conductors as well, since even at low power frequencies non-uniform distribution of current would otherwise exist in high-current windings. Each strand is individually insulated, and the strands are arranged so that at certain points in the winding, or throughout the whole winding, each portion occupies different relative positions in the complete conductor. The transposition equalizes the current flowing in each strand of the conductor, and reduces eddy current losses in the winding itself. The stranded conductor is also more flexible than a solid conductor of similar size, aiding manufacture.

For signal transformers, the windings may be arranged in a way to minimize leakage inductance and stray capacitance to improve high-frequency response. This can be done by splitting up each coil into sections, and those sections placed in layers between the sections of the other winding. This is known as a stacked type or interleaved winding.

Both the primary and secondary windings on power transformers may have external connections, called taps, to intermediate points on the winding to allow selection of the voltage ratio. In power distribution transformers the taps may be connected to an automatic on-load tap changer for voltage regulation of distribution circuits. Audio-frequency transformers, used for the distribution of audio to public address loudspeakers, have taps to allow adjustment of impedance to each speaker. A center-tapped transformer is often used in the output stage of an audio power amplifier in a push-pull circuit. Modulation transformers in AM transmitters are very similar.

Certain transformers have the windings protected by epoxy resin. By impregnating the transformer with epoxy under a vacuum, one can replace air spaces within the windings with epoxy, thus sealing the windings and helping to prevent the possible formation of corona and absorption of dirt or water. This produces transformers more suited to damp or dirty environments, but at increased manufacturing cost.

Coolant

Cut-away view of three-phase oil-cooled transformer. The oil reservoir is visible at the top. Radiative fins aid the dissipation of heat.

High temperatures will damage the winding insulation. Small transformers do not generate significant heat and are cooled by air circulation and radiation of heat. Power transformers rated up to several hundred kVA can be adequately cooled by natural convective air-cooling, sometimes assisted by fans. In larger transformers, part of the design problem is removal of heat. Some power transformers are immersed in transformer oil that both cools and insulates the windings. The oil is a highly refined mineral oil that remains stable at transformer operating temperature. Indoor liquid-filled transformers are required by building regulations in many jurisdictions to use a non-flammable liquid, or to be located in fire-resistant rooms. Air-cooled dry transformers are preferred for indoor applications even at capacity ratings where oil-cooled construction would be more economical, because their cost is offset by the reduced building construction cost.

The oil-filled tank often has radiators through which the oil circulates by natural convection; some large transformers employ forced circulation of the oil by electric pumps, aided by external fans or water-cooled heat exchangers. Oil-filled transformers undergo prolonged drying processes to ensure that the transformer is completely free of water vapor before the cooling oil is introduced. This helps prevent electrical breakdown under load. Oil-filled transformers may be equipped with Buchholz relays, which detect gas evolved during internal arcing and rapidly de-energize the transformer to avert catastrophic failure. Oil-filled transformers may fail, rupture, and burn, causing power outages and losses. Installations of oil-filled transformers usually includes fire protection measures such as walls, oil containment, and fire-suppression sprinkler systems.

Polychlorinated biphenyls have properties that once favored their use as a coolant, though concerns over their environmental persistence led to a widespread ban on their use. Today, non-toxic, stable silicone-based oils, or fluorinated hydrocarbons may be used where the expense of a fire-resistant liquid offsets additional building cost for a transformer vault. Before 1977, even transformers that were nominally filled only with mineral oils may also have been contaminated with polychlorinated biphenyls at 10-20 ppm. Since mineral oil and PCB fluid mix, maintenance equipment used for both PCB and oil-filled transformers could carry over small amounts of PCB, contaminating oil-filled transformers.

Some "dry" transformers (containing no liquid) are enclosed in sealed, pressurized tanks and cooled by nitrogen or sulfur hexafluoride gas.

Experimental power transformers in the 2 MVA range have been built with superconducting windings which eliminates the copper losses, but not the core steel loss. These are cooled by liquid nitrogen or helium.

Insulation drying

Construction of oil-filled transformers requires that the insulation covering the windings be thoroughly dried before the oil is introduced. There are several different methods of drying. Common for all is that they are carried out in vacuum environment. The vacuum makes it difficult to transfer energy (heat) to the insulation. For this there are several different methods. The traditional drying is done by circulating hot air over the active part and cycle this with periods of vacuum (Hot Air Vacuum drying, HAV). More common for larger transformers is to use evaporated solvent which condenses on the colder active part. The benefit is that the entire process can be carried out at lower pressure and without influence of added oxygen. This process is commonly called Vapour Phase Drying (VPD).

For distribution transformers which are smaller and have a smaller insulation weight, resistance heating can be used. This is a method where current is injected in the windings and the resistance in the windings is heating up the insulation. The benefit is that the heating can be controlled very well and it is energy efficient. The method is called Low Frequency Heating (LFH) since the current is injected at a much lower frequency than the nominal of the grid, which is normally 50 or 60 Hz. A lower frequency reduces the affect of the inductance in the transformer and the voltage can be reduced.

Terminals

Very small transformers will have wire leads connected directly to the ends of the coils, and brought out to the base of the unit for circuit connections. Larger transformers may have heavy bolted terminals, bus bars or high-voltage insulated bushings made of polymers or porcelain. A large bushing can be a complex structure since it must provide careful control of the electric field gradient without letting the transformer leak oil.

Applications

Image of an electrical substation in Melbourne, Australia showing 3 of 5 220kV/66kV transformers, each with a capacity of 185MVA

A major application of transformers is to increase voltage before transmitting electrical energy over long distances through wires. Wires have resistance and so dissipate electrical energy at a rate proportional to the square of the current through the wire. By transforming electrical power to a high-voltage (and therefore low-current) form for transmission and back again afterward, transformers enable economic transmission of power over long distances. Consequently, transformers have shaped the electricity supply industry, permitting generation to be located remotely from points of demand. All but a tiny fraction of the world's electrical power has passed through a series of transformers by the time it reaches the consumer.

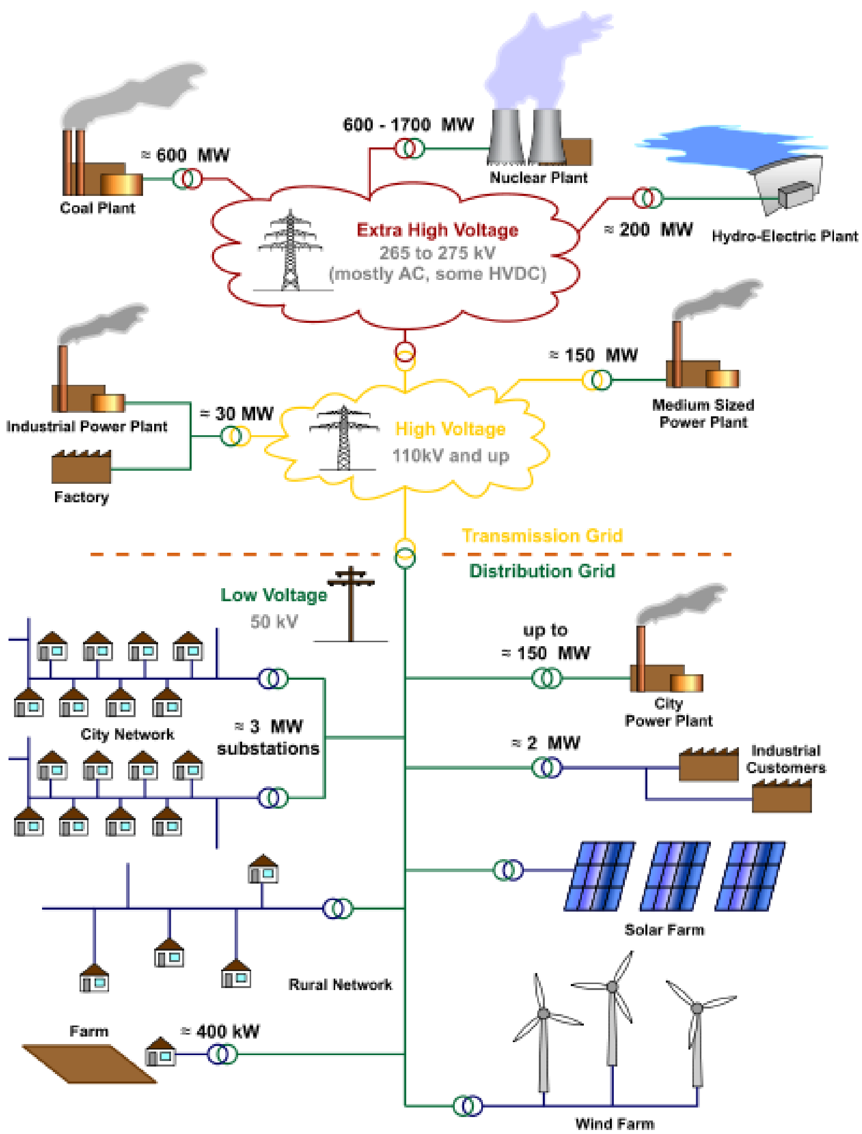
Transformers are also used extensively in electronic products to step down the supply voltage to a level suitable for the low voltage circuits they contain. The transformer also electrically isolates the end user from contact with the supply voltage.

Signal and audio transformers are used to couple stages of amplifiers and to match devices such as microphones and record players to the input of amplifiers. Audio transformers allowed telephone circuits to carry on a two-way conversation over a single pair of wires. A balun transformer converts a signal that is referenced to ground to a signal that has balanced voltages to ground, such as between external cables and internal circuits.

The principle of open-circuit (unloaded) transformer is widely used for characterisation of soft magnetic materials, for example in the internationally standardised Epstein frame method.

Chapter-12

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.

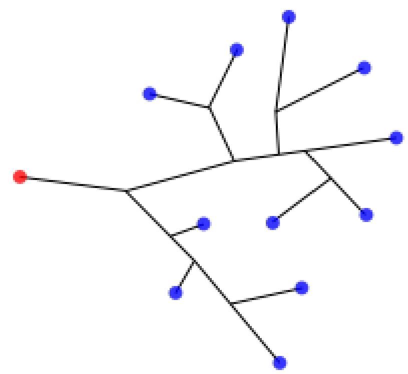
Electricity in a remote location might be provided by a simple distribution grid linking a central generator to homes. The traditional paradigm for moving electricity around in developed countries is more complex. Generating plants are usually located near a source of water, and away from heavily populated 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 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.



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).

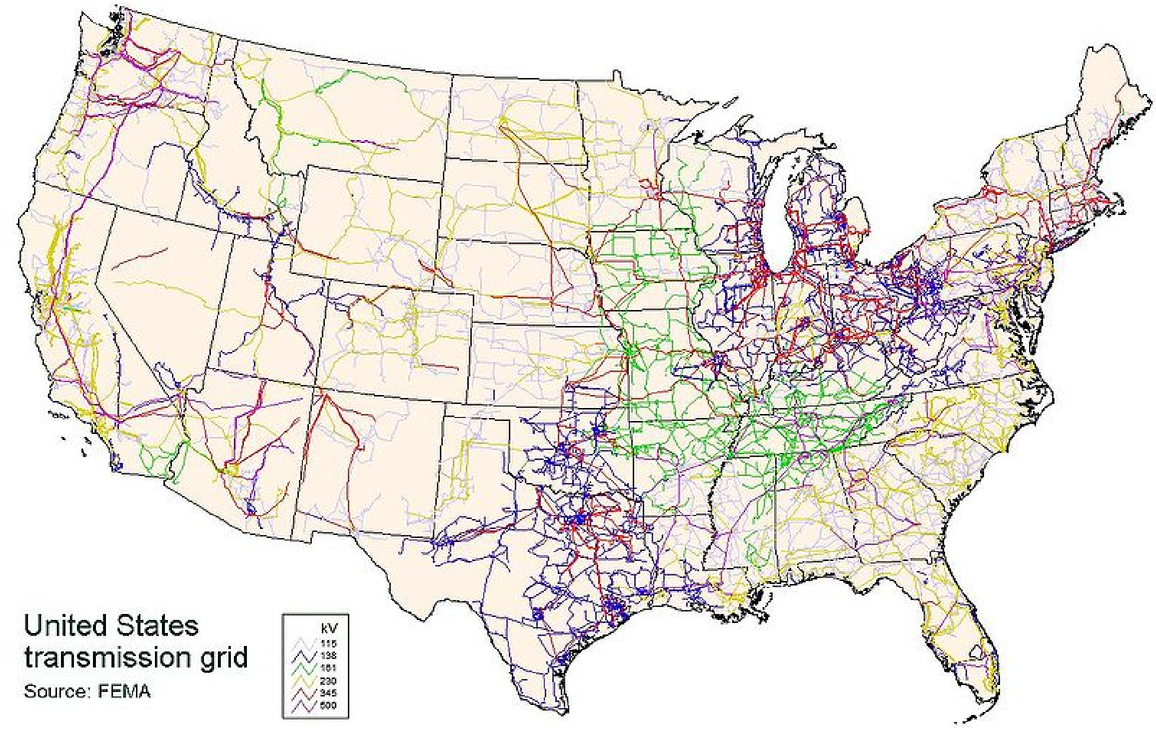
The cheapest and simplest topology for a distribution or transmission grid is a radial structure. This is a tree shape where power from a large supply radiates out into progressively lower voltage lines until the destination homes and businesses are reached.

Most transmission grids require the reliability that more complex mesh networks provide. If one were to imagine running redundant lines between each limb and branch 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.

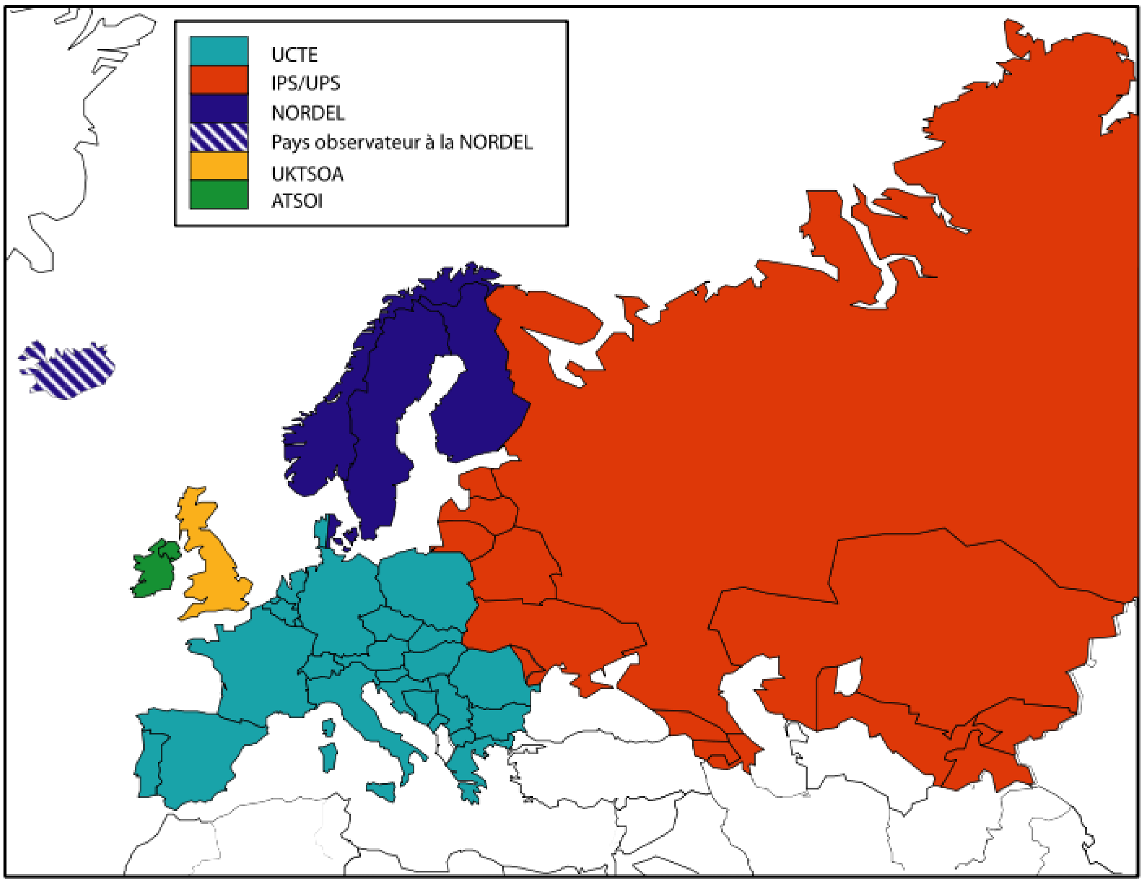
Transmission networks are more complex with redundant pathways. For example, see the map of the United States' (right) high-voltage transmission network.

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).

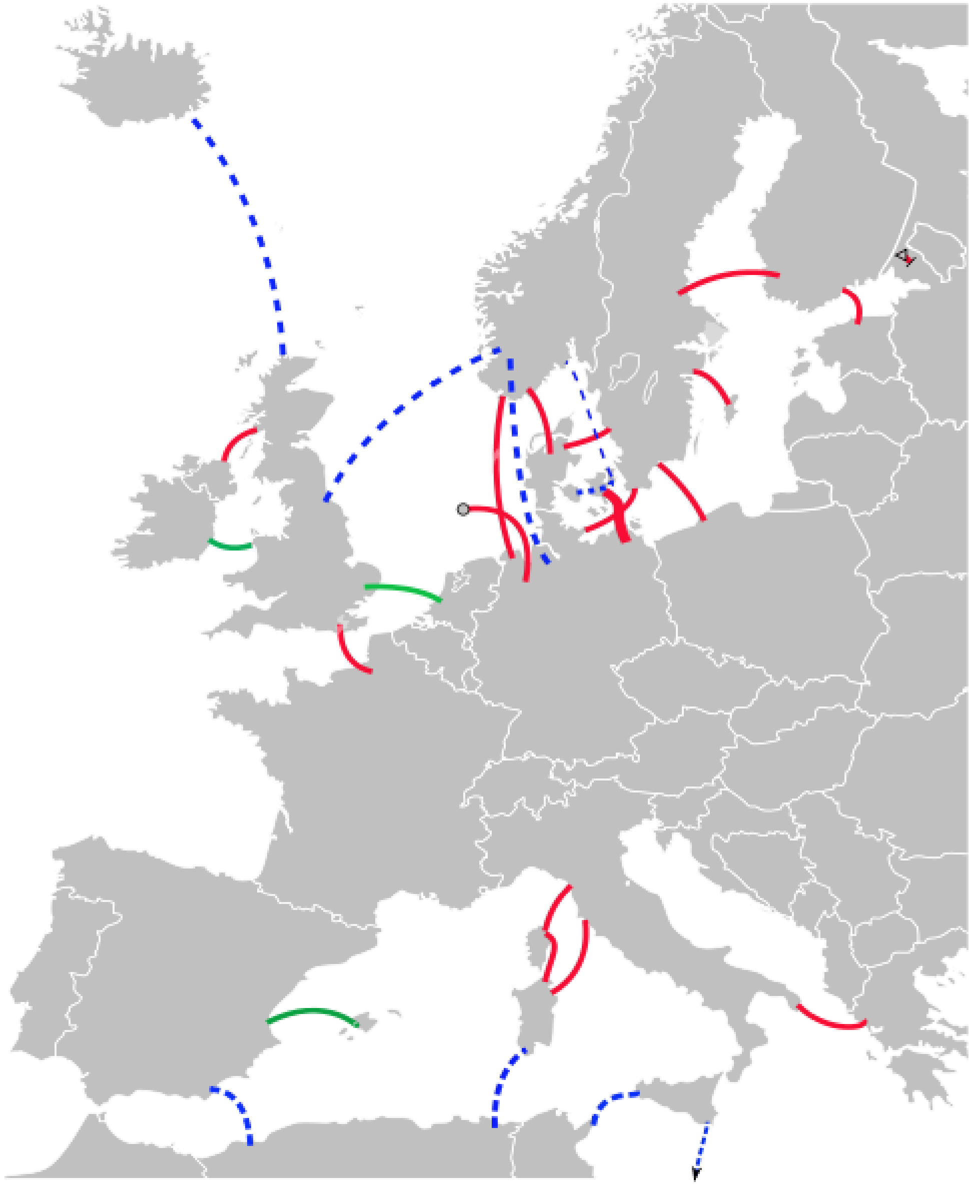
Electricity generation and consumption must be balanced across the entire grid, because energy is consumed almost immediately after it is produced. A large failure in one part of the grid - unless quickly compensated for - can cause current to re-route itself to flow from the remaining generators to 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).



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



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.

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-13

Electricity Meter

An **electric meter** or **energy meter** is a device that measures the amount of electrical energy consumed by a residence, business, or an electrically powered device.

Electric meters are typically calibrated in billing units, the most common one being the kilowatt hour. Periodic readings of electric meters establishes billing cycles and energy used during a cycle.

In settings when energy savings during certain periods are desired, meters may measure demand, the maximum use of power in some interval. In some areas, the electric rates are higher during certain times of day, to encourage reduction in use. Also, in some areas meters have relays to turn off nonessential equipment.

Typical North American domestic analog electricity meter

Typical North American domestic digital electricity meter

History

As commercial use of electric power spread in the 1880s, it became increasingly important that an electrical energy meter, similar to the then existing gas meters, was required to properly bill customers for the cost of energy, instead of billing for a fixed number of lamps per month. Many experimental types of meter were developed. Edison at first worked on a DC electromechanical meter with a direct reading register, but instead developed an electrochemical metering system, which used an electrolytic cell to totalize current consumption. At periodic intervals the plates were removed, weighed, and the customer billed. The electrochemical meter was labor-intensive to read and not well received by customers. In 1885 Ferranti offered a mercury motor meter with a register similar to gas meters; this had the advantage that the consumer could easily read the meter and verify consumption. The first accurate, recording electricity consumption meter was a DC meter by Dr Hermann Aron, who patented it in 1883. Hugo Hirst of the British General Electric Company introduced it commercially into Great Britain from 1888. Meters had been used prior to this, but they measured the rate of power consumption at that particular moment. Aron's meter recorded the total energy used over time, and showed it on a series of clock dials.

The first specimen of the AC kilowatt-hour meter produced on the basis of Hungarian Ottó Bláthy's patent and named after him was presented by the Ganz Works at the Frankfurt Fair in the autumn of 1889, and the first induction kilowatt-hour meter was already marketed by the factory at the end of the same year. These were the first alternating-current watt meters, known by the name of Bláthy-meters. The AC kilowatt hour meters used at present operate on the same principle as Bláthy's original invention Also around 1889, Elihu Thomson of the American General Electric company developed a recording watt meter (watt-hour meter) based on an ironless commutator motor. This meter overcame the disadvantages of the electrochemical type and could operate on either alternating or direct current.

In 1894 Oliver Shallenberger of the Westinghouse Electric Corporation applied the induction principle previously used only in AC ampere-hour meters to produce a watt-hour meter of the modern electromechanical form, using an induction disk whose rotational speed was made proportional to the power in the circuit. Although the induction meter would only work on alternating current, it eliminated the delicate and troublesome commutator of the Thomson design. Shallenberger fell ill and was unable to refine his initial large and heavy design, although he did also develop a polyphase version.

Unit of measurement

Panel-mounted solid state electricity meter, connected to a 2 MVA electricity substation. Remote current and voltage sensors can be read and programmed remotely by modem and locally by infra-red. The circle with two dots is the infra-red port. Tamper-evident seals can be seen.

The most common unit of measurement on the electricity meter is the kilowatt hour, which is equal to the amount of energy used by a load of one kilowatt over a period of one hour, or 3,600,000 joules. Some electricity companies use the SI megajoule instead.

Demand is normally measured in watts, but averaged over a period, most often a quarter or half hour.

Reactive power is measured in "Volt-amperes reactive", (varh) in kilovar-hours. By convention, a "lagging" or inductive load, such as a motor, will have positive reactive power. A "leading", or capacitive load, will have negative reactive power.

Volt-amperes measures all power passed through a distribution network, including reactive and actual. This is equal to the product of root-mean-square volts and amperes.

Distortion of the electric current by loads is measured in several ways. Power factor is the ratio of resistive (or real power) to volt-amperes. A capacitive load has a leading power factor, and an inductive load has a lagging power factor. A purely resistive load (such as a filament lamp, heater or kettle) exhibits a power factor of 1. Current harmonics are a measure of distortion of the wave form. For example, electronic loads such as computer power supplies draw their current at the voltage peak to fill their internal storage elements. This can lead to a significant voltage drop near the supply voltage peak which shows as a flattening of the voltage waveform. This flattening causes odd harmonics which are not permissible if they exceed specific limits, as they are not only wasteful, but may interfere with the operation of other equipment. Harmonic emissions are mandated by law in EU and other countries to fall within specified limits.

Other units of measurement

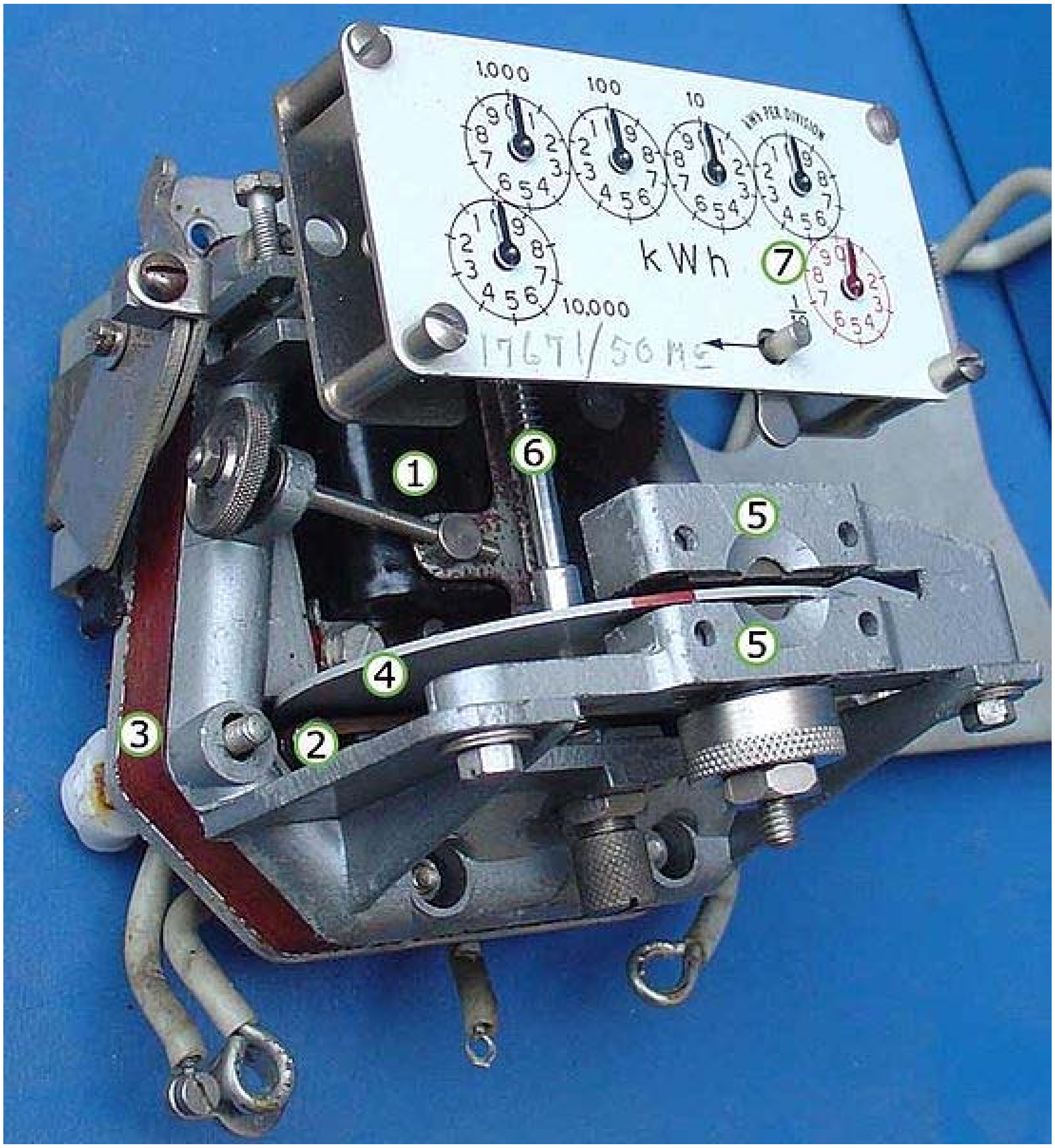
In addition to metering based on the amount of energy used, other types of metering are available.

Meters which measured the amount of charge (coulombs) used, known as ampere-hour meters, were used in the early days of electrification. These were dependent upon the supply voltage remaining constant for accurate measurement of energy usage, which was not a likely circumstance with most supplies.

Some meters measured only the length of time for which charge flowed, with no measurement of the magnitude of voltage or current being made. These were only suited for constant-load applications.

Neither type is likely to be used today.

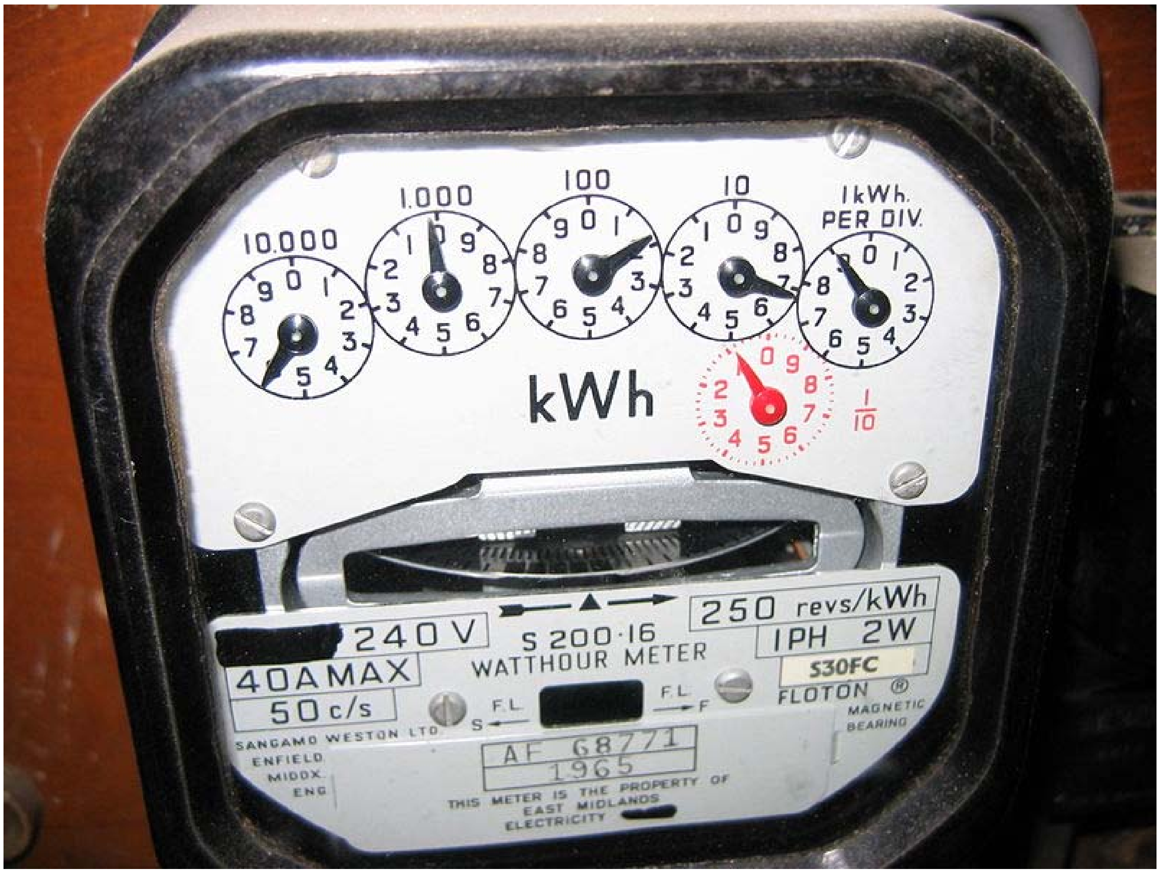
Types of meters



Mechanism of electromechanical induction meter.
1 - Voltage coil - many turns of fine wire encased in plastic, connected in parallel with load.
2 - Current coil - three turns of thick wire, connected in series with load.
3 - Stator - concentrates and confines magnetic field.
4 - Aluminum rotor disc.
5 - rotor brake magnets.
6 - spindle with worm gear.
7 - display dials - note that the 1/10, 10 and 1000 dials rotate clockwise while the 1, 100 and 10000 dials rotate counter-clockwise.

Electricity meters operate by continuously measuring the instantaneous voltage (volts) and current (amperes) and finding the product of these to give instantaneous electrical power (watts) which is then integrated against time to give energy used (joules, kilowatt-hours etc.). Meters for smaller services (such as small residential customers) can be connected directly in-line between source and customer. For larger loads, more than about 200 amps of load, current transformers are used, so that the meter can be located other than in line with the service conductors. The meters fall into two basic categories, electromechanical and electronic.

Electromechanical meters



This mechanical electricity meter has every other dial rotating counter-clockwise.

The most common type of electricity meter is the electromechanical induction watt-hour meter.

The electromechanical induction meter operates by counting the revolutions of an aluminium disc which is made to rotate at a speed proportional to the power. The number of revolutions is thus proportional to the energy usage. It consumes a small amount of power, typically around 2 watts.

The metallic disc is acted upon by two coils. One coil is connected in such a way that it produces a magnetic flux in proportion to the voltage and the other produces a magnetic flux in proportion to the current. The field of the voltage coil is delayed by 90 degrees using a lag coil. This produces eddy currents in the disc and the effect is such that a force is exerted on the disc in proportion to the product of the instantaneous current and voltage. A permanent magnet exerts an opposing force proportional to the speed of rotation of the disc. The equilibrium between these two opposing forces results in the disc rotating at a speed proportional to the power being used. The disc drives a register mechanism which integrates the speed of the disc over time by counting revolutions, much like the odometer in a car, in order to render a measurement of the total energy used over a period of time.

The type of meter described above is used on a single-phase AC supply. Different phase configurations use additional voltage and current coils.

Three-phase electromechanical induction meter, metering 100 A 230/400 V supply. Horizontal aluminum rotor disc is visible in center of meter

The aluminum disc is supported by a spindle which has a worm gear which drives the register. The register is a series of dials which record the amount of energy used. The dials may be of the cyclometer type, an odometer-like display that is easy to read where for each dial a single digit is shown through a window in the face of the meter, or of the pointer type where a pointer indicates each digit. With the dial pointer type, adjacent pointers generally rotate in opposite directions due to the gearing mechanism.

The amount of energy represented by one revolution of the disc is denoted by the symbol Kh which is given in units of watt-hours per revolution. The value 7.2 is commonly seen. Using the value of Kh, one can determine their power consumption at any given time by timing the disc with a stopwatch. If the time in seconds taken by the disc to complete one revolution is t, then the power in watts is $P = \frac{3600 \cdot Kh}{t}$. For example, if Kh = 7.2, as above, and one revolution took place in 14.4 seconds, the power is 1800 watts. This method can be used to determine the power consumption of household devices by switching them on one by one.

Most domestic electricity meters must be read manually, whether by a representative of the power company or by the customer. Where the customer reads the meter, the reading may be supplied to the power company by telephone, post or over the internet. The electricity company will normally require a visit by a company representative at least annually in order to verify customer-supplied readings and to make a basic safety check of the meter.

In an induction type meter, creep is a phenomenon that can adversely affect accuracy, that occurs when the meter disc rotates continuously with potential applied and the load terminals open circuited. A test for error due to creep is called a creep test.

Two standards govern meter accuracy, ANSI C12.20 for North America and IEC 62053.

Electronic meters

Electronic meters display the energy used on an LCD or LED display, and can also transmit readings to remote places. In addition to measuring energy used, electronic meters can also record other parameters of the load and supply such as maximum demand, power factor and reactive power used etc. They can also support time-of-day billing, for example, recording the amount of energy used during on-peak and off-peak hours.

Solid state electricity meter used in a home in the Netherlands.

Communication

Remote meter reading is a practical example of telemetry. It saves the cost of a human meter reader and the resulting mistakes, but it also allows more measurements, and remote provisioning. Many smart meters now include a switch to interrupt or restore service.

Historically, rotating meters could report their power information remotely, using a pair of contact closures attached to a KYZ line.

In a KYZ interface, the Y and Z wires are switch contacts, shorted to K for half of a rotor's circumference. To measure the rotor direction, the Z signal is offset by 90 degrees from the Y. When the rotor rotates in the opposite direction, showing export of power, the sequence reverses. The time between pulses measures the demand. The number of pulses is total power usage.

KYZ outputs were historically attached to "totalizer relays" feeding a "totalizer" so that many meters could be read all at once in one place.

KYZ outputs are also the classic way of attaching electric meters to programmable logic controllers, HVACs or other control systems. Some modern meters also supply a contact closure that warns when the meter detects a demand near a higher tariff.

Some meters have an open collector output that gives 32-100 ms pulses for a constant amount of used electrical energy. Usually 1000-10000 pulses per kWh. Output is limited to max 27 V DC and 27 mA DC. The output usually follows the DIN 43864 standard.

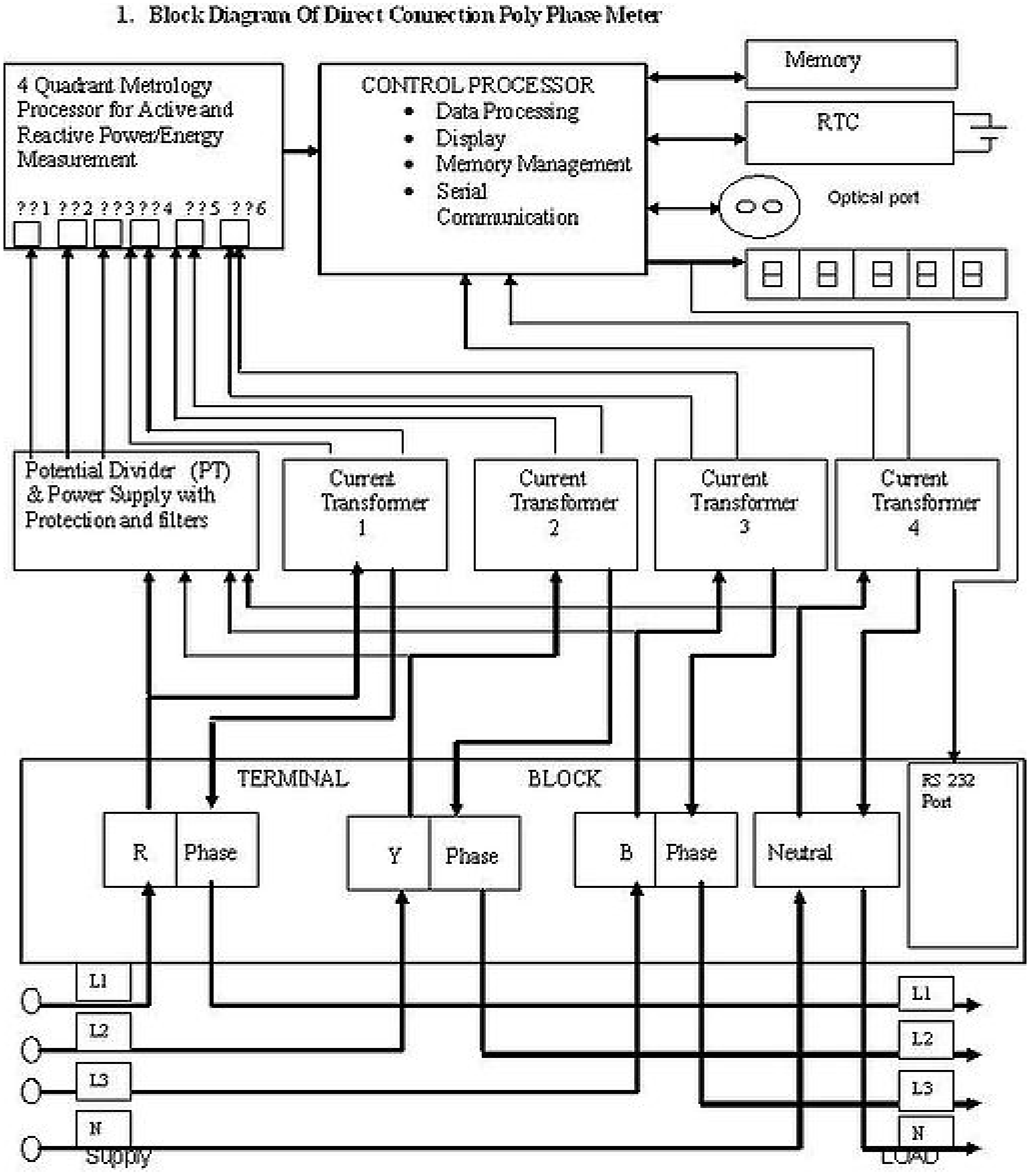
Often, meters designed for semi-automated reading have a serial port on that communicates by infrared LED through the faceplate of the meter. In some apartment buildings, a similar protocol is used, but in a wired bus using a serial current loop to connect all the meters to a single plug. The plug is often near the mailboxes. In the European Union, the most common infrared and protocol is "FLAG", a simplified subset of mode C of IEC 61107. In the U.S. and Canada, the favoured infrared protocol is ANSI C12.18. Some industrial meters use a protocol for programmable logic controllers (Modbus).

The most modern protocol proposed for this purpose is DLM/COSEM which can operate over any medium, including serial ports. The data can be transmitted by Zigbee, WiFi, telephone lines or over the power lines themselves. Some meters can be read over the internet.

Electronic meters now use Low Power Radio, GSM, GPRS, Bluetooth, IrDA, as well as RS-485 wired link. The meters can now store the entire usage profiles with time stamps and relay them at a click of a button. The demand readings stored with the profiles accurately indicate the load requirements of the customer. This load profile data is processed at the utilities for billing and planning purposes.

AMR (Automatic Meter Reading) and RMR (Remote Meter Reading) describe various systems that allow meters to be checked without the need to send a meter reader out. An electronic meter can transmit its readings by telephone line or radio to a central billing office. Automatic meter reading can be done with GSM (Global System for Mobile Communications) modems, one is attached to each meter and the other is placed at the central utility office.

Solid-state design



Basic block diagram of an electronic energy meter

As in the block diagram, the meter has a power supply, a metering engine, a processing and communication engine (i.e. a microcontroller), and other add-on modules such as RTC, LCD display, communication ports/modules and so on.

The metering engine is given the voltage and current inputs and has a voltage reference, samplers and quantisers followed by an ADC section to yield the digitised equivalents of all the inputs. These inputs are then processed using a **Digital Signal Processor** to calculate the various metering parameters such as powers, energies etc.

The largest source of long-term errors in the meter is drift in the preamp, followed by the precision of the voltage reference. Both of these vary with temperature as well, and vary wildly because most meters are outdoors. Characterizing and compensating for these is a major part of meter design.

The processing and communication section has the responsibility of calculating the various derived quantities from the digital values generated by the metering engine. This also has the responsibility of communication using various protocols and interface with other addon modules connected as slaves to it.

RTC and other add-on modules are attached as slaves to the processing and communication section for various input/output functions. On a modern meter most if not all of this will be implemented inside the microprocessor, such as the Real Time Clock (RTC), LCD controller, temperature sensor, memory and analog to digital converters.

Multiple tariff (variable rate) meters

Electricity retailers may wish to charge customers different tariffs at different times of the day to better reflect the costs of generation and transmission. Since it is typically not cost effective to store significant amounts of electricity during a period of low demand for use during a period of high demand, costs will vary significantly depending on the time of day. Low cost generation capacity (baseload) such as nuclear can take many hours to start, meaning a surplus in times of low demand, whereas high cost but flexible generating capacity (such as gas turbines) must be kept available to respond at a moment's notice (spinning reserve) to peak demand, perhaps being used for a few minutes per day, which is very expensive.

Some multiple tariff meters use different tariffs for different amounts of demand. These are usually industrial meters.

Domestic usage

Domestic variable-rate meters generally permit two to three tariffs ("peak", "off-peak" and "shoulder") and in such installations a simple electromechanical time switch may be used. Historically, these have often been used in conjunction with electrical storage heaters or hot water storage systems.

Multiple tariffs are made easier by time of use (TOU) meters which incorporate or are connected to a time switch and which have multiple registers.

Switching between the tariffs may happen via a radio-activated switch rather than a time switch to prevent tampering with a sealed time switch to obtain cheaper electricity.

United Kingdom

Economy 7 Meter and Teleswitcher

Radio-activated switching is common in the UK, with a nightly data signal sent within the longwave carrier of BBC Radio 4, 198 kHz. The time of off-peak charging is usually seven hours between 11.30pm and 8.30am GMT, and this is designed to power storage heaters and immersion heaters. In the UK, such tariffs are branded Economy 7 or White Meter. The popularity of such tariffs has declined in recent years, at least in the domestic market, due to the (perceived or real) deficiencies of storage heaters and the comparatively low cost of natural gas. An "Economy 10" meter is also available, giving five hours of heating overnight, with boosts in mid-morning and mid-afternoon.

Most meters using Economy 7 switch the entire electricity supply to the cheaper rate during the 7 hour night time period, not just the storage heater circuit. The downside of this is that the daytime rate will be significantly higher, and standing charges may be a little higher too. For instance, normal rate electricity may be 9p per kWh, whereas Economy 7's daytime rate might be 14 to 17 p per kWh, but only 5.43p per kWh at night. Timer switches installed on washing machines, tumble dryers, dishwashers and immersion heaters may be set so that they switch on only when the rate is lower.

Commercial usage

Large commercial and industrial premises may use electronic meters which record power usage in blocks of half an hour or less. This is because most electricity grids have demand surges throughout the day, and the power company may wish to give price incentives to large customers to reduce demand at these times. These demand surges often correspond to meal times or, famously, to advertisements in popular television programmes.

Appliance energy meters

Plug in electricity meters (or "Plug load" meters) measure energy used by individual appliances. The meter is plugged into an outlet, and the appliance to be measured is plugged into the meter. Such meters can help in energy conservation by identifying major energy users, or devices that consume excessive standby power. A power meter can often be borrowed from the local power authorities or a local public library.

In-home energy use displays

A potentially powerful means to reduce household energy consumption is to provide convenient real-time feedback to users so they can change their energy using behavior. Recently, low-cost energy feedback displays have become available. A study using a consumer-readable meter in 500 Ontario homes by Hydro One showed an average 6.5% drop in total electricity use when compared with a similarly sized control group. Hydro One subsequently offered free power monitors to 30,000 customers based on the success of the pilot. Projects such as Google PowerMeter, take information from a smart meter and make it more readily available to users to help encourage conservation.

Smart meters

Smart meters go a step further than simple AMR (automatic meter reading). They offer additional functionality including a real-time or near real-time reads, power outage notification, and power quality monitoring. They allow price setting agencies to introduce different prices for consumption based on the time of day and the season.

These price differences can be used to reduce peaks in demand (load shifting or peak lopping), reducing the need for additional power plants and in particular the higher polluting and costly to operate natural gas powered peaker plants. The feedback they provide to consumers has also been shown to cut overall energy consumption.

Another type of smart meter uses nonintrusive load monitoring to automatically determine the number and type of appliances in a residence, how much energy each uses and when. This meter is used by electric utilities to do surveys of energy use. It eliminates the need to put timers on all of the appliances in a house to determine how much energy each uses.

Prepayment meters

Prepayment meter and magnetic stripe tokens, from a rented accommodation in the UK. The button labeled **A** displays information and statistics such as current tariff and remaining credit. The button labeled **B** activates a small amount of emergency credit should the customer run out

A prepayment key

The standard business model of electricity retailing involves the electricity company billing the customer for the amount of energy used in the previous month or quarter. In some countries, if the retailer believes that the customer may not pay the bill, a prepayment meter may be installed. This requires the customer to make advance payment before electricity can be used. If the available credit is exhausted then the supply of electricity is cut off by a relay.

In the UK, mechanical prepayment meters used to be common in rented accommodation. Disadvantages of these included the need for regular visits to remove cash, and risk of theft of the cash in the meter.

Modern solid-state electricity meters, in conjunction with smart cards, have removed these disadvantages and such meters are commonly used for customers considered to be a poor credit risk. In the UK, one system is the PayPoint network, where rechargeable tokens (Quantum cards for natural gas, or plastic "keys" for electricity) can be loaded with whatever money the customer has available.

Recently smartcards are introduced as much reliable tokens that allows two way data exchange between meter and the utility.

In South Africa, Sudan and Northern Ireland prepaid meters are recharged by entering a unique, encoded twenty digit number using a keypad. This makes the tokens, essentially a slip of paper, very cheap to produce.

Around the world, experiments are going on, especially in developing countries, to test pre-payment systems. In some cases, prepayment meters have not been accepted by customers. There are various groups, such as the Standard Transfer Specification (STS) association, which promote common standards for prepayment metering systems across manufacturers. However in spite of these efforts prepayment meter market had not spread except in South Africa.

Time of day metering

Time of Day metering (TOD), also known as Time of Usage (TOU) or Seasonal Time of Day (SToD), metering involves dividing the day, month and year into tariff slots and with higher rates at peak load periods and low tariff rates at off-peak load periods. While this can be used to automatically control usage on the part of the customer (resulting in automatic load control), it is often simply the customers responsibility to control his own usage, or pay accordingly (voluntary load control). This also allows the utilities to plan their transmission infrastructure appropriately.

TOD metering normally splits rates into two segments, peak and off-peak, with peak typically occurring during the day (non-holiday days only), such as from 1 pm to 9 pm Monday through Friday during the summer and from 6:30 am to 12 noon and 5 pm to 9 pm during the winter. The times of peak demand/cost will vary in different markets around the world.

Large commercial users can purchase power by the hour using either forecast pricing or real time pricing. Prices range from we pay you to take it (negative) to $1000/MWh (100 cents/kWh).

Some utilities allow residential customers to pay hourly rates, such as Illinois, which uses day ahead pricing.

Power export metering

Many electricity customers are installing their own electricity generating equipment, whether for reasons of economy, redundancy or environmental reasons. When a customer is generating more electricity than required for his own use, the surplus may be exported back to the power grid. Customers that generate back into the "grid" usually must have special equipment and/or safety devices to protect the grid components (as well as the customer's own) in case of faults (electrical short circuits) or maintenance of the grid (say voltage potential on a downed line going into an exporting customers facility).

This exported energy may be accounted for in the simplest case by the meter running backwards during periods of net export, thus reducing the customer's recorded energy usage by the amount exported. This in effect results in the customer being paid for his/her exports at the full retail price of electricity. Unless equipped with a detent or equivalent, a standard meter will accurately record power flow in each direction by simply running backwards when power is exported. Such meters are no longer legal in the UK but instead a meter capable of separately measuring imported and exported energy is required. Where allowed by law, utilities maintain a profitable margin between the price of energy delivered to the consumer and the rate credited for consumer-generated energy that flows back to the grid. Lately, upload sources typically originate from renewable sources (e.g., wind turbines, photovoltaic cells), or gas or steam turbines, which are often found in cogeneration systems. Another potential upload source that has been proposed is plug-in hybrid car batteries (vehicle-to-grid power systems). This requires a "smart grid," which includes meters that measure electricity via communication networks that require remote control and give customers timing and pricing options. Vehicle-to-grid systems could be installed at workplace parking lots and garages and at park and rides and could help drivers charge their batteries at home at night when off-peak power prices are cheaper, and receive bill crediting for selling excess electricity back to the grid during high-demand hours.

Ownership

Following the deregulation of electricity supply markets in many countries (e.g., UK), the company responsible for an electricity meter may not be obvious. Depending on the arrangements in place, the meter may be the property of the meter Operator, electricity distributor, the retailer or for some large users of electricity the meter may belong to the customer.

The company responsible for reading the meter may not always be the company which owns it. Meter reading is now sometimes subcontracted and in some areas the same person may read gas, water and electricity meters at the same time.

Location

The location of an electricity meter varies with each installation. Possible locations include on a power pylon serving the property, in a street-side cabinet (meter box) or inside the premises adjacent to the consumer unit / distribution board. Electricity companies may prefer external locations as the meter can be read without gaining access to the premises but external meters may be more prone to vandalism.

Current transformers used as part of metering equipment for three-phase 400 A electricity supply. The fourth neutral wire does not require a current transformer because current cannot flow in this wire without also flowing in one of the three phase wires

Current transformers permit the meter to be located remotely from the current-carrying conductors. This is common in large installations. For example a substation serving a single large customer may have metering equipment installed in a cabinet, without bringing heavy cables into the cabinet.

Connection

In North America, it is common for electricity meters to plug into a standardised socket. This allows the meter to be replaced without disturbing the wires to the socket. Some sockets may have a bypass while the meter is removed for service. The amount of electricity used without being recorded during this small time is considered insignificant when compared to the inconvenience which might be caused to the customer by cutting off the electricity supply.

In the UK, the supply and load terminals are normally provided in the meter housing itself, at least for smaller meters (up to around 100 A).


A commercial power meter

A Duke Energy technician removes the tamper-proof seal from a electricity meter at a residence in Durham, North Carolina

Tampering and security

Meters can be manipulated to make them under-register, effectively allowing power use without paying for it. This theft or fraud can be dangerous as well as dishonest.

Power companies often install remote-reporting meters specifically to enable remote detection of tampering, and specifically to discover energy theft. The change to smart power meters is useful to stop energy theft.

When tampering is detected, the normal tactic, legal in most areas of the USA, is to switch the subscriber to a "tampering" tariff charged at the meter's maximum designed current. At US$ 0.095/kWh, a standard residential 50 A meter causes a legally collectible charge of about US$ 5,000.00 per month. Meter readers are trained to spot signs of tampering, and with crude mechanical meters, the maximum rate may be charged each billing period until the tamper is removed, or the service is disconnected.

A common method of tampering on older meters is to attach magnets to the outside of the meter. These magnetically saturate the coils or current transformers, preventing the alternating current from forming eddy currents in the rotor, or inducing voltages in the current transformer.

Rectified DC loads cause mechanical (but not electronic) meters to under-register. DC current does not cause the coils to make eddy currents in the disk, so this causes reduced rotation and a lower bill.

Some combinations of capacitive and inductive load can interact with the coils and mass of a rotor and cause reduced or reverse motion.

All of these effects can be detected by the electric company, and many modern meters can detect or compensate for them.

The owner of the meter normally secures the meter against tampering. Revenue meters' mechanisms and connections are sealed. Meters may also measure VAR-hours (the reflected load), neutral and DC currents (elevated by most electrical tampering), ambient magnetic fields, etc. Even simple mechanical meters can have mechanical flags that are dropped by magnetic tampering or large DC currents.

Newer computerized meters usually have counter-measures against tampering. AMR (Automated Meter Reading) meters often have sensors that can report opening of the meter cover, magnetic anomalies, extra clock setting, glued buttons, inverted installation, reversed or switched phases etc.

Some tampers bypass the meter, wholly or in part. Safe tampers of this type normally increase the neutral current at the meter. Most split-phase residential meters in the United States are unable to detect neutral currents. However, modern tamper-resistant meters can detect and bill it at standard rates.

Disconnecting a meter's neutral connector is unsafe because shorts can then pass through people or equipment rather than a metallic ground to the generator.

A phantom loop connection via an earth ground is often much higher resistance than the metallic neutral connector. Even in these cases, metering at the substation can alert the operator to tampering. Substations, interties and transformers normally have a high-accuracy meter for the area served. Power companies normally investigate discrepancies between the total billed and the total generated, in order to find and fix power distribution problems. These investigations are an effective method of discovering tampering.

In North America power thefts are often connected with indoor marijuana grow operations. Narcotics detectives associate abnormally high power usage with the lighting such operations require. Indoor marijuana growers aware of this are particularly motivated to steal electricity simply to conceal their usage of it.

Privacy issues

The introduction of advanced meters in residential areas has produced additional privacy issues that may affect ordinary customers. These meters are often capable of recording energy usage every 15, 30 or 60 minutes. These can be used for surveillance, revealing information about people's possessions and behavior. For instance, it can show when the customer is away for extended periods. Nonintrusive load monitoring gives even more detail about what appliances people have and their living and use patterns.

A more detailed and recent analysis of this issue was performed by the Illinois Security Lab.

Chapter-14

Earthing System

In electricity supply systems, an **earthing system** defines the electrical potential of the conductors relative to that of the Earth's conductive surface. The choice of earthing system has implications for the safety and electromagnetic compatibility of the power supply. Note that regulations for earthing (grounding) systems vary considerably among different countries.

A protective earth (PE) connection ensures that all exposed conductive surfaces are at the same electrical potential as the surface of the Earth, to avoid the risk of electrical shock if a person touches a device in which an insulation fault has occurred. It ensures that in the case of an insulation fault (a "short circuit"), a very high current flows, which will trigger an overcurrent protection device (fuse, circuit breaker) that disconnects the power supply.

A functional earth connection serves a purpose other than providing protection against electrical shock. In contrast to a protective earth connection, a functional earth connection may carry a current during the normal operation of a device. Functional earth connections may be required by devices such as surge suppression and electromagnetic interference filters, some types of antennas and various measurement instruments. Generally the protective earth is also used as a functional earth, though this requires care in some situations.

IEC terminology

International standard IEC 60364 distinguishes three families of earthing arrangements, using the two-letter codes **TN**, **TT**, and **IT**.

The first letter indicates the connection between earth and the power-supply equipment (generator or transformer):

T
: Direct connection of a point with earth (Latin: terra);

I
: No point is connected with earth (isolation), except perhaps via a high impedance.

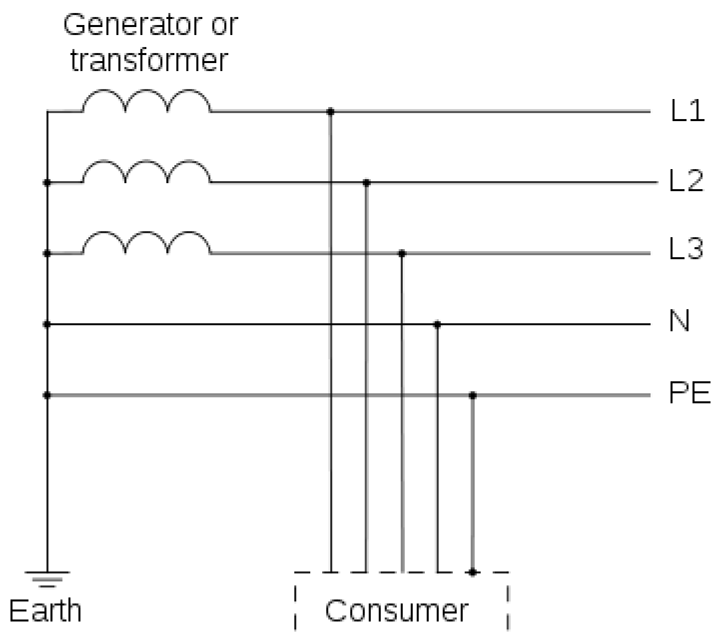
The second letter indicates the connection between earth and the electrical device being supplied:

T
: Direct connection of a point with earth

N
: Direct connection to neutral at the origin of installation, which is connected to the earth

TN networks

In a **TN** earthing system, one of the points in the generator or transformer is connected with earth, usually the star point in a three-phase system. The body of the electrical device is connected with earth via this earth connection at the transformer.



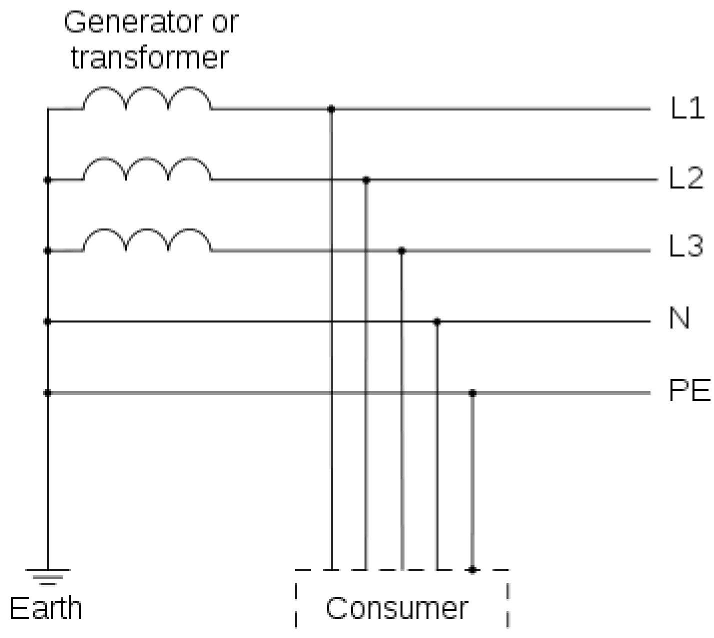
The conductor that connects the exposed metallic parts of the consumer is called protective earth (PE). The conductor that connects to the star point in a three-phase system, or that carries the return current in a single-phase system, is called neutral (N). Three variants of TN systems are distinguished:

TN−S
: PE and N are separate conductors that are connected together only near the power source.

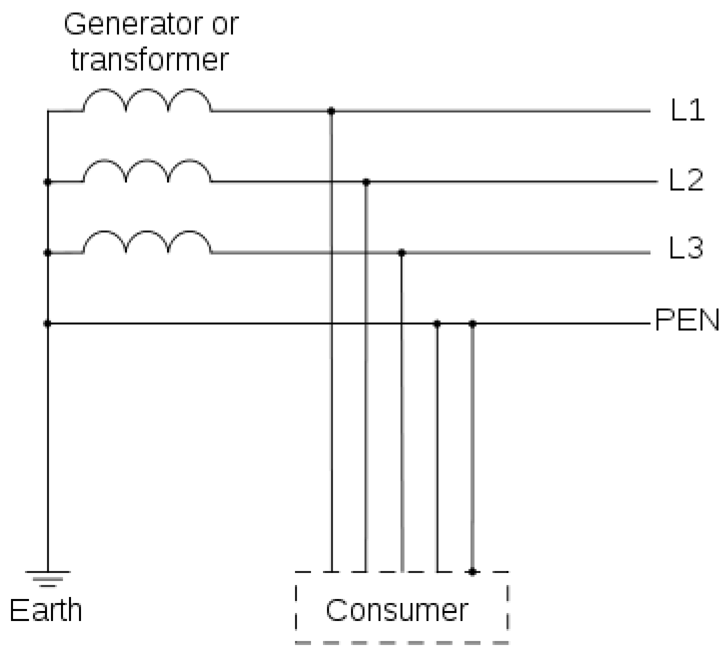
TN−C
: A combined PEN conductor fulfills the functions of both a PE and an N conductor. Rarely used.

TN−C−S

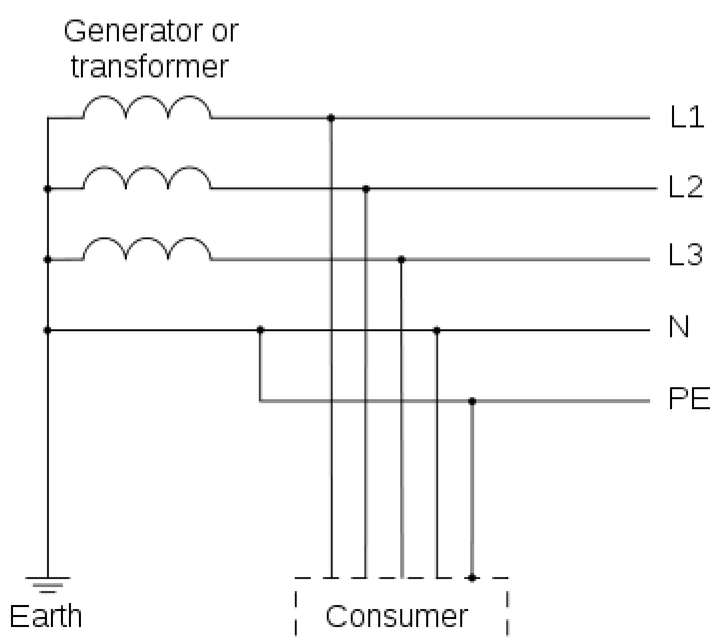
Part of the system uses a combined PEN conductor, which is at some point split up into separate PE and N lines. The combined PEN conductor typically occurs between the substation and the entry point into the building, and separated in the service head. In the UK, this system is also known as protective multiple earthing (PME), because of the practice of connecting the combined neutral-and-earth conductor to real earth at many locations, to reduce the risk of broken neutrals - with a similar system in Australia being designated as multiple earthed neutral (MEN).



TN-S: separate protective earth (PE) and neutral (N) conductors from transformer to consuming device, which are not connected together at any point after the building distribution point.



TN-C: combined PE and N conductor all the way from the transformer to the consuming device.



TN-C-S earthing system: combined PEN conductor from transformer to building distribution point, but separate PE and N conductors in fixed indoor wiring and flexible power cords.

It is possible to have both TN-S and TN-C-S supplies from the same transformer. For example, the sheaths on some underground cables corrode and stop providing good earth connections, and so homes where "bad earths" are found get converted to TN-C-S.

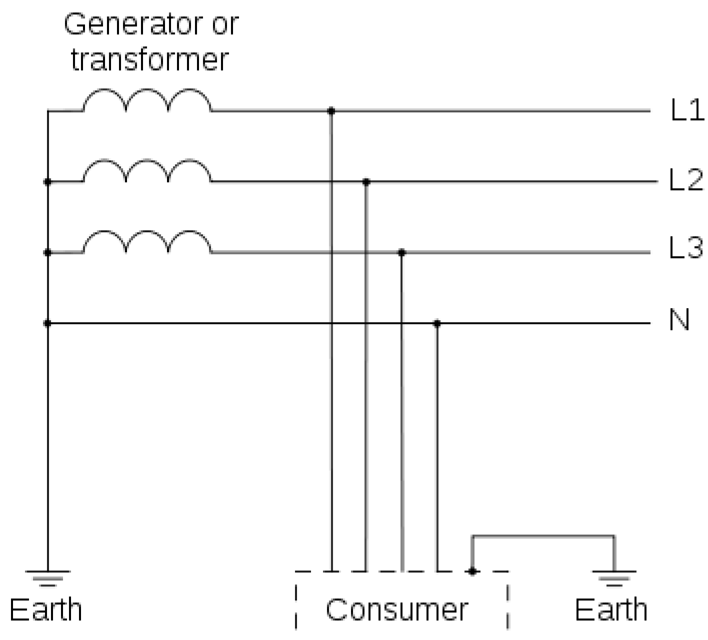
TT network

In a **TT** earthing system, the protective earth connection of the consumer is provided by a local connection to earth, independent of any earth connection at the generator.

The big advantage of the TT earthing system is the fact that it is clear of high and low frequency noises that come through the neutral wire from various electrical equipment connected to it. This is why TT has always been preferable for special applications like telecommunication sites that benefit from the interference-free earthing. Also, TT does not have the risk of a broken neutral.

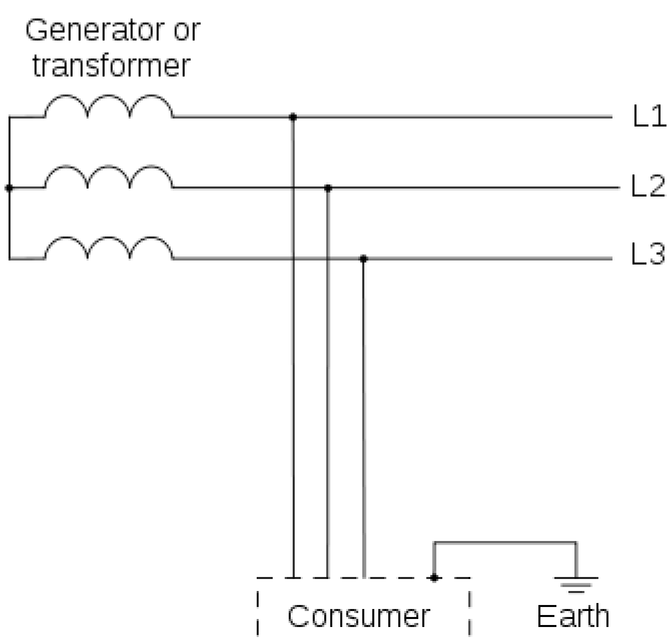
In locations where power is distributed overhead and TT is used, installation earth conductors are not at risk should any overhead distribution conductor be fractured by, say, a fallen tree or branch.

In pre-RCD era, the TT earthing system was unattractive for general use because of its worse capability of accepting high currents in case of a live-to-PE short circuit (in comparison with TN systems). But as residual current devices mitigate this disadvantage, the TT earthing system becomes attractive for premises where all AC power circuits are RCD-protected.



IT network

In an **IT** network, the distribution system has no connection to earth at all, or it has only a high impedance connection. In such systems, an insulation monitoring device is used to monitor the impedance



Other terminologies

While the national wiring regulations for buildings of many countries follow the IEC 60364 terminology, in North America (United States and Canada), the term "equipment grounding conductor" refers to equipment grounds and ground wires on branch circuits, and "grounding electrode conductor" is used for conductors bonding an earth ground rod (or similar) to a service panel. "Grounded conductor" is the system "neutral".

Properties

Cost

- TN networks save the cost of a low-impedance earth connection at the site of each consumer. Such a connection (a buried metal structure) is required to provide protective earth in IT and TT systems.
- TN-C networks save the cost of an additional conductor needed for separate N and PE connections. However, to mitigate the risk of broken neutrals, special cable types and lots of connections to earth are needed.
- TT networks require proper RCD protection.

Fault path impedance

If the fault path between accidentally energized objects and the supply connection has low impedance, the fault current will be so large that the circuit overcurrent protection device (fuse or circuit breaker) will open to clear the ground fault. Where the earthing system does not provide a low-impedance metallic conductor between equipment enclosures and supply return (such as in a TT separately earthed system), fault currents are smaller, and will not necessarily operate the overcurrent protection device. In such case a residual current detector is installed to detect the current leaking to ground and interrupt the circuit.

Safety

- In TN, an insulation fault is very likely to lead to a high short-circuit current that will trigger an overcurrent circuit-breaker or fuse and disconnect the L conductors. With TT systems, the earth fault loop impedance can be too high to do this, or too high to do it quickly, so an RCD (or formerly ELCB) is usually employed. The provision of a Residual-current device (RCD) or ELCB to ensure safe disconnection makes these installations EEBAD (Earthed Equipotential Bonding and Automatic Disconnection).
- Many 1950s and earlier earlier TT installations in the UK may lack this important safety feature. Non-EEBAD installations are capable of the whole installation CPC (Circuit Protective Conductor) remaining live for extended periods under fault conditions, which is a real danger.
- In TN-S and TT systems (and in TN-C-S beyond the point of the split), a residual-current device can be used as an additional protection. In the absence of any

insulation fault in the consumer device, the equation $I_{L1}+I_{L2}+I_{L3}+I_N = 0$ holds, and an RCD can disconnect the supply as soon as this sum reaches a threshold (typically 10-500 mA). An insulation fault between either L or N and PE will trigger an RCD with high probability.

- In IT and TN-C networks, residual current devices are far less likely to detect an insulation fault. In a TN-C system, they would also be very vulnerable to unwanted triggering from contact between earth conductors of circuits on different RCDs or with real ground, thus making their use impracticable. Also, RCDs usually isolate the neutral core. Since it is unsafe to do this in a TN-C system, RCDs on TN-C should be wired to only interrupt the live conductor.
- In single-ended single-phase systems where the Earth and neutral are combined (TN-C, and the part of TN-C-S systems which uses a combined neutral and earth core), if there is a contact problem in the PEN conductor, then all parts of the earthing system beyond the break will rise to the potential of the L conductor. In an unbalanced multi-phase system, the potential of the earthing system will move towards that of the most loaded live conductor. Therefore, TN-C connections must not go across plug/socket connections or flexible cables, where there is a higher probability of contact problems than with fixed wiring. There is also a risk if a cable is damaged, which can be mitigated by the use of concentric cable construction and/or multiple earth electrodes. Due to the (small) risks of the lost neutral, use of TN-C-S supplies is banned for caravans and boats in the UK, and it is often recommended to make outdoor wiring TT with a separate earth electrode.
- In IT systems, a single insulation fault is unlikely to cause dangerous currents to flow through a human body in contact with earth, because no low-impedance circuit exists for such a current to flow. However, a first insulation fault can effectively turn an IT system into a TN system, and then a second insulation fault can lead to dangerous body currents. Worse, in a multi-phase system, if one of the live conductors made contact with earth, it would cause the other phase cores to rise to the phase-phase voltage relative to earth rather than the phase-neutral voltage. IT systems also experience larger transient overvoltages than other systems.
- In TN-C and TN-C-S systems, any connection between the combined neutral-and-earth core and the body of the earth could end up carrying significant current under normal conditions, and could carry even more under a broken neutral situation. Therefore, main equipotential bonding conductors must be sized with this in mind; use of TN-C-S is inadvisable in situations such as petrol stations, where there is a combination of lots of buried metalwork and explosive gases.

Electromagnetic compatibility

- In TN-S and TT systems, the consumer has a low-noise connection to earth, which does not suffer from the voltage that appears on the N conductor as a result of the return currents and the impedance of that conductor. This is of particular importance with some types of telecommunication and measurement equipment.
- In TT systems, each consumer has its own connection to earth, and will not notice any currents that may be caused by other consumers on a shared PE line.

Regulations

- In the United States National Electrical Code and Canadian Electrical Code the feed from the distribution transformer uses a combined neutral and grounding conductor, but within the structure separate neutral and protective earth conductors are used (TN-C-S). The neutral must be connected to the earth (ground) conductor only on the supply side of the customer's disconnecting switch. Additional connections of neutral to ground within the customer's wiring are prohibited.
- In Argentina, France (TT) and Australia (TN-C-S), the customers must provide their own ground connections.
- Japan is governed by PSE law.

Application examples

- Most modern homes in Europe have a TN-C-S earthing system. The combined neutral and earth occurs between the nearest transformer substation and the service cut out (the fuse before the meter). After this, separate earth and neutral cores are used in all the internal wiring.
- Older urban and suburban homes in the UK tend to have TN-S supplies, with the earth connection delivered through the lead sheath of the underground lead-and-paper cable.
- Some older homes, especially those built before the invention of residual-current circuit breakers and wired home area networks, use an in-house TN-C arrangement. This is no longer recommended practice.
- Laboratory rooms, medical facilities, construction sites, repair workshops, mobile electrical installations, and other environments that are supplied via engine-generators where there is an increased risk of insulation faults, often use an IT earthing arrangement supplied from isolation transformers. To mitigate the two-fault issues with IT systems, the isolation transformers should supply only a small number of loads each and/or should be protected with an insulation monitoring device (generally used only by medical, railway or military IT systems, because of cost).
- In remote areas, where the cost of an additional PE conductor outweighs the cost of a local earth connection, TT networks are commonly used in some countries, especially in older properties or in rural areas, where safety might otherwise be threatened by the fracture of an overhead PE conductor by, say, a fallen tree branch. TT supplies to individual properties are also seen in mostly TN-C-S systems where an individual property is considered unsuitable for TN-C-S supply.
- In Australia, and Israel the TN-C-S system is in use; however, the wiring rules currently state that, in addition, each customer must provide a separate connection to earth via both a water pipe bond (if metallic water pipes enter the consumer's premises) and a dedicated earth electrode. In older installations, it is not uncommon to find only the water pipe bond, and it is allowed to remain as such, but the additional earth electrode must be installed if any upgrade work is done. The protective earth and neutral conductors are combined until the consumer's

neutral link (located on the customer's side of the electricity meter's neutral connection) - beyond this point, the protective earth and neutral conductors are separate.

Chapter-15

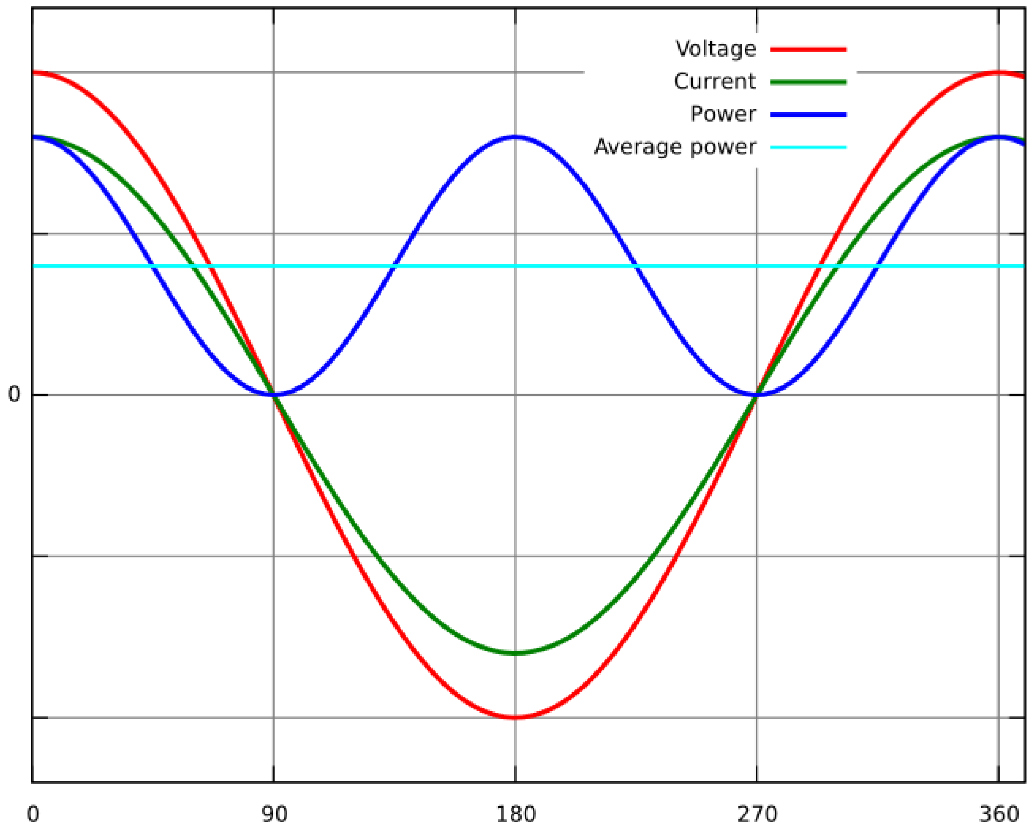
Power Factor System

The **power factor** of an AC electric power system is defined as the ratio of the real power flowing to the load to the apparent power in the circuit, and is a dimensionless number between 0 and 1 (frequently expressed as a percentage, e.g. 0.5 pf = 50% pf). Real power is the capacity of the circuit for performing work in a particular time. Apparent power is the product of the current and voltage of the circuit. Due to energy stored in the load and returned to the source, or due to a non-linear load that distorts the wave shape of the current drawn from the source, the apparent power will be greater than the real power.

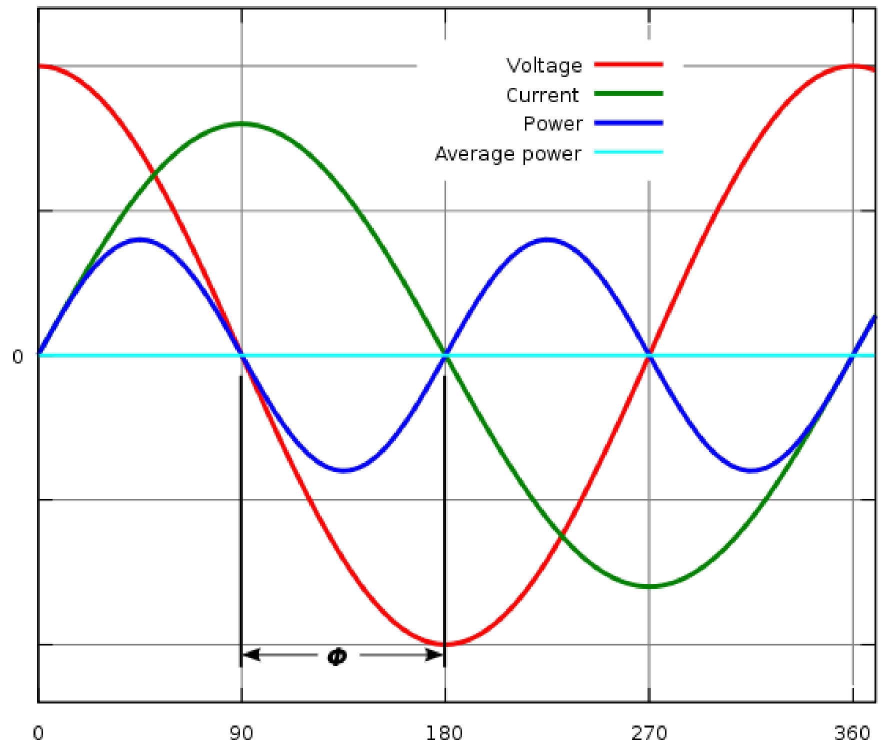
In an electric power system, a load with a low power factor draws more current than a load with a high power factor for the same amount of useful power transferred. The higher currents increase the energy lost in the distribution system, and require larger wires and other equipment. Because of the costs of larger equipment and wasted energy, electrical utilities will usually charge a higher cost to industrial or commercial customers where there is a low power factor.

Linear loads with low power factor (such as induction motors) can be corrected with a passive network of capacitors or inductors. Non-linear loads, such as rectifiers, distort the current drawn from the system. In such cases, active or passive power factor correction may be used to counteract the distortion and raise the power factor. The devices for correction of the power factor may be at a central substation, spread out over a distribution system, or built into power-consuming equipment.

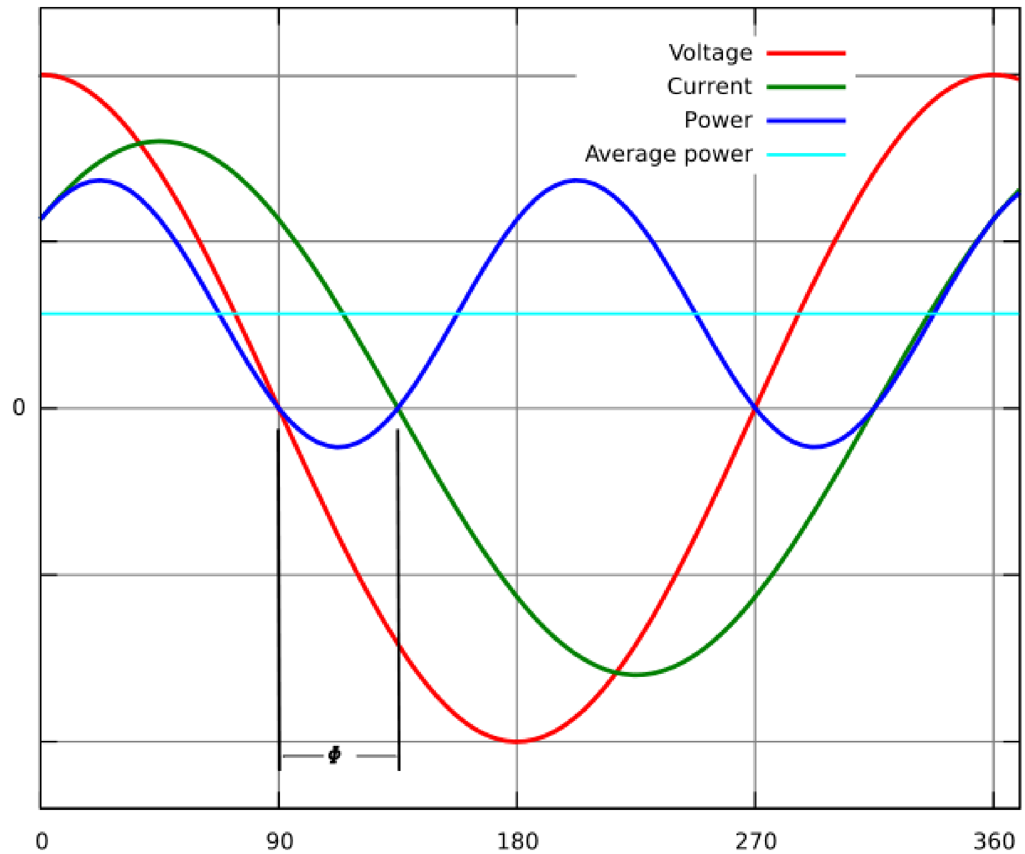
Power factor in linear circuits



Instantaneous and average power calculated from AC voltage and current with a unity power factor (ϕ=0, cosϕ=1). Since the blue line is above the axis, all power is real power consumed by the load.



Instantaneous and average power calculated from AC voltage and current with a zero power factor (ϕ=90, cosϕ=0). The blue line shows all the power is stored temporarily in the load during the first quarter cycle and returned to the grid during the second quarter cycle, so no real power is consumed.



Instantaneous and average power calculated from AC voltage and current with a lagging power factor (ϕ=45, cosϕ=0.71). The blue line shows some of the power is returned to the grid during the part of the cycle labelled φ

In a purely resistive AC circuit, voltage and current waveforms are in step (or in phase), changing polarity at the same instant in each cycle. All the power entering the loads is consumed. Where reactive loads are present, such as with capacitors or inductors, energy storage in the loads result in a time difference between the current and voltage waveforms. During each cycle of the AC voltage, extra energy, in addition to any energy consumed in the load, is temporarily stored in the load in electric or magnetic fields, and then returned to the power grid a fraction of a second later in the cycle. The "ebb and flow" of this nonproductive power increases the current in the line. Thus, a circuit with a low power factor will use higher currents to transfer a given quantity of real power than a circuit with a high power factor. A linear load does not change the shape of the waveform of the current, but may change the relative timing (phase) between voltage and current.

Circuits containing purely resistive heating elements (filament lamps, strip heaters, cooking stoves, etc.) have a power factor of 1.0. Circuits containing inductive or capacitive elements (electric motors, solenoid valves, lamp ballasts, and others) often have a power factor below 1.0.

Definition and calculation

AC power flow has the three components: real power(Active power)(P), measured in watts (W); apparent power (S), measured in volt-amperes (VA); and reactive power (Q), measured in reactive volt-amperes (var) .

The power factor is defined as:

$$\frac{P}{S}.$$

In the case of a perfectly sinusoidal waveform, P, Q and S can be expressed as vectors that form a vector triangle such that:

$$S^2 = P^2 + Q^2.$$

If φ is the phase angle between the current and voltage, then the power factor is equal to the cosine of the angle, $|\cos\varphi|$, and:

$$|P| = |S|\,|\cos\varphi|\,.$$

Since the units are consistent, the power factor is by definition a dimensionless number between 0 and 1. When power factor is equal to 0, the energy flow is entirely reactive, and stored energy in the load returns to the source on each cycle. When the power factor is 1, all the energy supplied by the source is consumed by the load. Power factors are usually stated as "leading" or "lagging" to show the sign of the phase angle.

If a purely resistive load is connected to a power supply, current and voltage will change polarity in step, the power factor will be unity (1), and the electrical energy flows in a single direction across the network in each cycle. Inductive loads such as transformers and motors (any type of wound coil) consume reactive power with current waveform lagging the voltage. Capacitive loads such as capacitor banks or buried cable generate reactive power with current phase leading the voltage. Both types of loads will absorb energy during part of the AC cycle, which is stored in the device's magnetic or electric field, only to return this energy back to the source during the rest of the cycle.

For example, to get 1 kW of real power, if the power factor is unity, 1 kVA of apparent power needs to be transferred (1 kW ÷ 1 = 1 kVA). At low values of power factor, more apparent power needs to be transferred to get the same real power. To get 1 kW of real power at 0.2 power factor, 5 kVA of apparent power needs to be transferred (1 kW ÷ 0.2 = 5 kVA). This apparent power must be produced and transmitted to the load in the conventional fashion, and is subject to the usual distributed losses in the production and transmission processes.

Electrical loads consuming alternating current power consume both real power and reactive power. The vector sum of real and reactive power is the apparent power. The presence of reactive power causes the real power to be less than the apparent power, and so, the electric load has a power factor of less than 1.

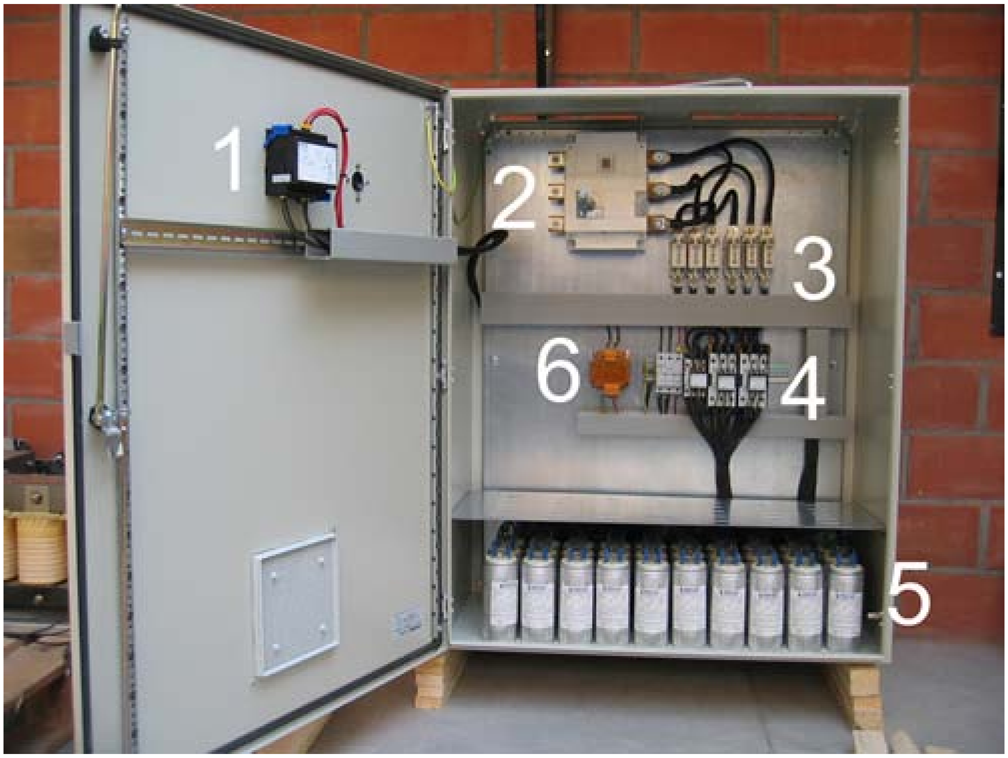
Power factor correction of linear loads

It is often desirable to adjust the power factor of a system to near 1.0. This power factor correction (PFC) is achieved by switching in or out banks of inductors or capacitors. For example the inductive effect of motor loads may be offset by locally connected capacitors. When reactive elements supply or absorb reactive power near the load, the apparent power is reduced.

Power factor correction may be applied by an electrical power transmission utility to improve the stability and efficiency of the transmission network. Correction equipment may be installed by individual electrical customers to reduce the costs charged to them by their electricity supplier. A high power factor is generally desirable in a transmission system to reduce transmission losses and improve voltage regulation at the load.

Power factor correction brings the power factor of an AC power circuit closer to 1 by supplying reactive power of opposite sign, adding capacitors or inductors which act to cancel the inductive or capacitive effects of the load, respectively. For example, the inductive effect of motor loads may be offset by locally connected capacitors. If a load had a capacitive value, inductors (also known as reactors in this context) are connected to correct the power factor. In the electricity industry, inductors are said to consume reactive power and capacitors are said to supply it, even though the reactive power is actually just moving back and forth on each AC cycle.

The reactive elements can create voltage fluctuations and harmonic noise when switched on or off. They will supply or sink reactive power regardless of whether there is a corresponding load operating nearby, increasing the system's no-load losses. In a worst case, reactive elements can interact with the system and with each other to create resonant conditions, resulting in system instability and severe overvoltage fluctuations. As such, reactive elements cannot simply be applied at will, and power factor correction is normally subject to engineering analysis.



1. Reactive Power Control Relay; 2. Network connection points; 3. Slow-blow Fuses; 4. Inrush Limiting Contactors; 5. Capacitors (single-phase or three-phase units, delta-connection); 6. Transformer Suitable voltage transformation to suit control power (contactors, ventilation,...)

An **automatic power factor correction unit** is used to improve power factor. A power factor correction unit usually consists of a number of capacitors that are switched by means of contactors. These contactors are controlled by a regulator that measures power factor in an electrical network. To be able to measure power factor, the regulator uses a current transformer to measure the current in one phase.

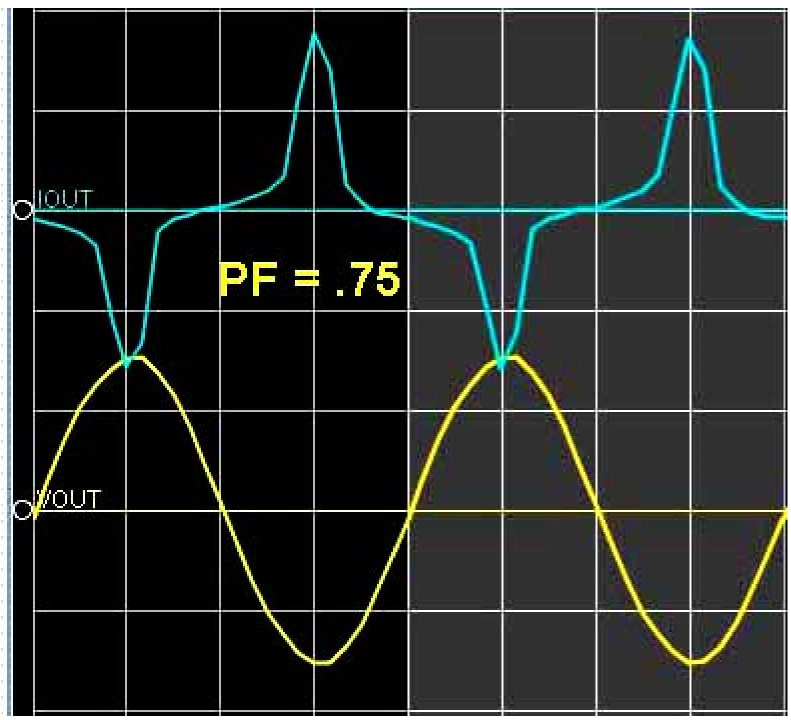
Depending on the load and power factor of the network, the power factor controller will switch the necessary blocks of capacitors in steps to make sure the power factor stays above a selected value (usually demanded by the energy supplier), say 0.9.

Instead of using a set of switched capacitors, an unloaded synchronous motor can supply reactive power. The reactive power drawn by the synchronous motor is a function of its field excitation. This is referred to as a synchronous condenser. It is started and connected to the electrical network. It operates at a leading power factor and puts vars onto the network as required to support a system's voltage or to maintain the system power factor at a specified level.

The condenser's installation and operation are identical to large electric motors. Its principal advantage is the ease with which the amount of correction can be adjusted; it behaves like an electrically variable capacitor. Unlike capacitors, the amount of reactive power supplied is proportional to voltage, not the square of voltage; this improves voltage stability on large networks. Synchronous condensors are often used in connection with high voltage direct current transmission projects or in large industrial plants such as steel mills.

Non-linear loads

A non-linear load on a power system is typically a rectifier (such as used in a power supply), or some kind of arc discharge device such as a fluorescent lamp, electric welding machine, or arc furnace. Because current in these systems is interrupted by a switching action, the current contains frequency components that are multiples of the power system frequency. Distortion power factor is a measure of how much the harmonic distortion of a load current decreases the average power transferred to the load.



Sinusoidal voltage and non-sinusoidal current give a distortion power factor of 0.75 for this computer power supply load.

Non-sinusoidal components

Non-linear loads change the shape of the current waveform from a sine wave to some other form. Non-linear loads create harmonic currents in addition to the original (fundamental frequency) AC current. Filters consisting of linear capacitors and inductors can prevent harmonic currents from entering the supplying system.

In linear circuits having only sinusoidal currents and voltages of one frequency, the power factor arises only from the difference in phase between the current and voltage.

This is "displacement power factor". The concept can be generalized to a total, distortion, or true power factor where the apparent power includes all harmonic components. This is of importance in practical power systems which contain non-linear loads such as rectifiers, some forms of electric lighting, electric arc furnaces, welding equipment, switched-mode power supplies and other devices.

A typical multimeter will give incorrect results when attempting to measure the AC current drawn by a non-sinusoidal load; the instruments sense the average value of a rectified waveform. The average response is then calibrated to the effective, RMS value. An RMS sensing multimeter must be used to measure the actual RMS currents and voltages (and therefore apparent power). To measure the real power or reactive power, a wattmeter designed to work properly with non-sinusoidal currents must be used.

Distortion power factor

The distortion power factor' describes how the harmonic distortion of a load current decreases the average power transferred to the load.

$$\text{distortion power factor} = \frac{1}{\sqrt{1 + \mathrm{THD}_i^2}} = \frac{I_{1,\mathrm{rms}}}{I_{\mathrm{rms}}}$$

THD_i is the total harmonic distortion of the load current. This definition assumes that the voltage stays undistorted (sinusoidal, without harmonics). This simplification is often a good approximation in practice. $I_{1,rms}$ is the fundamental component of the current and I_{rms} is the total current - both are root mean square-values.

The result when multiplied with the displacement power factor (DPF) is the overall, true power factor or just power factor (PF):

$$\mathrm{PF} = \mathrm{DPF}\frac{I_{1,\mathrm{rms}}}{I_{\mathrm{rms}}}$$

Switched-mode power supplies

A particularly important class of non-linear loads is the millions of personal computers that typically incorporate switched-mode power supplies (SMPS) with rated output power ranging from a few watts to more than 1 kW. Historically, these very-low-cost power supplies incorporated a simple full-wave rectifier that conducted only when the mains instantaneous voltage exceeded the voltage on the input capacitors. This leads to very high ratios of peak-to-average input current, which also lead to a low distortion power factor and potentially serious phase and neutral loading concerns.

A typical switched-mode power supply first makes a DC bus, using a bridge rectifier or similar circuit. The output voltage is then derived from this DC bus. The problem with this is that the rectifier is a non-linear device, so the input current is highly non-linear. That means that the input current has energy at harmonics of the frequency of the voltage.

This presents a particular problem for the power companies, because they cannot compensate for the harmonic current by adding simple capacitors or inductors, as they could for the reactive power drawn by a linear load. Many jurisdictions are beginning to legally require power factor correction for all power supplies above a certain power level.

Regulatory agencies such as the EU have set harmonic limits as a method of improving power factor. Declining component cost has hastened implementation of two different methods. To comply with current EU standard EN61000-3-2, all switched-mode power supplies with output power more than 75 W must include passive PFC, at least. 80 PLUS power supply certification requires a power factor of 0.9 or more.

Power factor correction in non-linear loads

Passive PFC

The simplest way to control the harmonic current is to use a filter: it is possible to design a filter that passes current only at line frequency (e.g. 50 or 60 Hz). This filter reduces the harmonic current, which means that the non-linear device now looks like a linear load. At this point the power factor can be brought to near unity, using capacitors or inductors as required. This filter requires large-value high-current inductors, however, which are bulky and expensive.

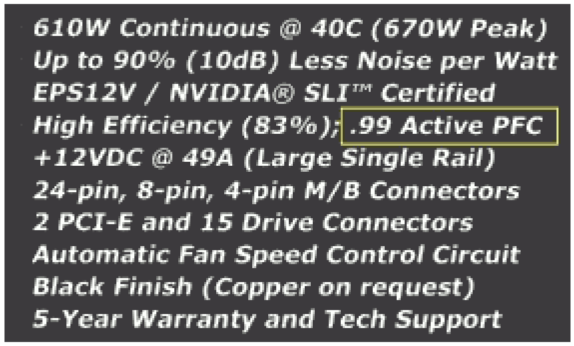
A passive PFC requires an inductor larger than the inductor in an active PFC, but costs less.

This is a simple way of correcting the nonlinearity of a load by using capacitor banks. It is not as effective as active PFC.

Passive PFCs are typically more power efficient than active PFCs. Efficiency is not to be confused with the PFC, though many computer hardware reviews conflate them. A passive PFC on a switching computer PSU has a typical power efficiency of around 96%, while an active PFC has a typical efficiency of about 94%.

Active PFC

An "active power factor corrector" (active PFC) is a power electronic system that controls the amount of power drawn by a load in order to obtain a power factor as close as possible to unity. In most applications, the active PFC controls the input current of the load so that the current waveform is proportional to the mains voltage waveform (a sine wave). The purpose of making the power factor as close to unity (1) as possible is to make the load circuitry that is power factor corrected appear purely resistive (apparent power equal to real power). In this case, the voltage and current are in phase and the reactive power consumption is zero. This enables the most efficient delivery of electrical power from the power company to the consumer.



Specifications taken from the packaging of a 610W PC power supply showing Active PFC rating

Some types of active PFC are:

- Boost
- Buck
- Buck-boost

Active power factor correctors can be single-stage or multi-stage.

In the case of a switched-mode power supply, a boost converter is inserted between the bridge rectifier and the main input capacitors. The boost converter attempts to maintain a constant DC bus voltage on its output while drawing a current that is always in phase with and at the same frequency as the line voltage. Another switchmode converter inside the power supply produces the desired output voltage from the DC bus. This approach requires additional semiconductor switches and control electronics, but permits cheaper and smaller passive components. It is frequently used in practice. For example, SMPS with passive PFC can achieve power factor of about 0.7–0.75, SMPS with active PFC, up to 0.99 power factor, while a SMPS without any power factor correction has a power factor of only about 0.55–0.65.

Due to their very wide input voltage range, many power supplies with active PFC can automatically adjust to operate on AC power from about 100 V (Japan) to 230 V (Europe). That feature is particularly welcome in power supplies for laptops.

Importance of power factor in distribution systems

The significance of power factor lies in the fact that utility companies supply customers with volt-amperes, but bill them for watts. Power factors below 1.0 require a utility to generate more than the minimum volt-amperes necessary to supply the real power (watts). This increases generation and transmission costs. For example, if the load power factor were as low as 0.7, the apparent power would be 1.4 times the real power used by the load. Line current in the circuit would also be 1.4 times the current required at 1.0 power factor, so the losses in the circuit would be doubled (since they are proportional to the square of the current). Alternatively all components of the system such as generators, conductors, transformers, and switchgear would be increased in size (and cost) to carry the extra current.

Utilities typically charge additional costs to customers who have a power factor below some limit, which is typically 0.9 to 0.95. Engineers are often interested in the power factor of a load as one of the factors that affect the efficiency of power transmission.

With the rising cost of energy and concerns over the efficient delivery of power, active PFC has become more common in consumer electronics. Current Energy Star guidelines for computers (ENERGY STAR® Program Requirements for Computers Version 5.0) call for a power factor of ≥ 0.9 at 100% of rated output in the PC's power supply. According to a white paper authored by Intel and the U.S. Environmental Protection Agency, PCs with internal power supplies will require the use of active power factor correction to meet the ENERGY STAR® 5.0 Program Requirements for Computers.

In Europe, IEC 555-2 requires power factor correction be incorporated into consumer products.

Measuring power factor

Power factor in a single-phase circuit (or balanced three-phase circuit) can be measured with the wattmeter-ammeter-voltmeter method, where the power in watts is divided by the product of measured voltage and current. The power factor of a balanced polyphase circuit is the same as that of any phase. The power factor of an unbalanced polyphase circuit is not uniquely defined.

A direct reading power factor meter can be made with a moving coil meter of the electrodynamic type, carrying two perpendicular coils on the moving part of the instrument. The field of the instrument is energized by the circuit current flow. The two moving coils, A and B, are connected in parallel with the circuit load. One coil, A, will be connected through a resistor and the second coil, B, through an inductor, so that the current in coil B is delayed with respect to current in A. At unity power factor, the current in A is in phase with the circuit current, and coil A provides maximum torque, driving the instrument pointer toward the 1.0 mark on the scale. At zero power factor, the current in coil B is in phase with circuit current, and coil B provides torque to drive the pointer towards 0. At intermediate values of power factor, the torques provided by the two coils add and the pointer takes up intermediate positions.

Another electromechanical instrument is the polarized-vane type. In this instrument a stationary field coil produces a rotating magnetic field, just like a polyphase motor. The field coils are connected either directly to polyphase voltage sources or to a phase-shifting reactor if a single-phase application. A second stationary field coil, perpendicular to the voltage coils, carries a current proportional to current in one phase of the circuit.

The moving system of the instrument consists of two vanes which are magnetized by the current coil. In operation the moving vanes take up a physical angle equivalent to the electrical angle between the voltage source and the current source. This type of instrument can be made to register for currents in both directions, giving a 4-quadrant display of power factor or phase angle.

Digital instruments can be made that either directly measure the time lag between voltage and current waveforms and so calculate the power factor, or by measuring both true and apparent power in the circuit and calculating the quotient. The first method is only accurate if voltage and current are sinusoidal; loads such as rectifiers distort the waveforms from the sinusoidal shape.

Mnemonics

English-language power engineering students are advised to remember: "ELI the ICE man" or "ELI on ICE" – the voltage E leads the current I in an inductor L, the current leads the voltage in a capacitor C.

Or CIVIL – in a capacitor(C) the current (I) leads voltage(V), voltage(V) leads current(I) in an inductor(L).