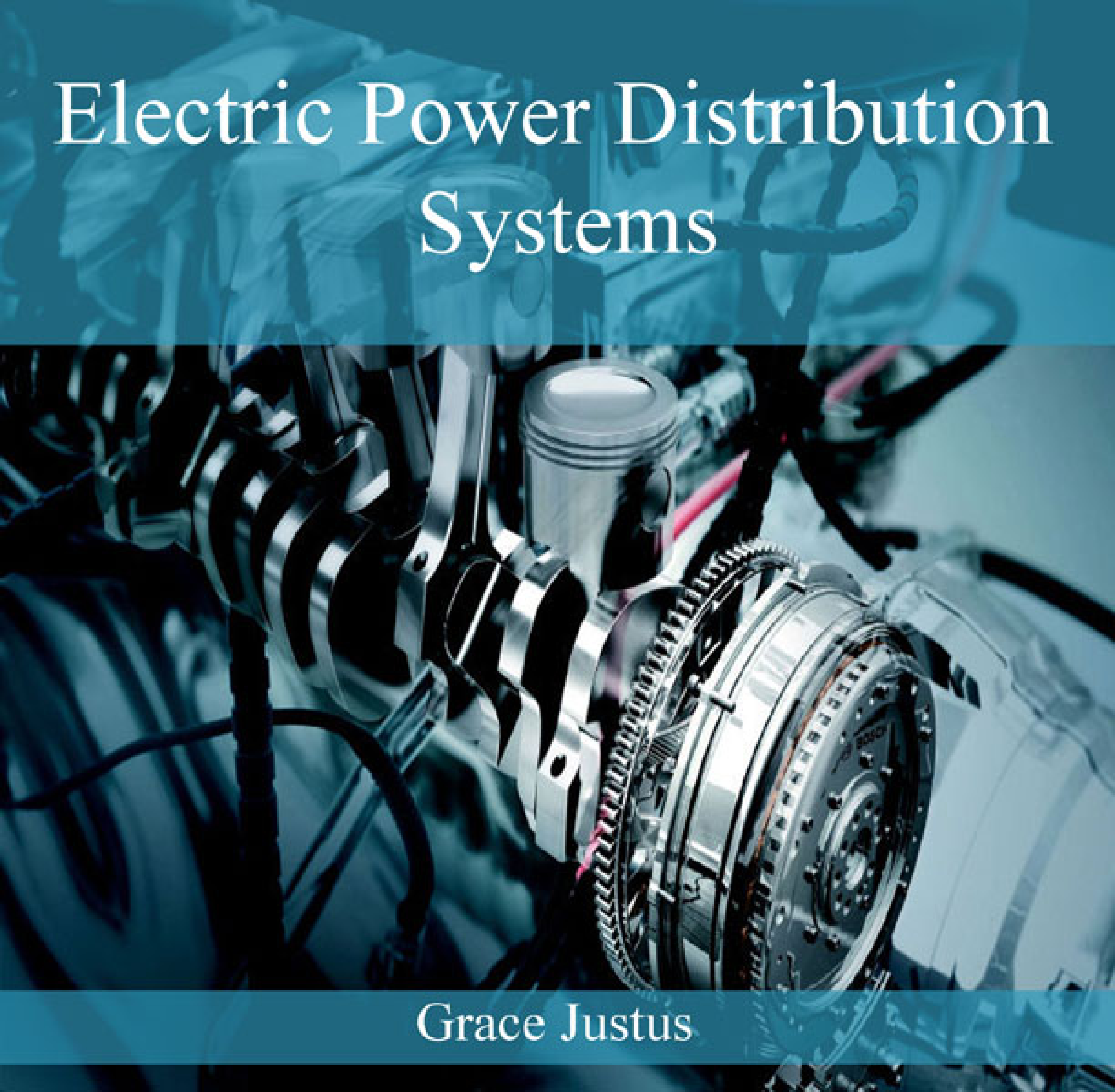
Electric Power Distribution Systems



Grace Justus

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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.

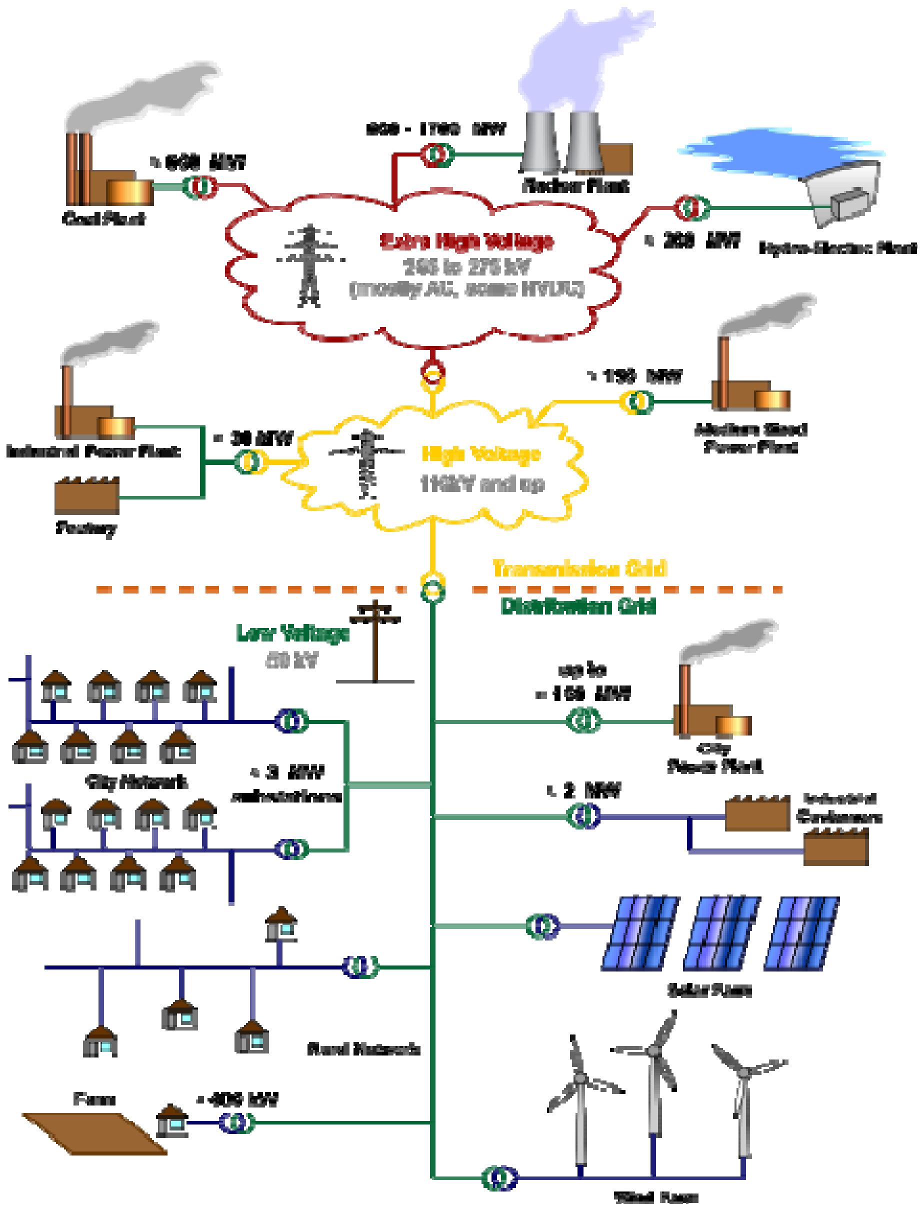
Electricity meters use different equations for each distribution system.

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- 2

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.

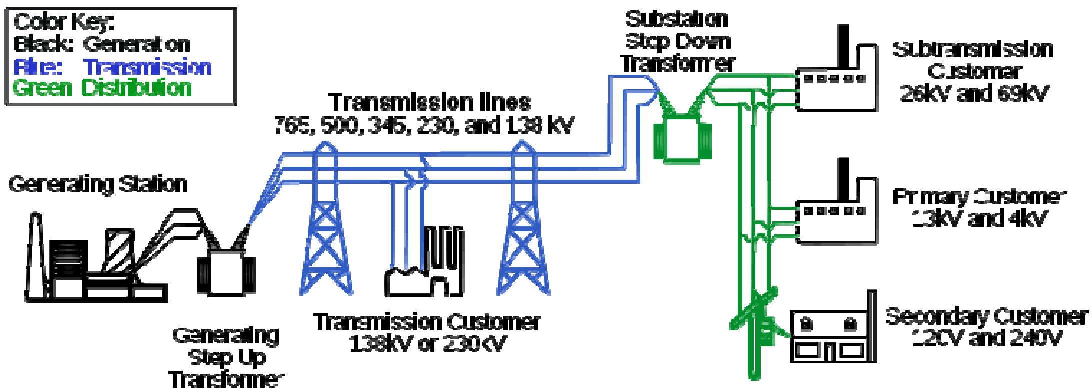
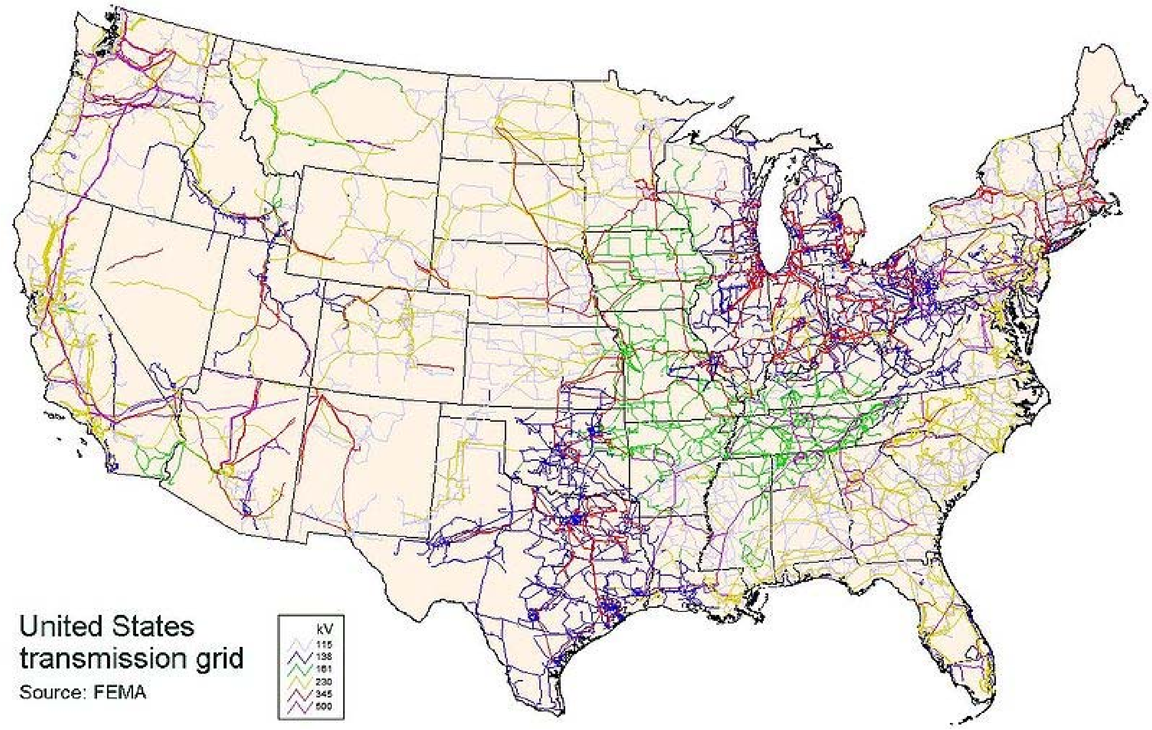


Diagram of an electrical system.

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:

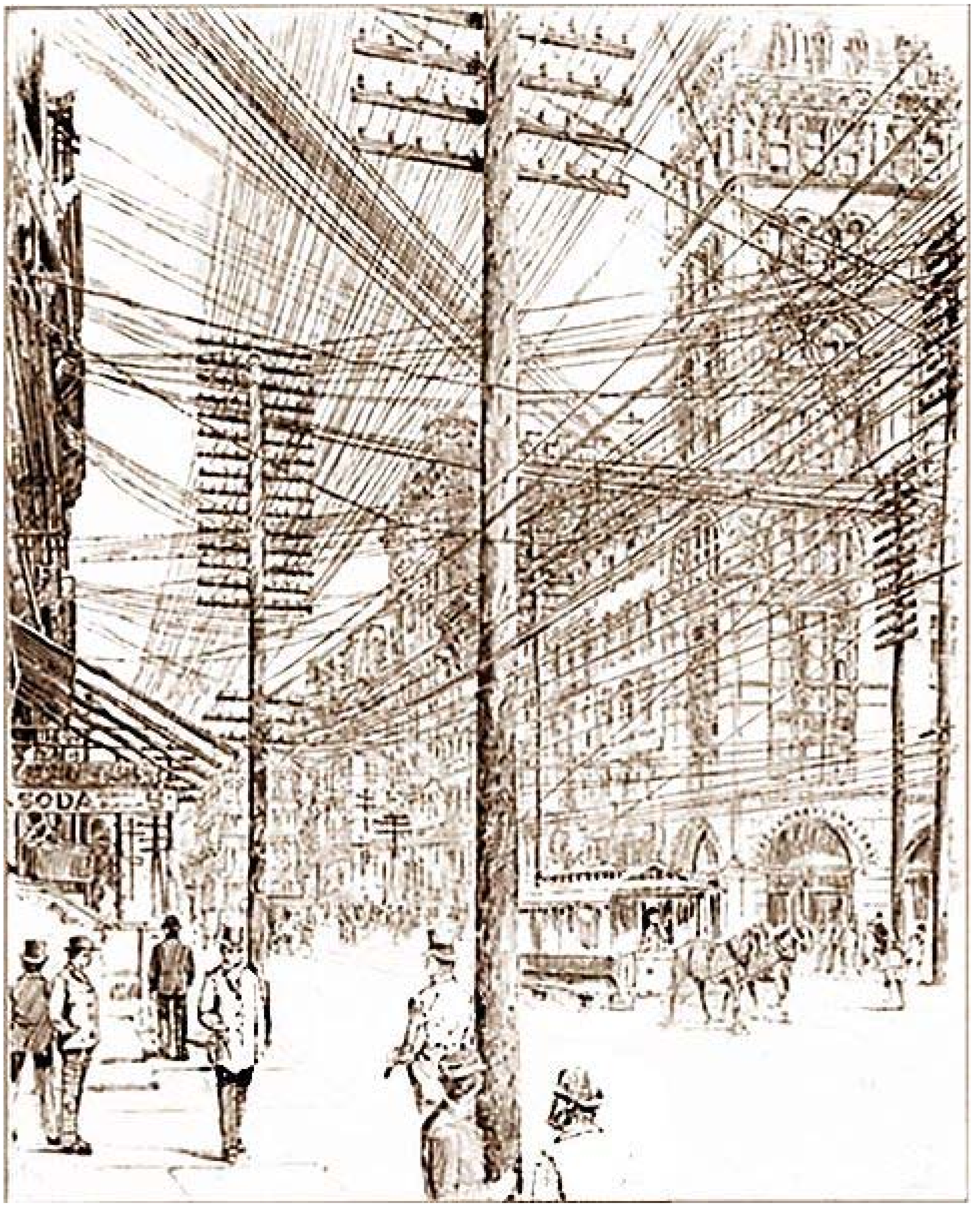
- Less subject to damage from severe weather conditions (mainly lightning, wind and freezing)
- Greatly reduced emission, into the surrounding area, of electromagnetic fields (EMF). All electric currents generate EMF, but the shielding provided by the earth surrounding underground cables restricts their 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

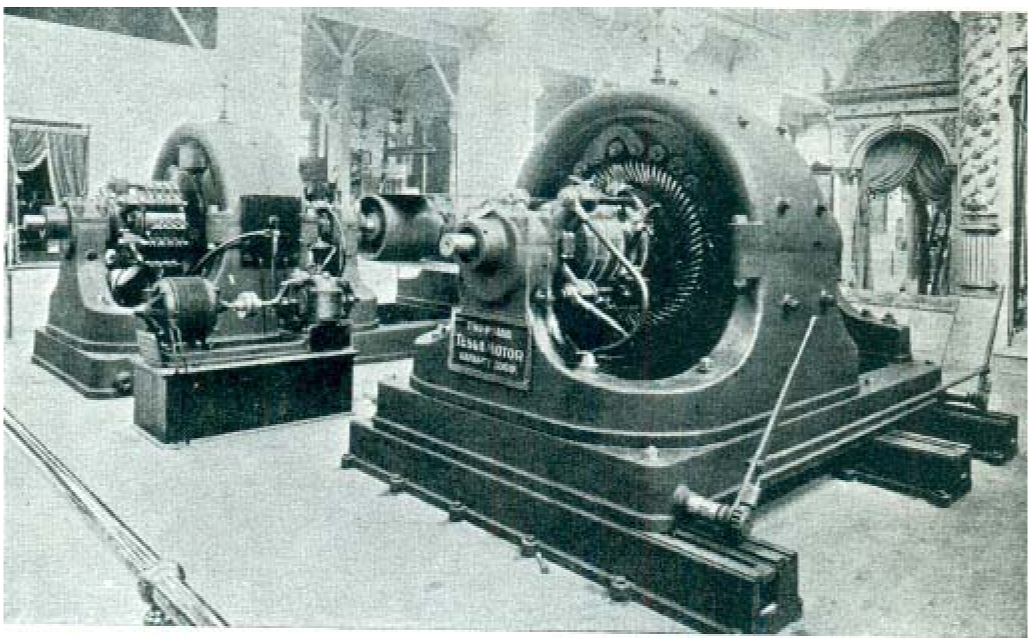


New York City streets in 1890. Besides telegraph lines, multiple electric lines were required for each class of device requiring different voltages.

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

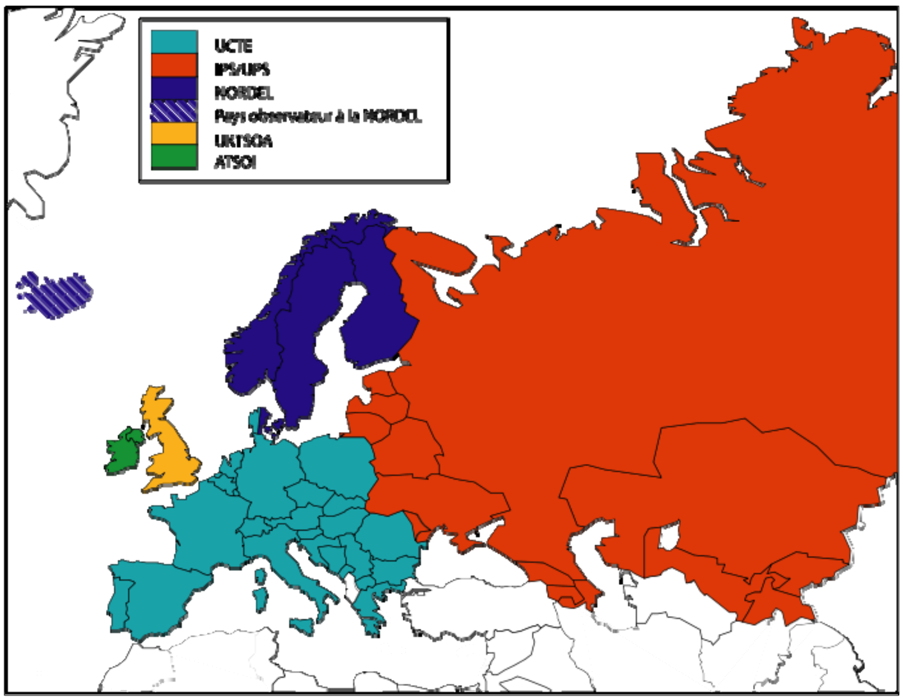
A transmission substation decreases the voltage of incoming electricity, allowing it to connect from long distance high voltage transmission, to local lower voltage distribution. It also reroutes power to other transmission lines that serve local markets. A transmission substation may include phase-shifting 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- 3

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- 4

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:

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

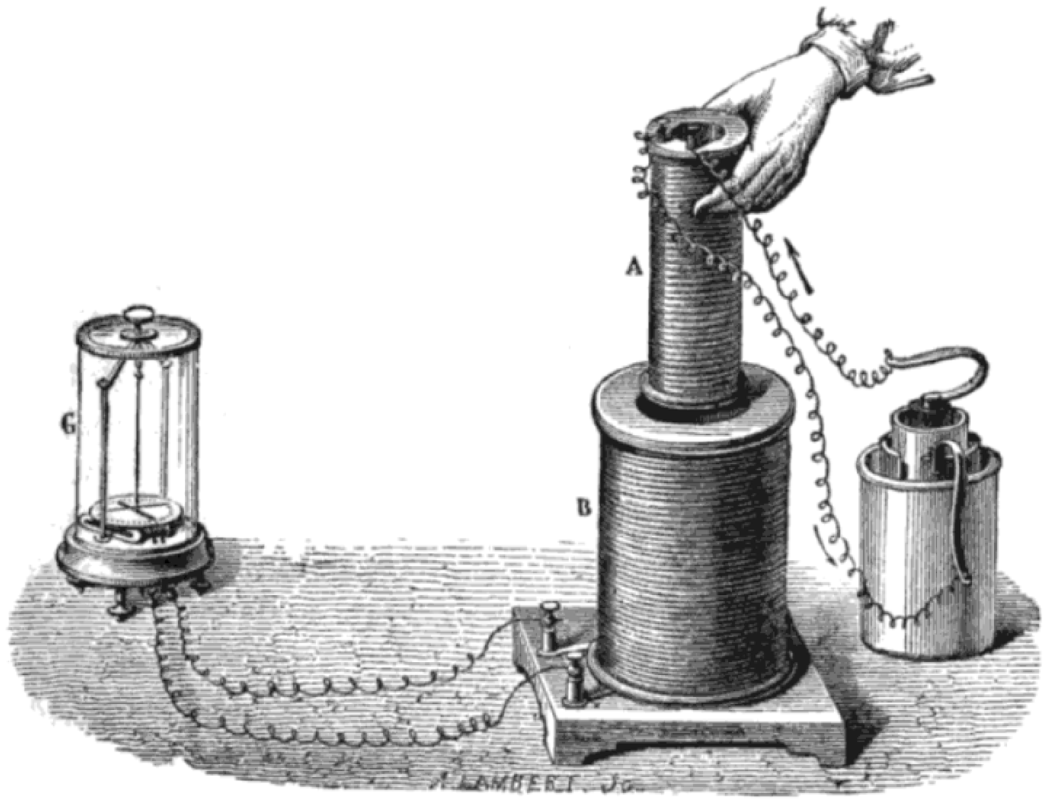
By appropriate selection of the ratio of turns, a transformer thus allows an alternating current (AC) voltage to be "stepped up" by making N_s greater than N_p, or "stepped down" by making N_s less than N_p.

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.

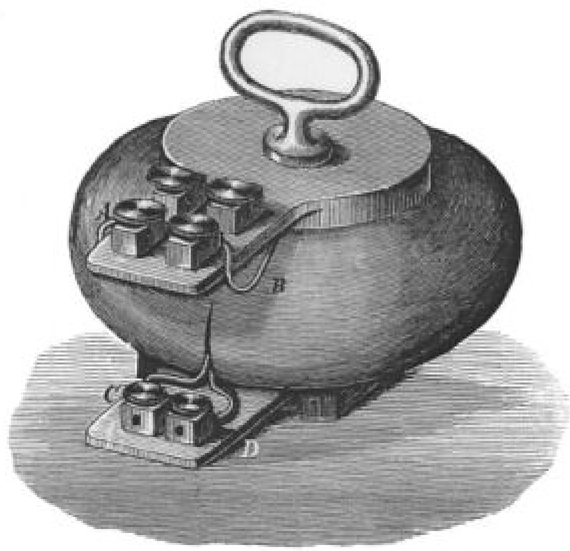
In 1878, the Ganz Company in Hungary began manufacturing equipment for electric lighting and, by 1883, had installed over fifty systems in Austria-Hungary. Their systems used alternating current exclusively and included those comprising both arc and incandescent lamps, along with generators and other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

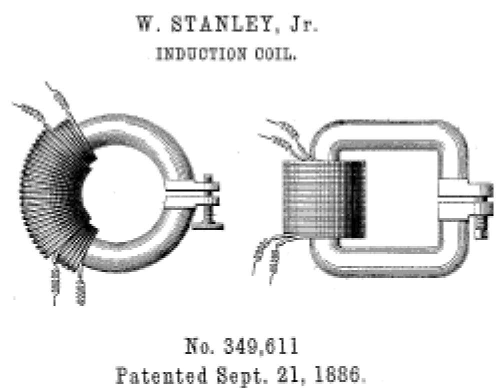
Closed-core lighting transformers



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, Vs/Vp = Ns/Np. 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

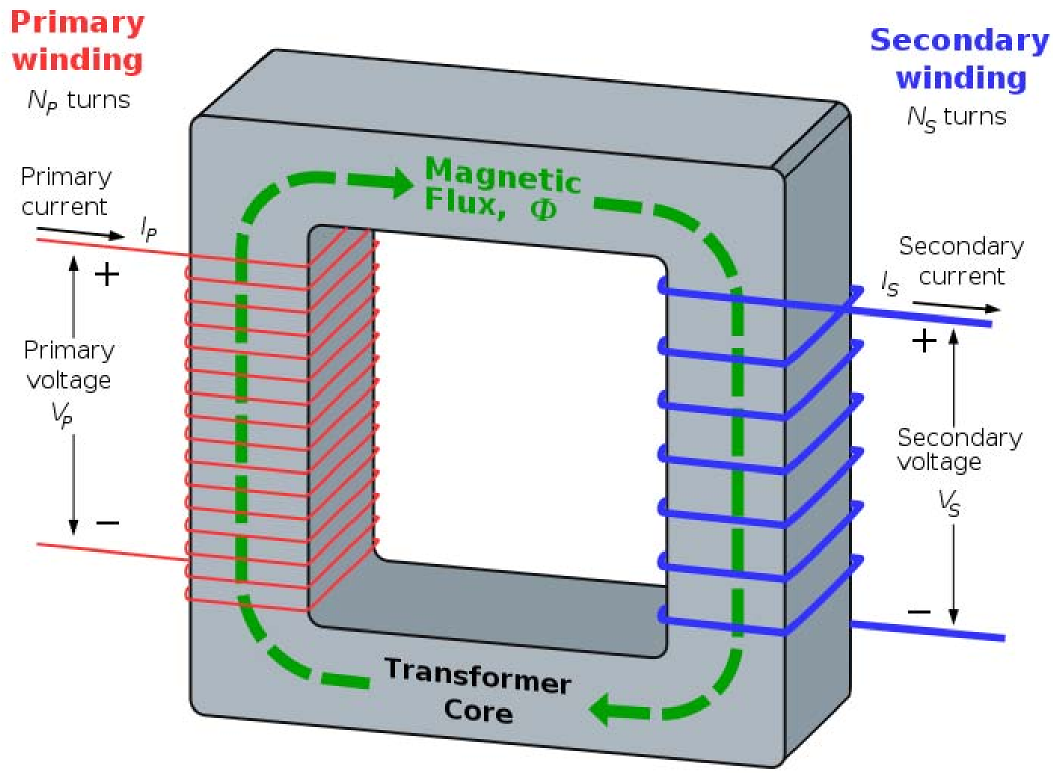
In 1889, Russian-born engineer Mikhail Dolivo-Dobrovolsky developed the first three-phase transformer at the Allgemeine Elektricitäts-Gesellschaft ("General Electricity Company") in Germany.

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:

$$V_s = N_s \frac{\mathrm{d}\Phi}{\mathrm{d}t},$$

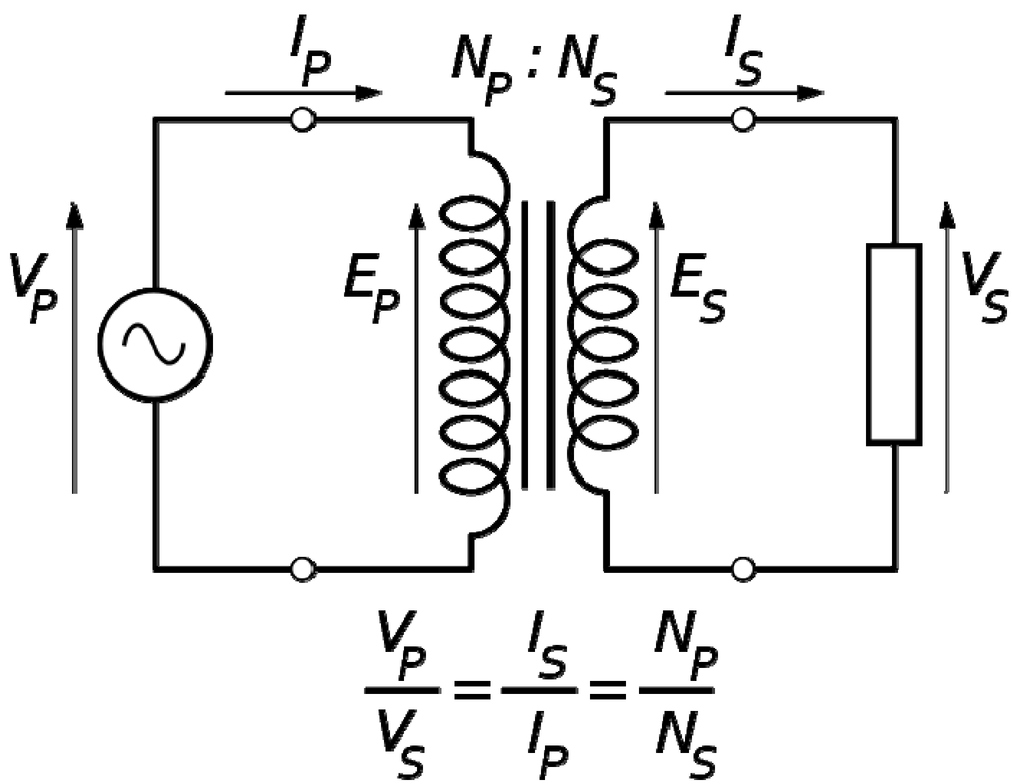
where V_s is the instantaneous voltage, N_s is the number of turns in the secondary coil and Φ is the magnetic flux through one turn of the coil. If the turns of the coil are oriented perpendicular to the magnetic field lines, the flux is the product of the magnetic flux density *B* and the area *A* 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:

$$P_{\text{incoming}} = I_p V_p = P_{\text{outgoing}} = I_s V_s,$$

giving the ideal transformer equation

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

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 $(N_p/N_s)^2 Z_s$. This relationship is reciprocal, so that the impedance Z_p of the primary circuit appears to the secondary to be $(N_s/N_p)^2 Z_p$.

Detailed operation

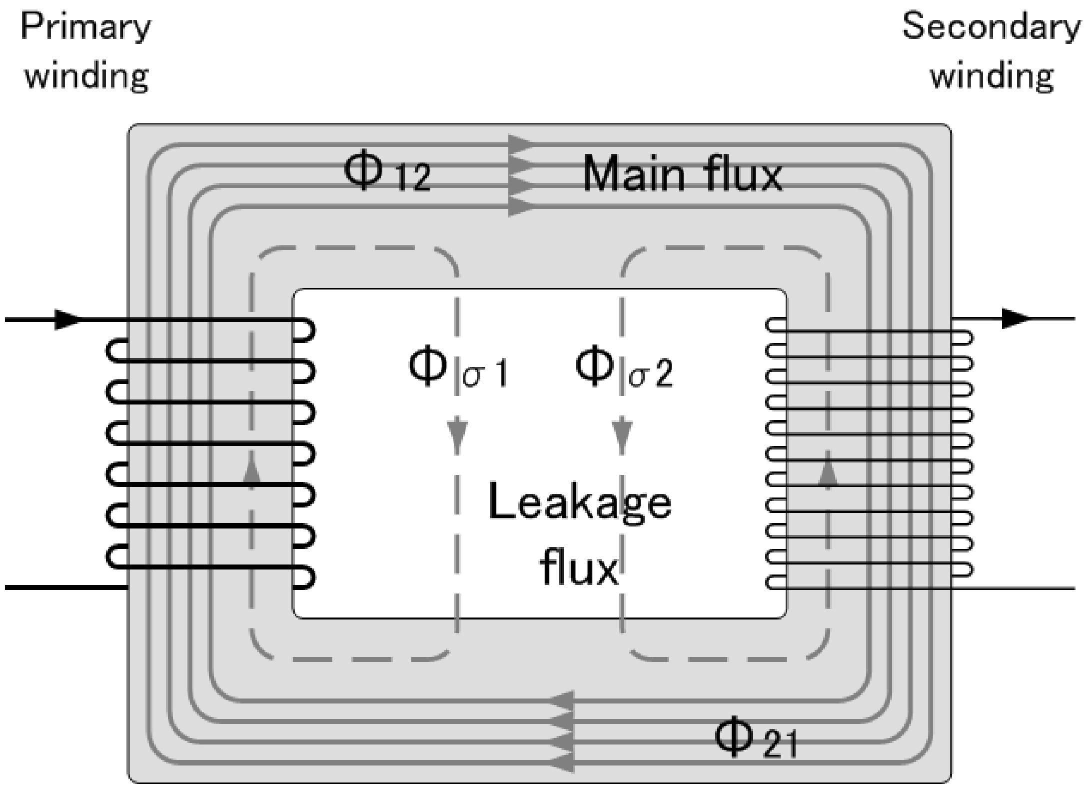
The simplified description above neglects several practical factors, in particular the primary current required to establish a magnetic field in the core, and the contribution to the field due to current in the secondary circuit.

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:

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

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

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

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.

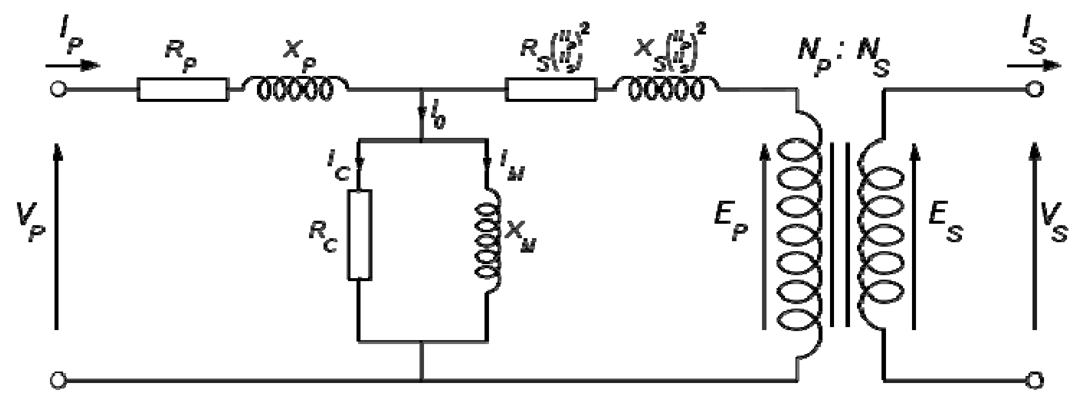
Equivalent circuit

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

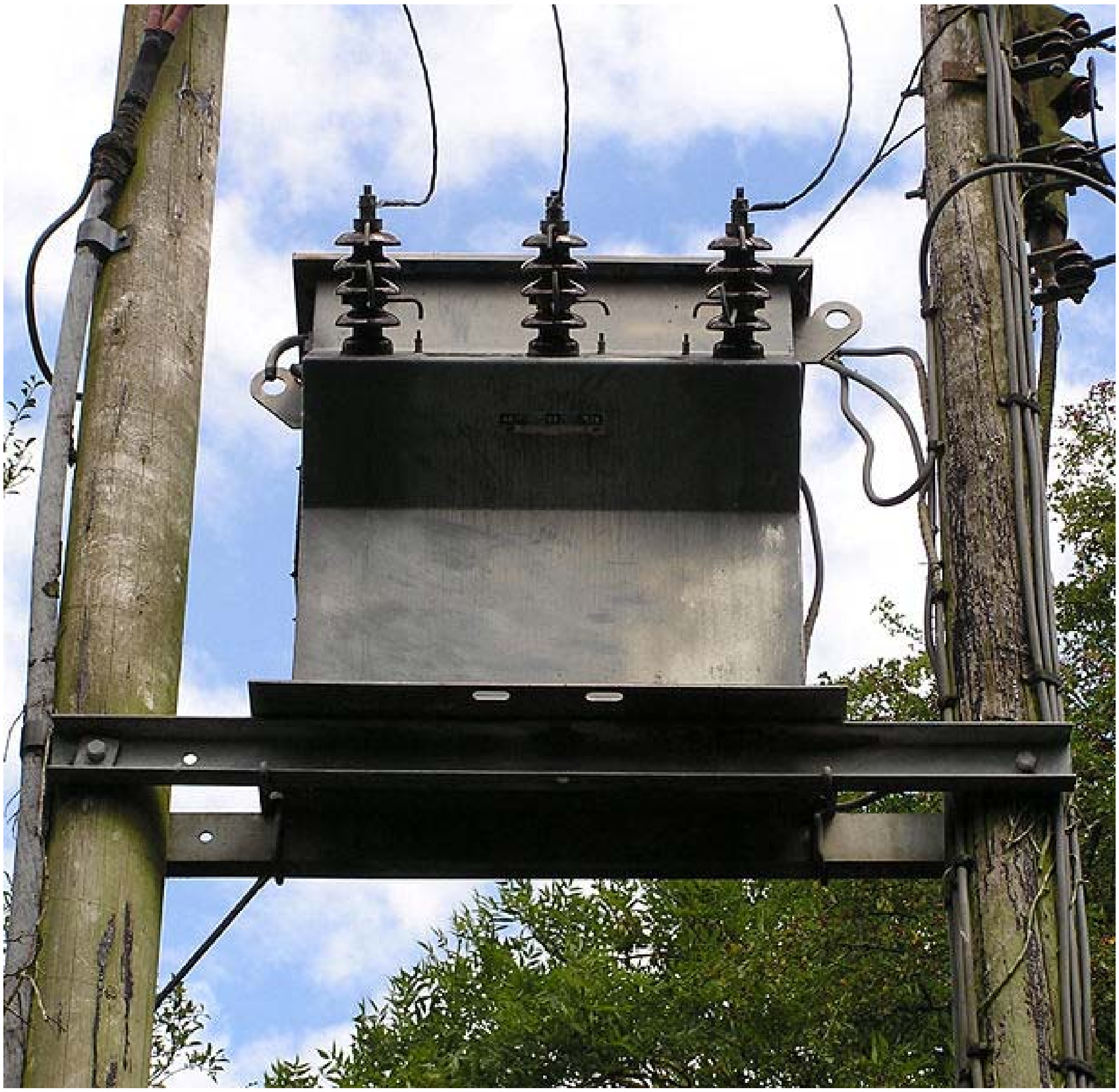
An autotransformer with a sliding brush contact

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

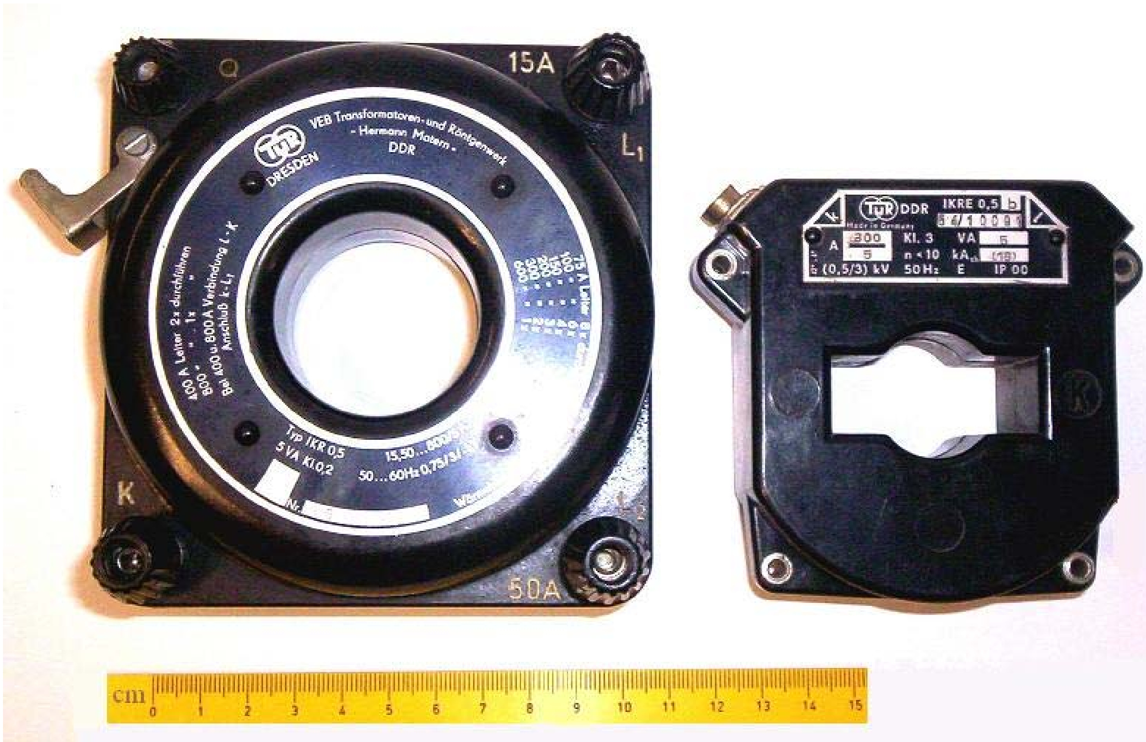
Audio transformers are those specifically designed for use in audio circuits. They can be used to block radio frequency interference or the DC component of an audio signal, to split or combine audio signals, or to provide impedance matching between high and low impedance circuits, such as between a high 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

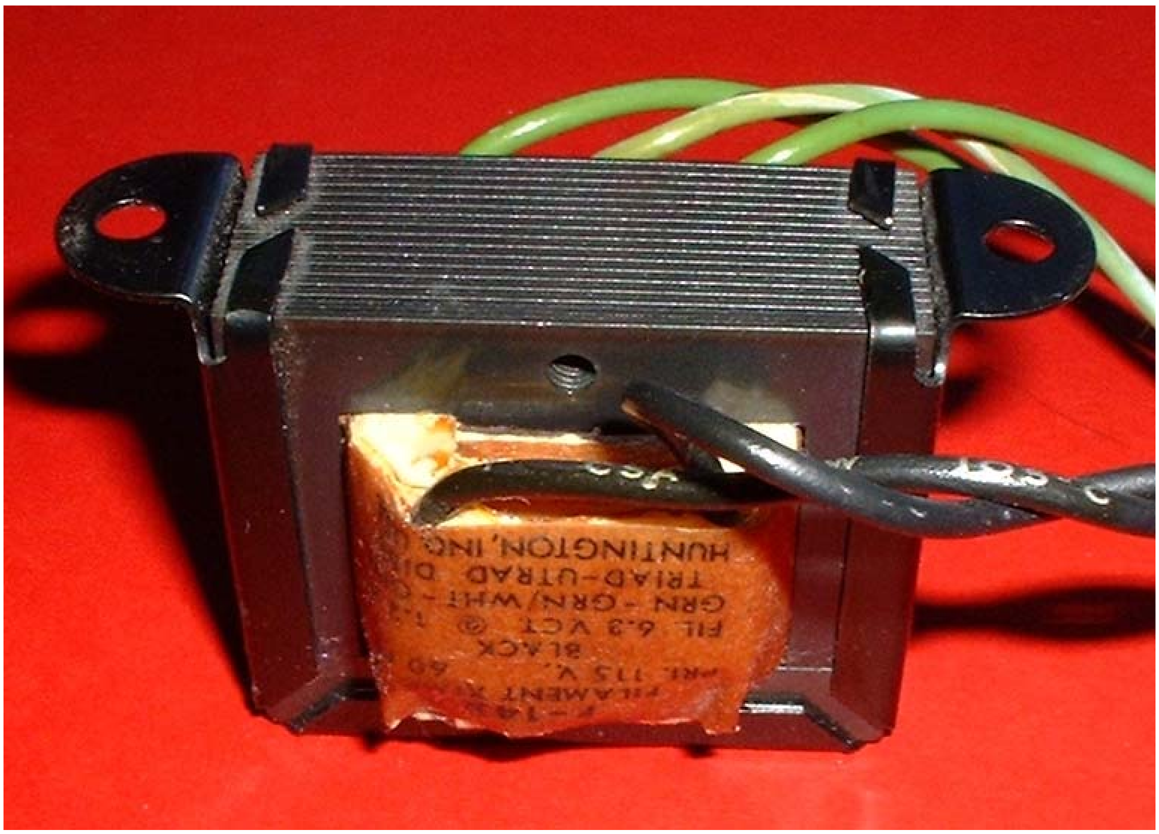
Transformers can be classified in many different ways; an incomplete list is:

- *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

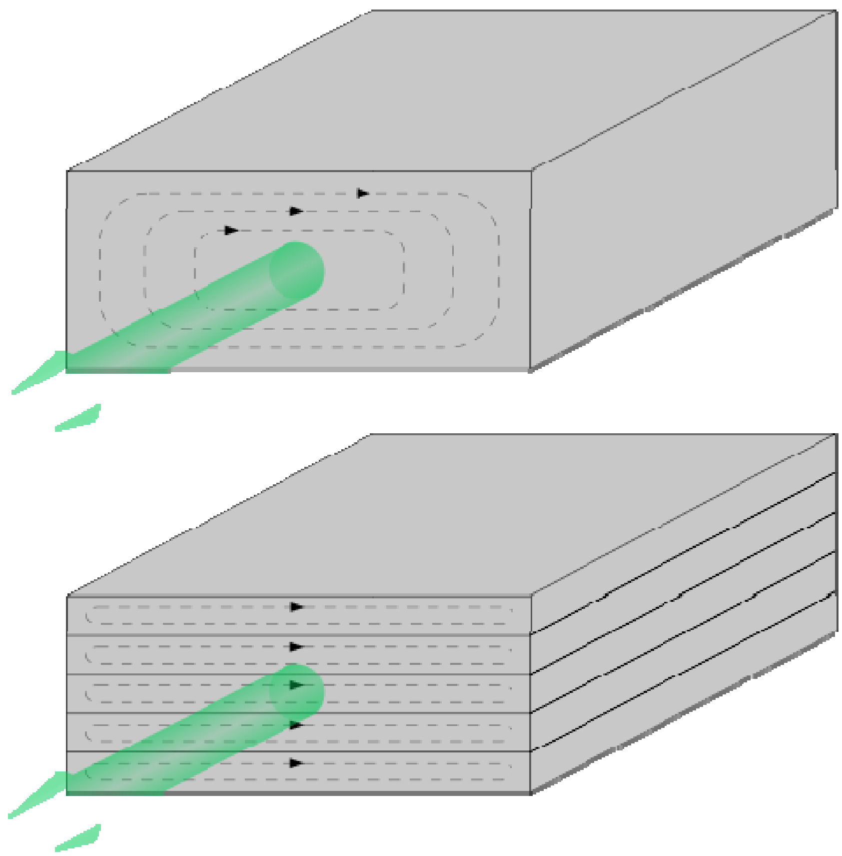


Laminated core transformer showing edge of laminations at top of photo

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.

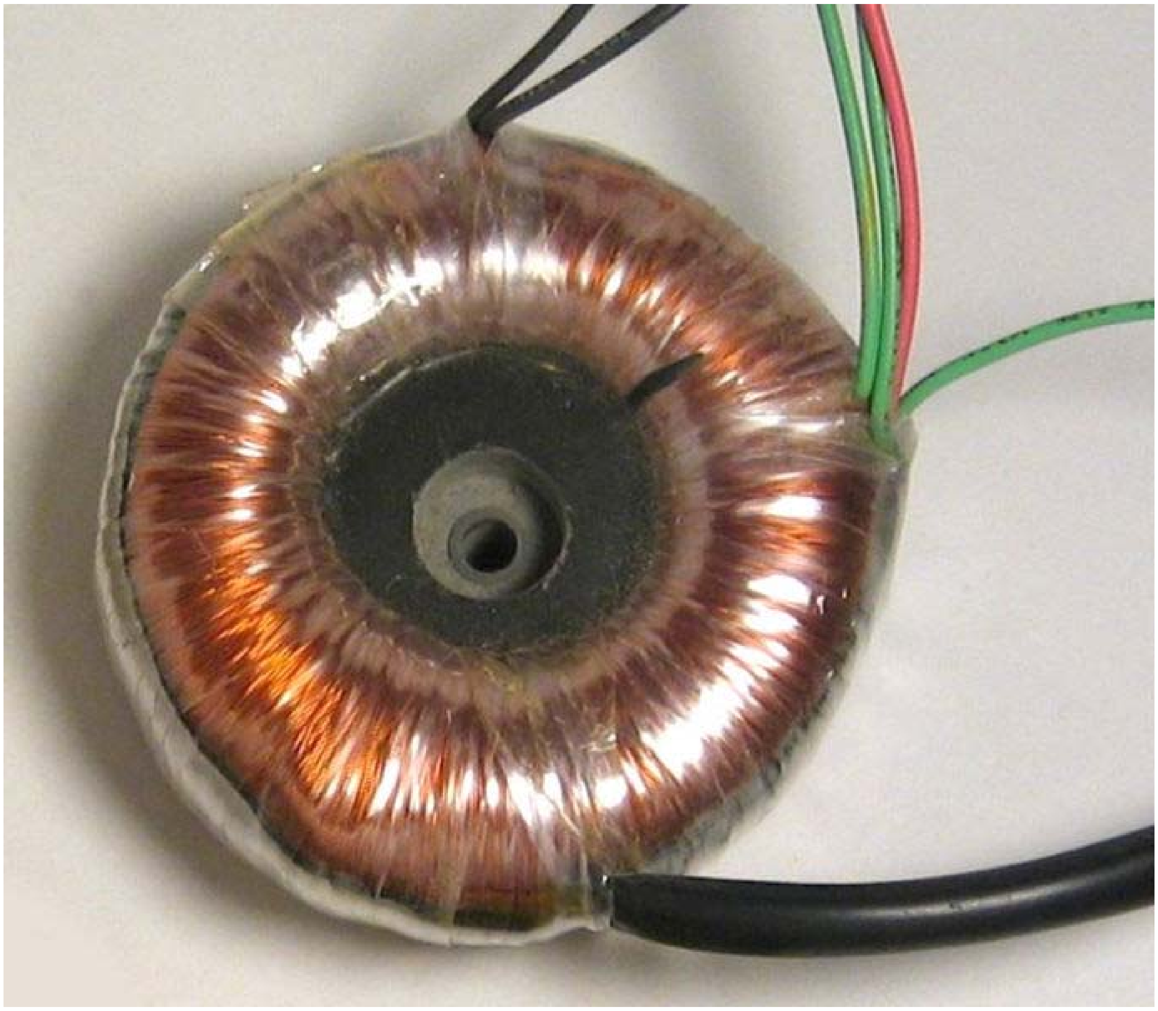
A steel core's remanence means that it retains a static magnetic field when power is removed. When power is then reapplied, the residual field will cause a high inrush current until the effect of the remaining magnetism is reduced, usually after a few cycles of the applied alternating current. Overcurrent 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.

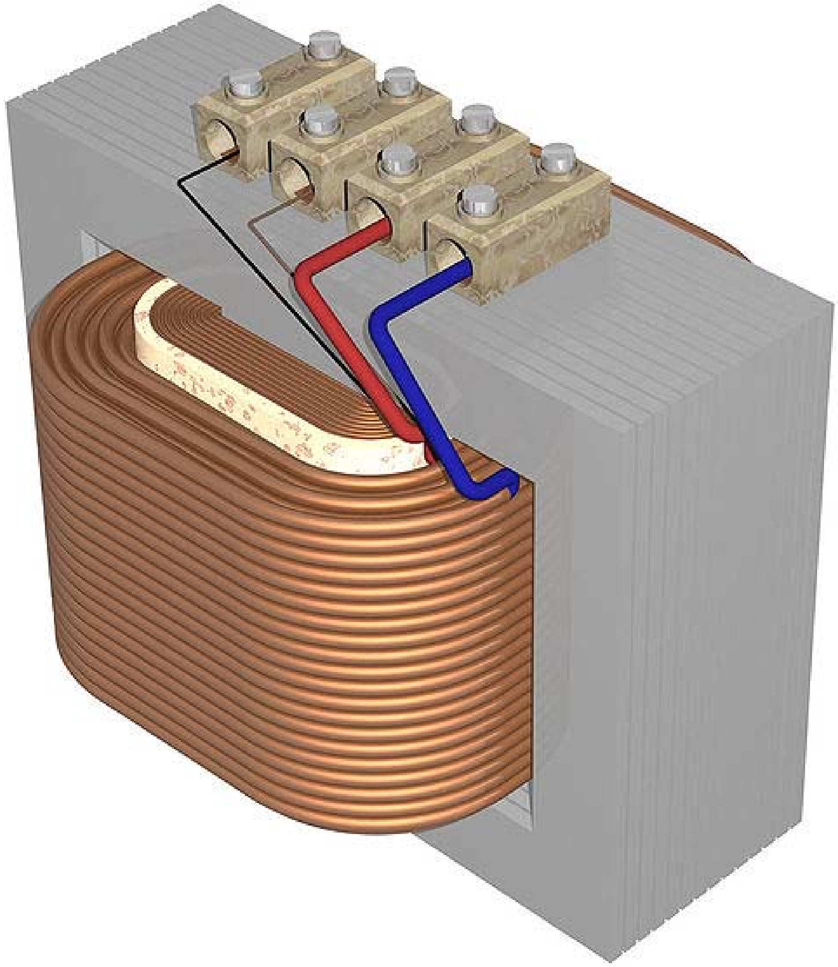
Toroidal transformers are more efficient than the cheaper laminated E-I types for a similar power level. Other advantages compared to E-I types, include smaller size (about half), lower weight (about half), less mechanical hum (making them superior in audio amplifiers), lower exterior magnetic field (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.

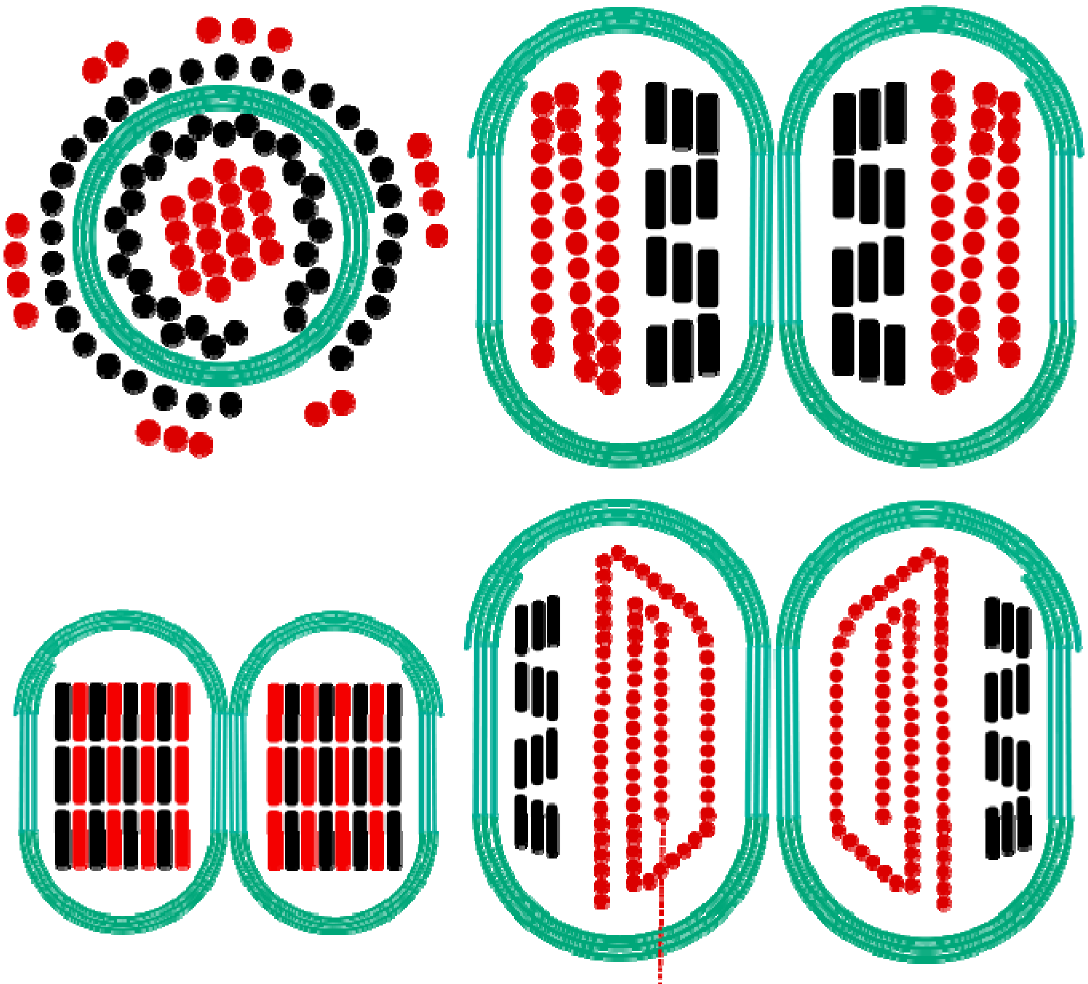
Air cores

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.

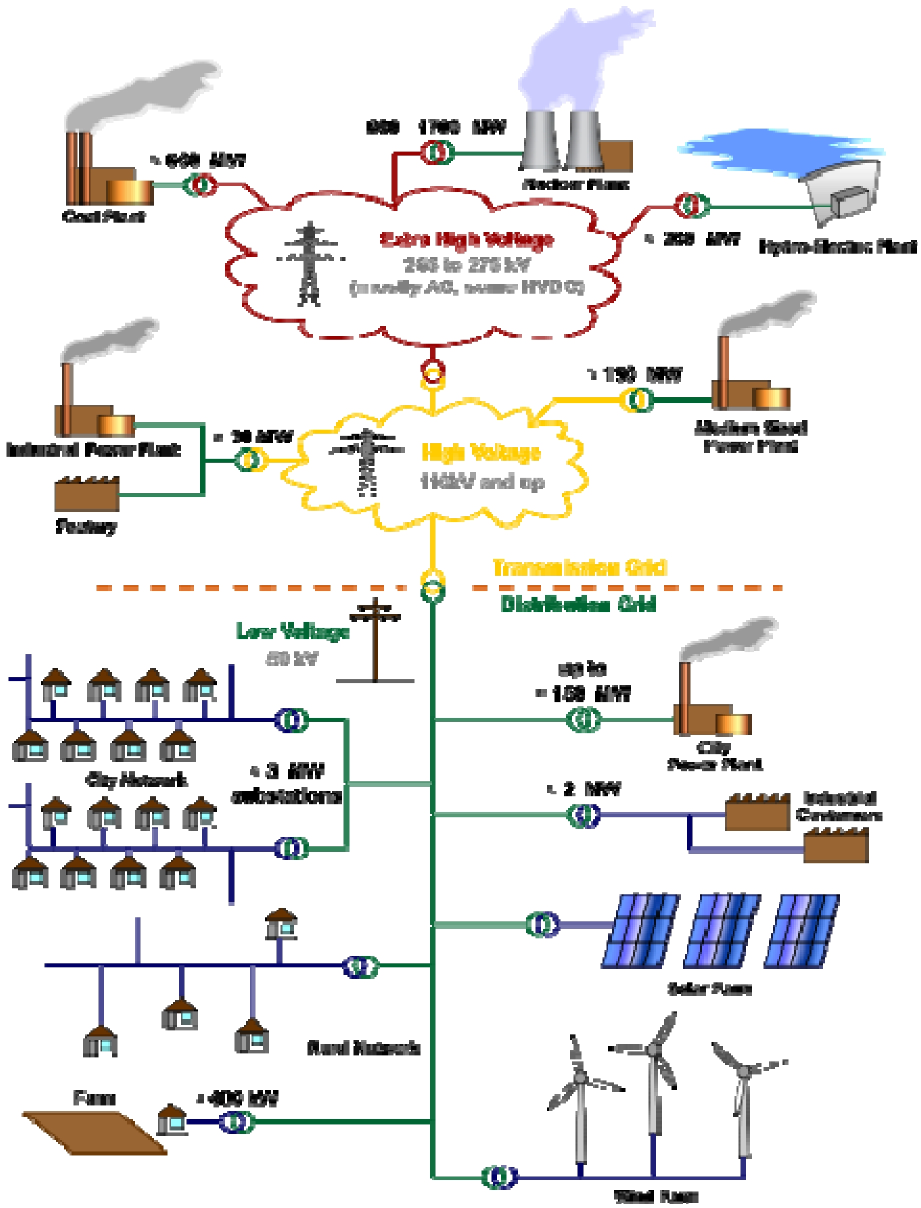
Transformers are also used extensively in electronic products to step down the supply voltage to a level suitable for the low voltage circuits they contain. The transformer also electrically isolates the end user from contact with the supply voltage.

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- 5

Electrical Grid



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

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

Overview

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

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

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

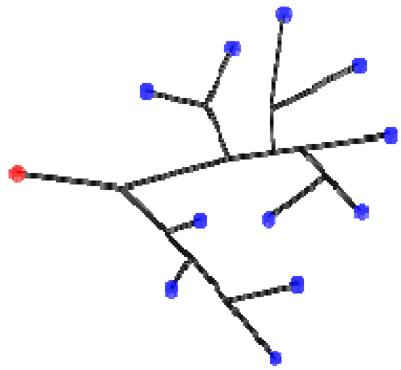
Electricity in a remote location might be provided by a simple distribution grid linking a central generator to homes. The traditional paradigm for moving electricity around in developed countries is more complex. Generating plants are usually located near a source of water, and away from heavily populated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

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

Features

Structure of distribution grids

The 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).

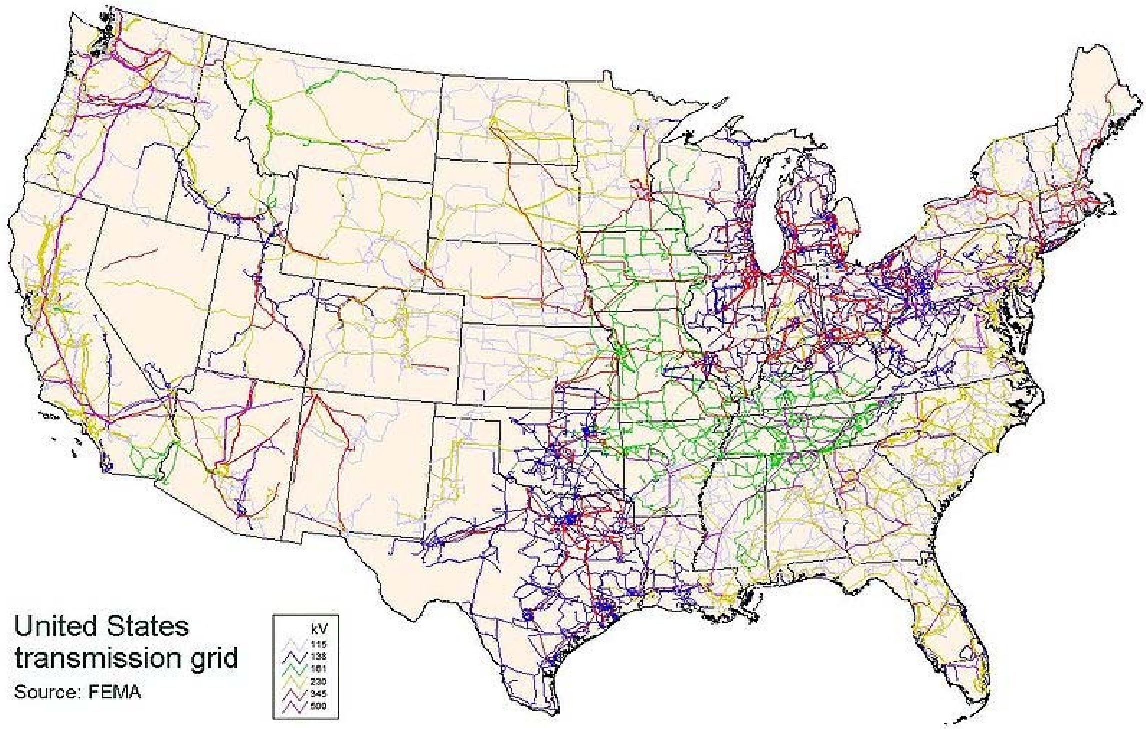
The cheapest and simplest topology for a distribution or transmission grid is a *radial* structure. This is a *tree* shape where power from a large supply radiates out into progressively lower voltage lines until the destination homes and businesses are reached.

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.

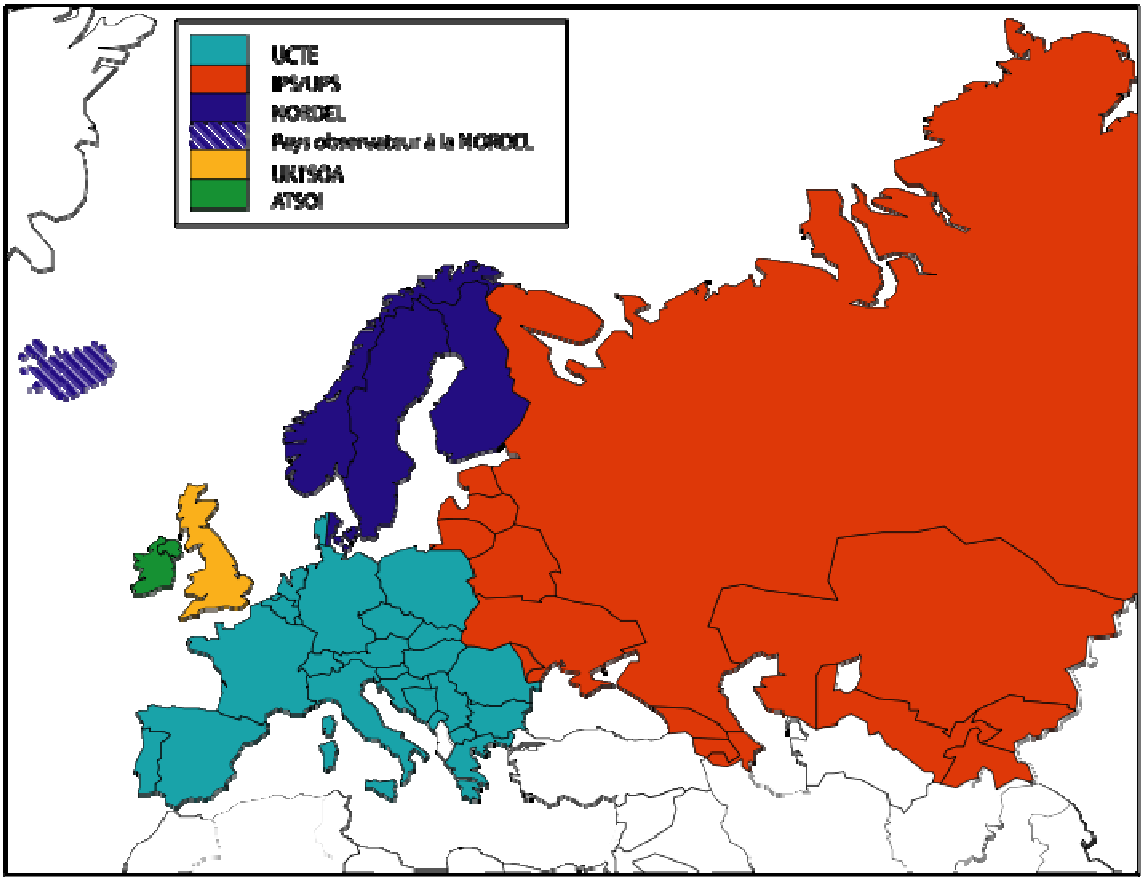
Transmission networks are more complex with redundant pathways. For example, see the map of the United States' (right) high-voltage transmission network.

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).

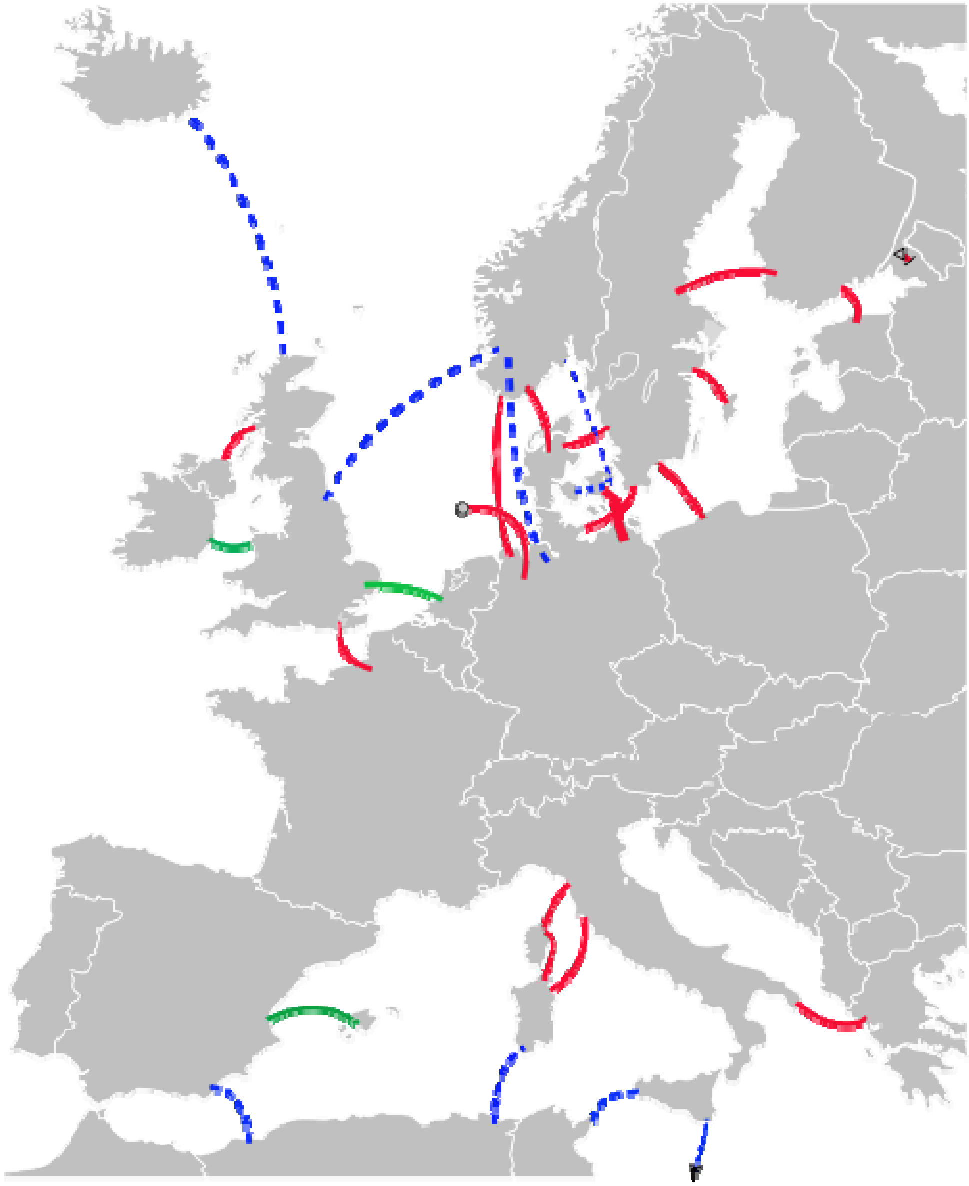
Electricity generation and consumption must be balanced across the entire grid, because energy is consumed almost immediately after it is produced. A large failure in one part of the grid - unless quickly compensated for - can cause current to re-route itself to flow from the remaining generators to 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- 6

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

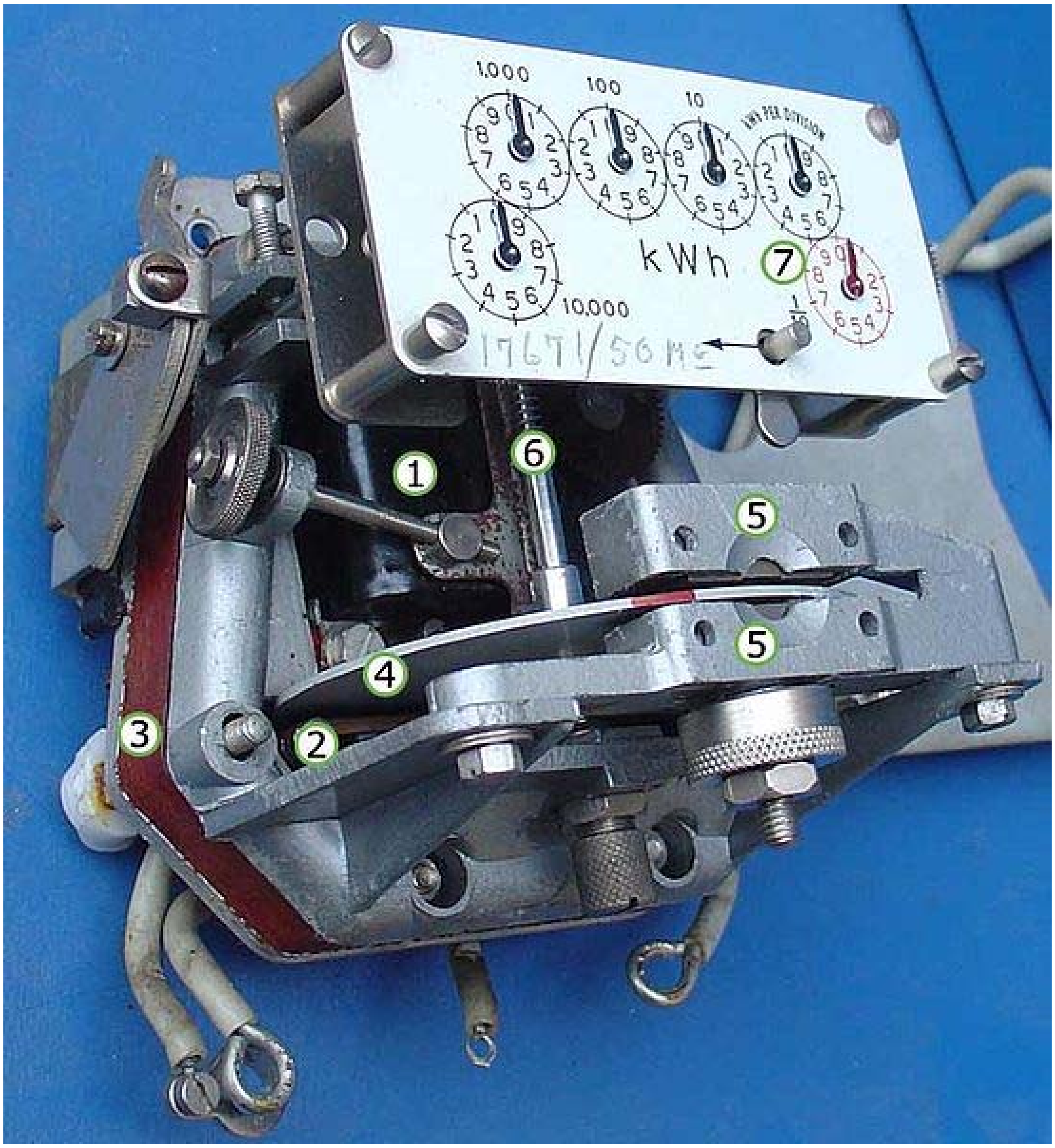
In addition to metering based on the amount of energy used, other types of metering are available.

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.

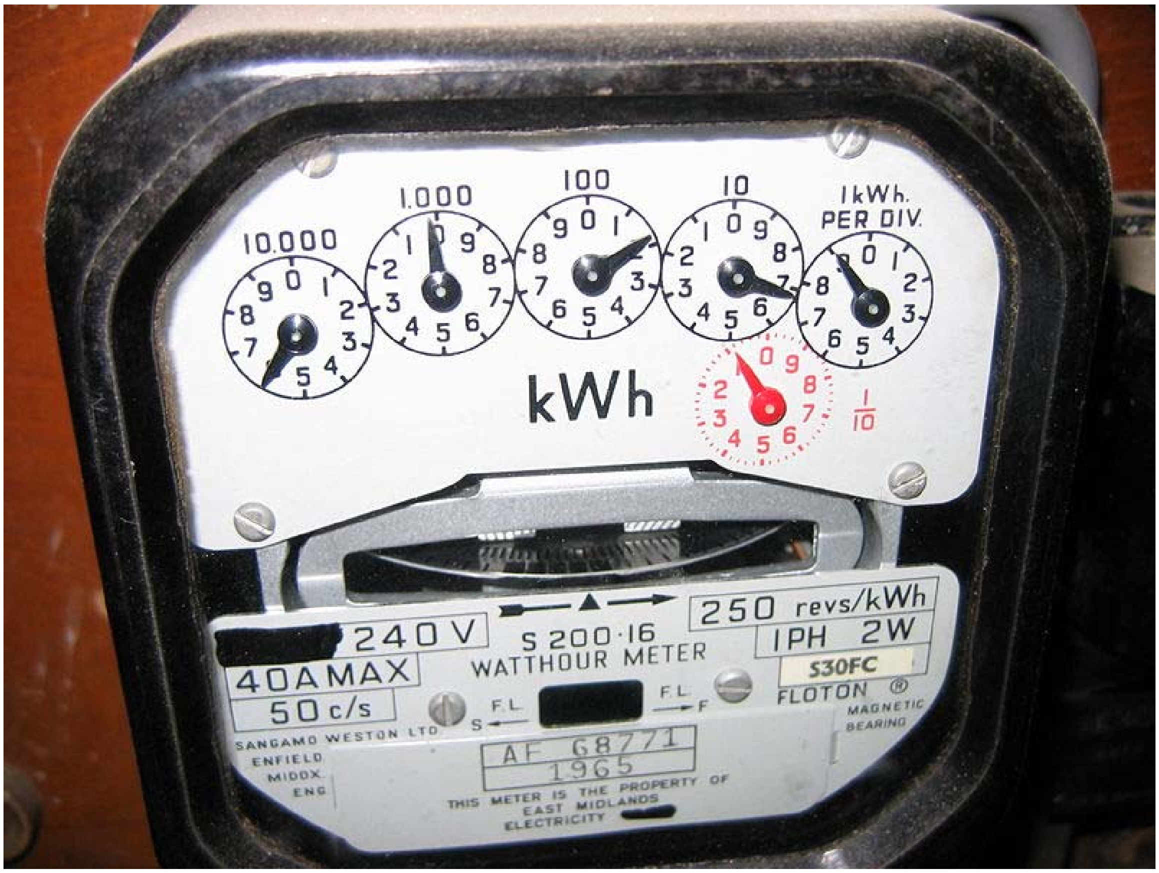
Types of meters



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).

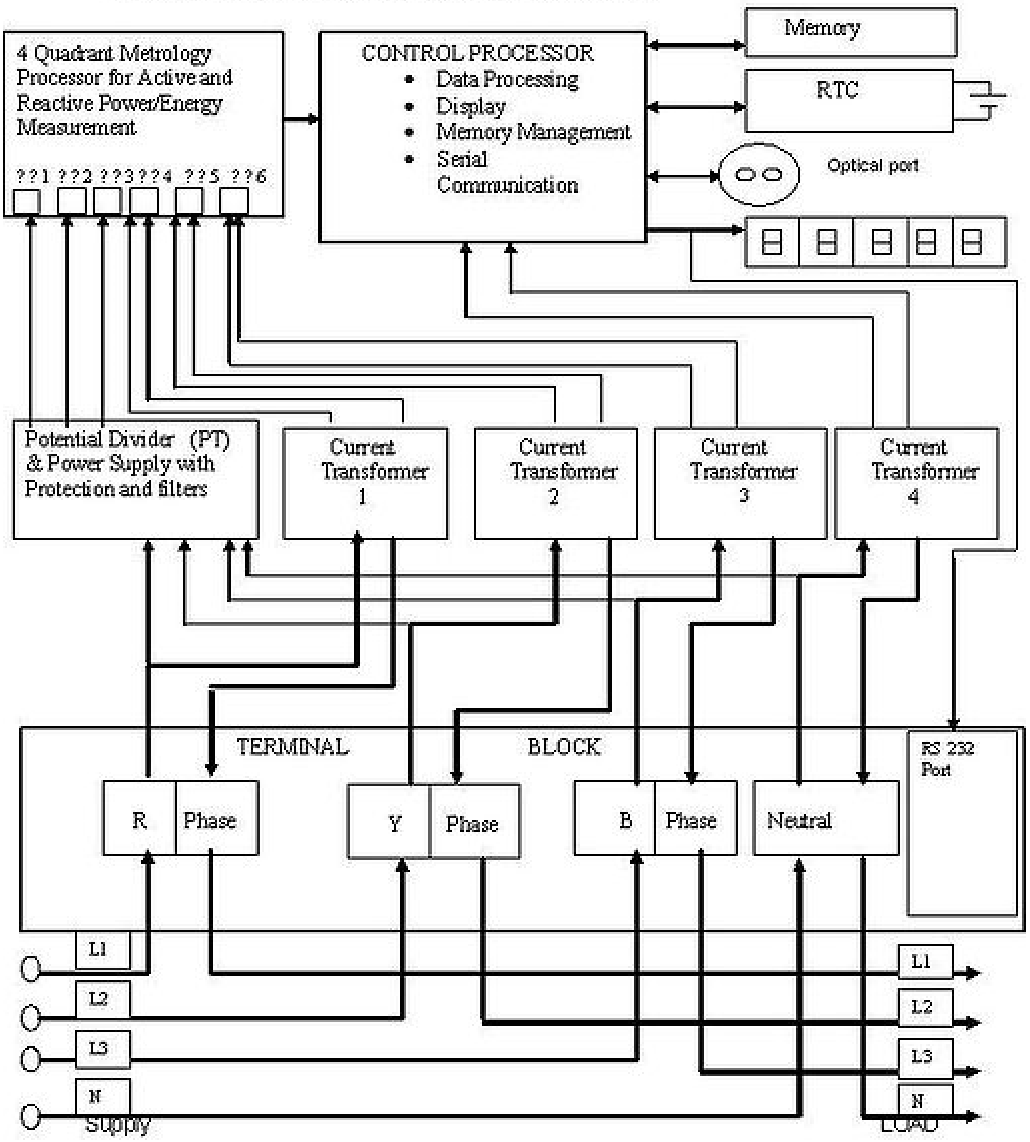
The most modern protocol proposed for this purpose is DLM/COSEM which can operate over any medium, including serial ports. The data can be transmitted by Zigbee, WiFi, telephone lines or over the power lines themselves. Some meters can be read over the internet.

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

1. Block Diagram Of Direct Connection Poly Phase Meter



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- 7

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.

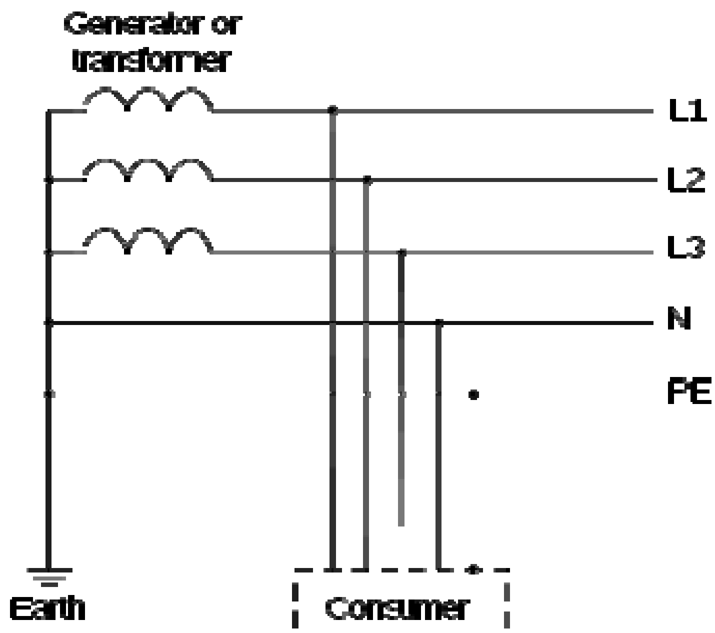
The second letter indicates the connection between earth and the electrical device being supplied:

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.



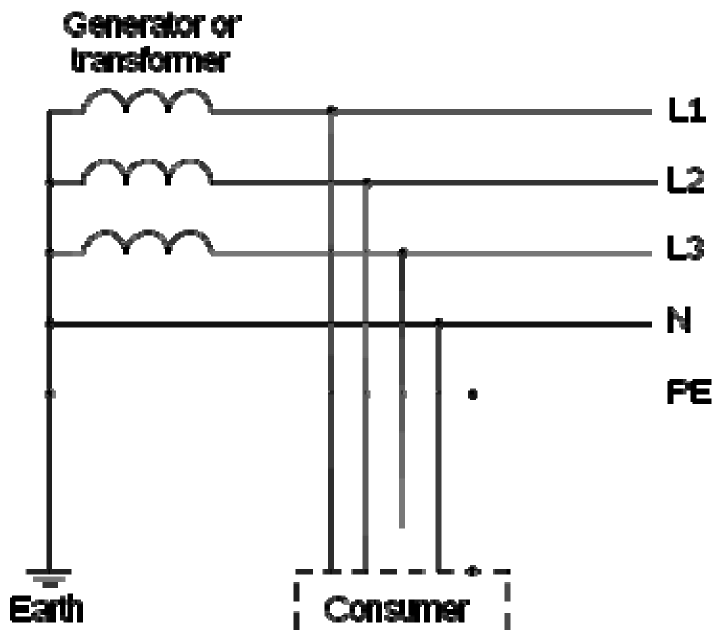
The conductor that connects the exposed metallic parts of the consumer is called *protective earth* (*PE*). The conductor that connects to the star point in a three-phase system, or that carries the return current in a single-phase system, is called *neutral* (*N*). Three variants of TN systems are distinguished:

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

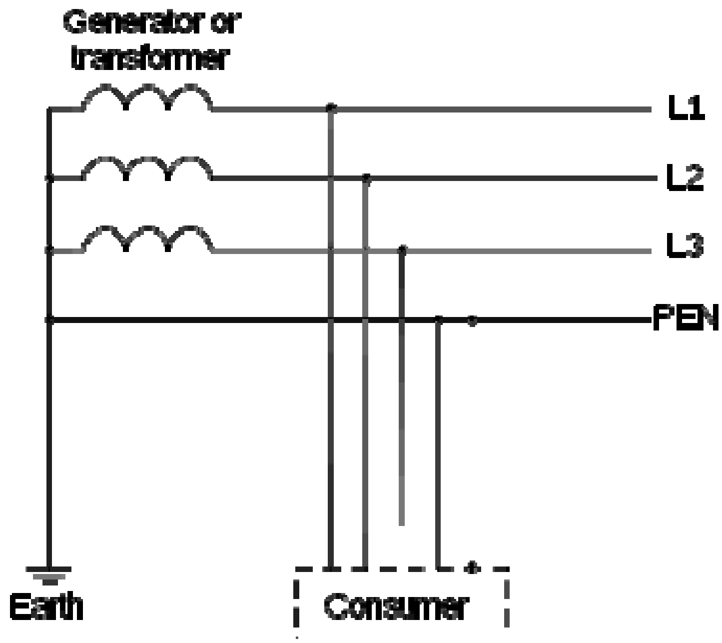
TN−C
: A combined PEN conductor fulfills the functions of both a PE and an N conductor. Rarely used.

TN−C−S

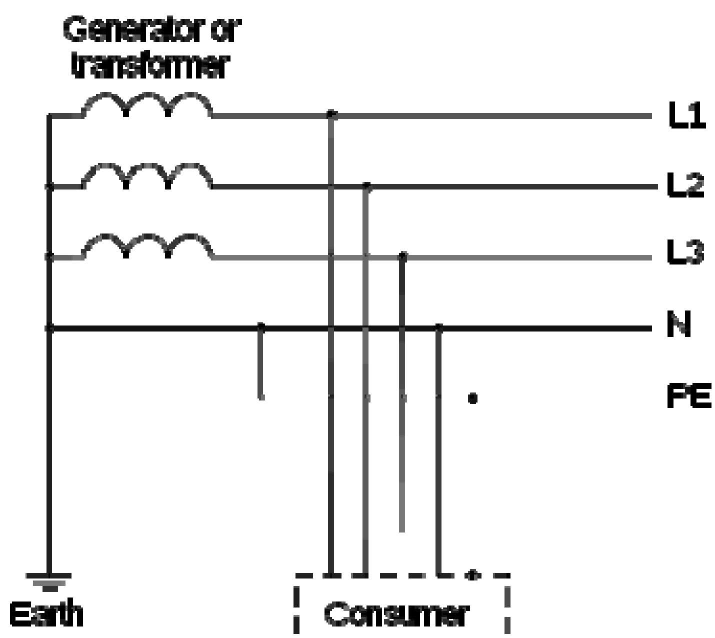
Part of the system uses a combined PEN conductor, which is at some point split up into separate PE and N lines. The combined PEN conductor typically occurs between the substation and the entry point into the building, and separated in the service head. In the UK, this system is also known as *protective 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.

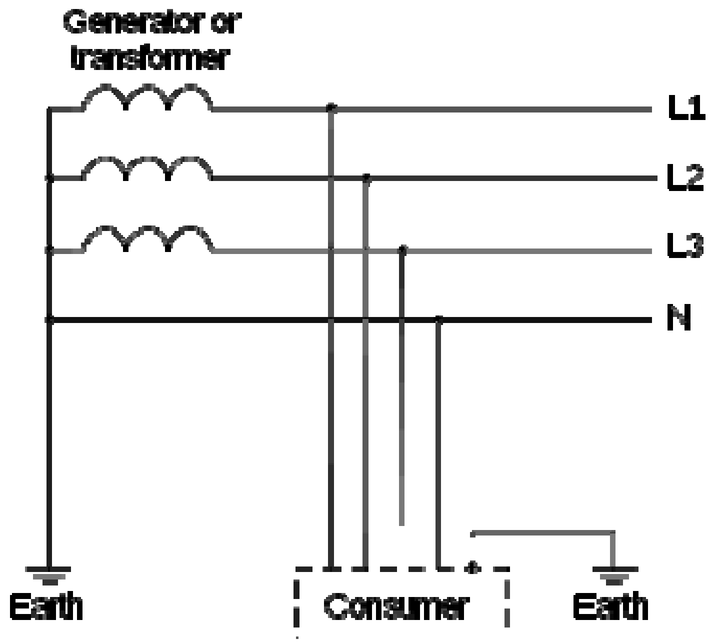
TT network

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.

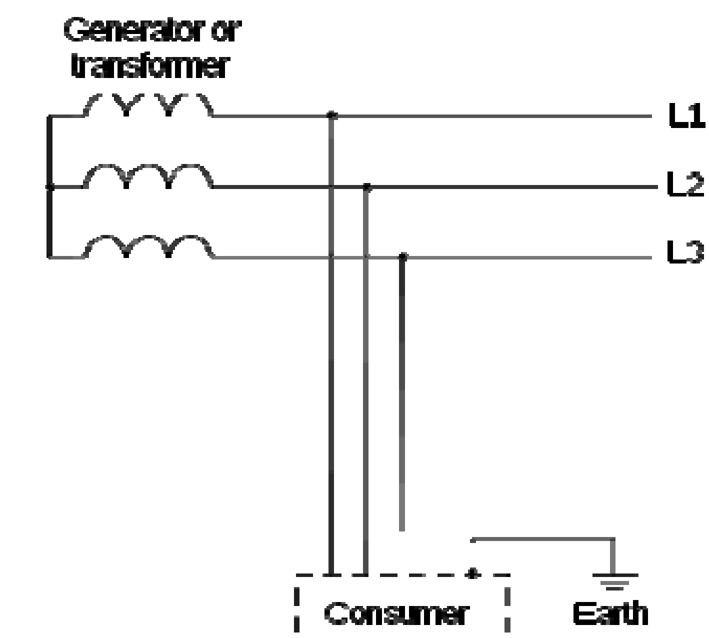
In locations where power is distributed overhead and TT is used, installation earth conductors are not at risk should any overhead distribution conductor be fractured by, say, a fallen tree or branch.

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- 8

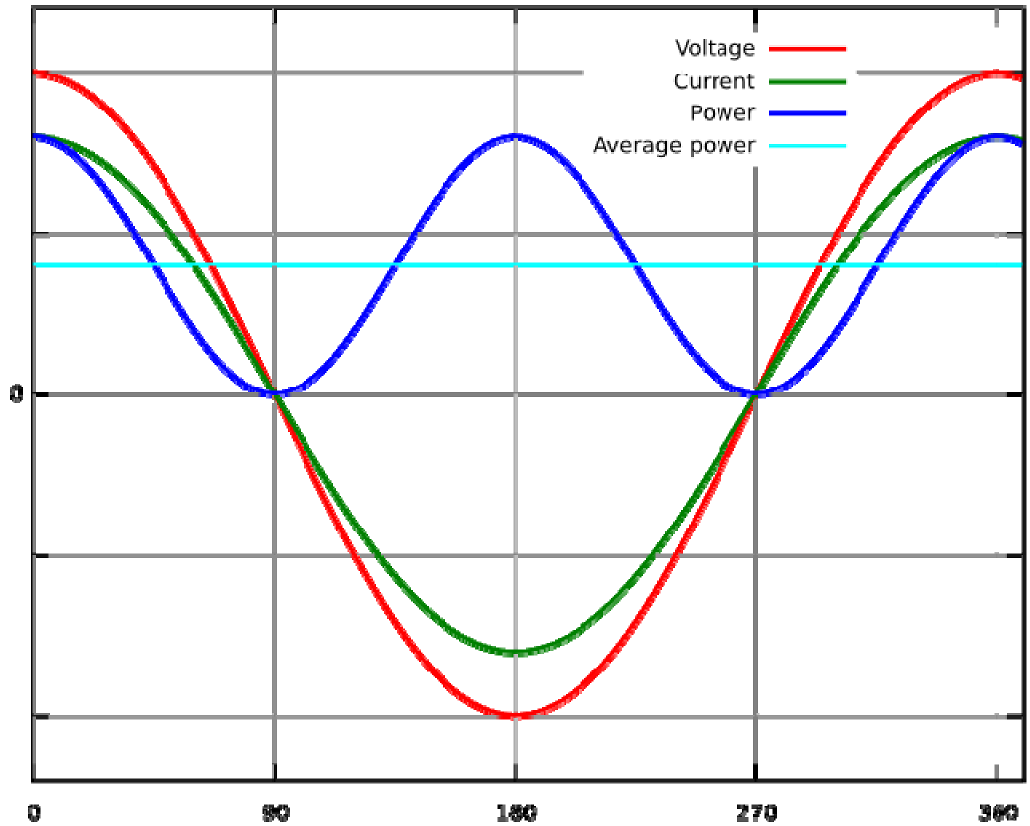
Power Factor System

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.

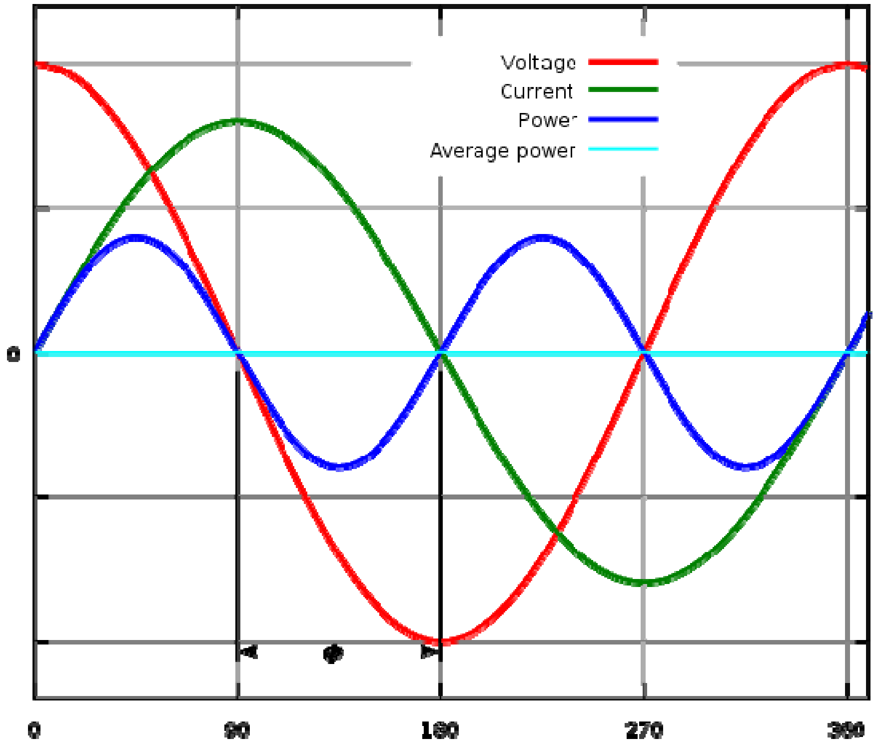
In an electric power system, a load with a low power factor draws more current than a load with a high power factor for the same amount of useful power transferred. The higher currents increase the energy lost in the distribution system, and require larger wires and other equipment. Because of the costs 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.

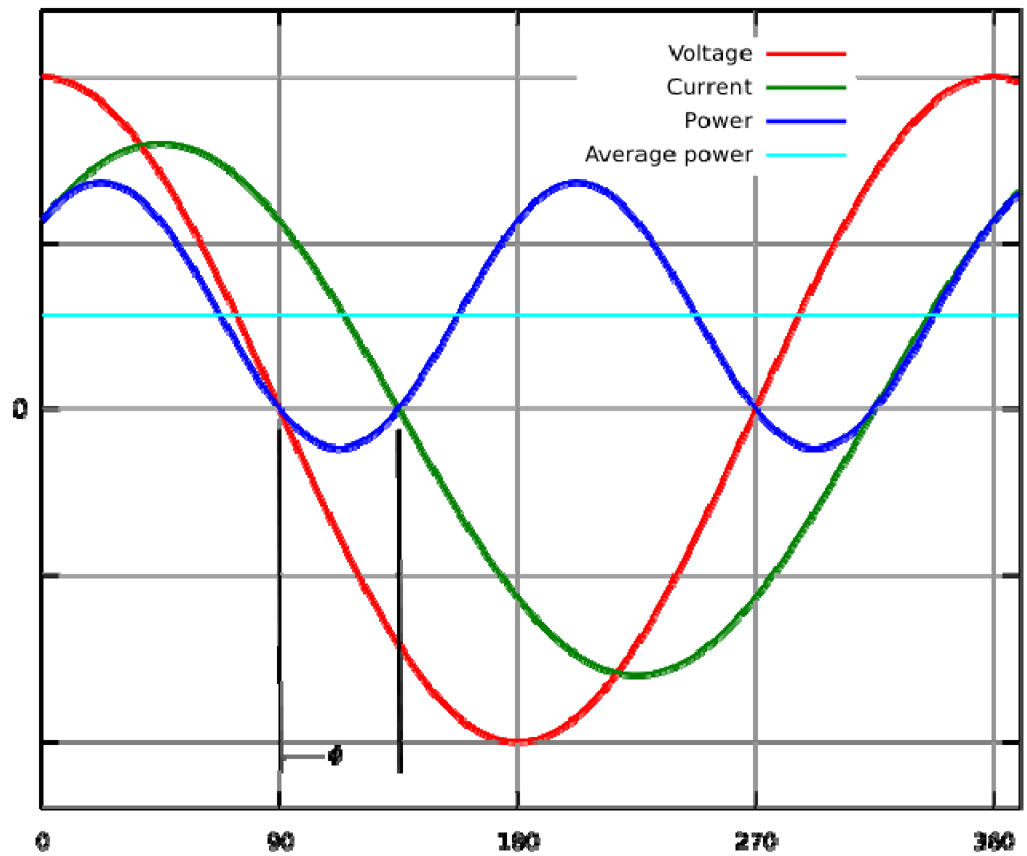
Power factor in linear circuits



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.

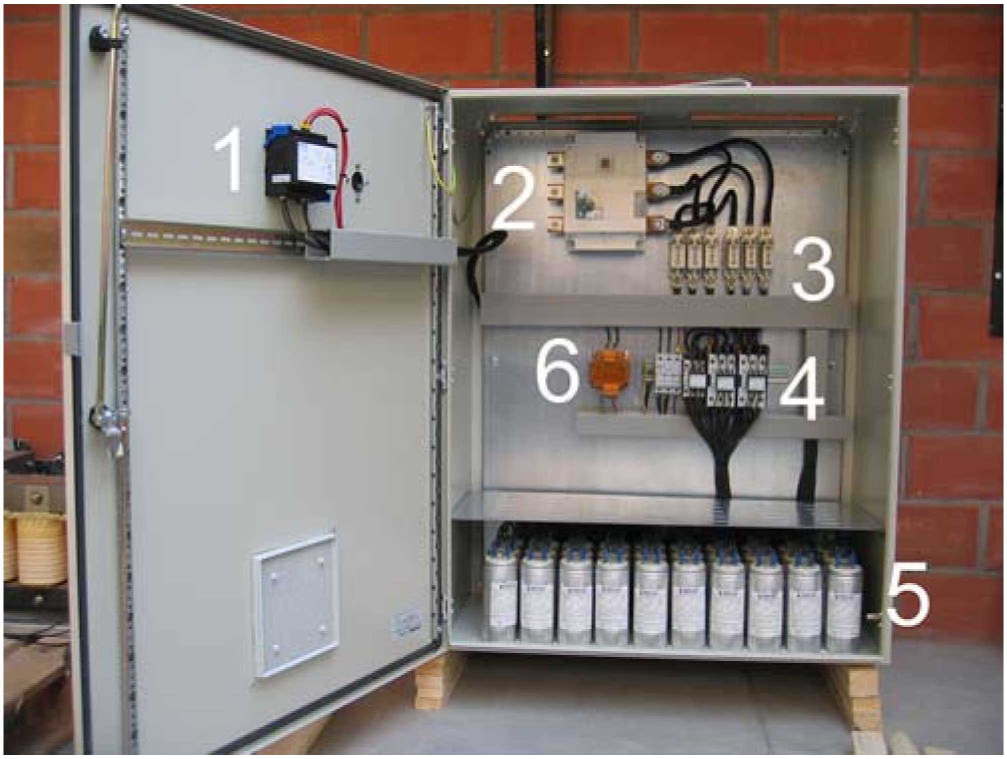
Power factor correction of linear loads

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.

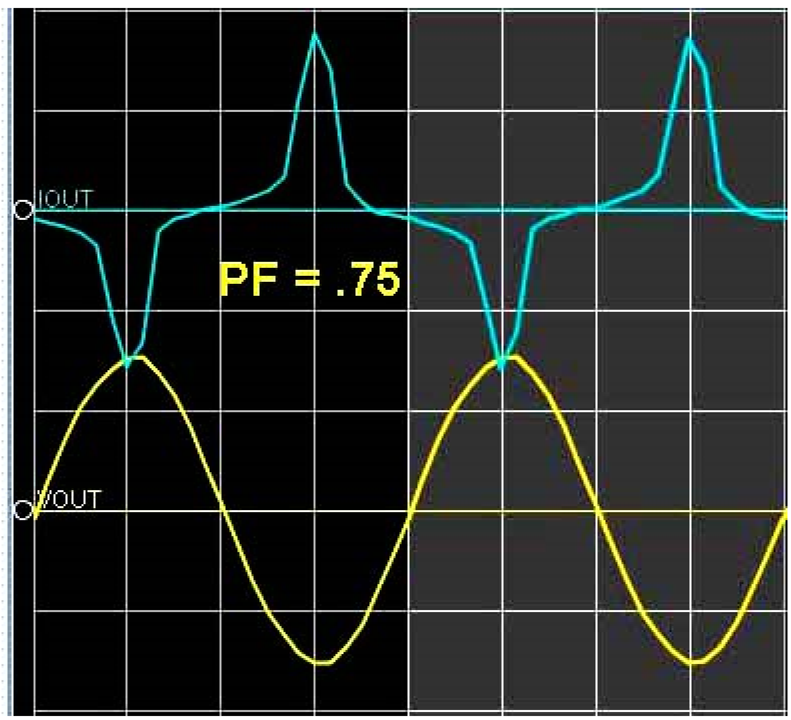
Depending on the load and power factor of the network, the power factor controller will switch the necessary blocks of capacitors in steps to make sure the power factor stays above a selected value (usually demanded by the energy supplier), say 0.9.

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. $I_{1,\mathrm{rms}}$ 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.

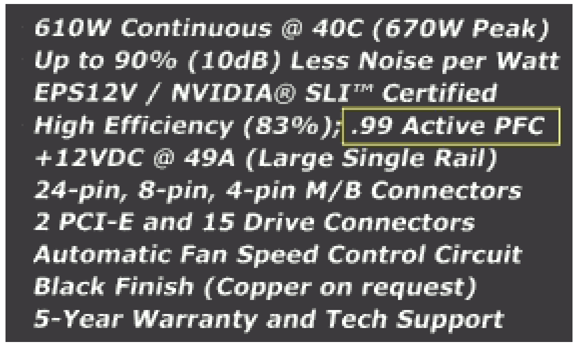
A passive PFC requires an inductor larger than the inductor in an active PFC, but costs less.

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).

Chapter- 9

Intermittent Energy Source

Intermittent energy source is a term usually used to refer to some sources of renewable energy, such as wind and solar, (but not to geothermal generated electricity or hydroelectricity), because these sources of electric power generation may be uncontrollably variable or more intermittent than conventional power sources in normal operational conditions. Intermittency is a problem related to dispatchability, or the ability to match the generated supply of electricity to actual demand.

At present, the penetration of intermittent renewables in most power grids is low, but wind for example generates 11% of electric energy in Spain and Portugal, 9% in the Republic of Ireland, and 7% in Germany. Wind provides nearly 20% of the electricity generated in Denmark, however this percentage forces Denmark to import and export large amounts of energy to and from the EU grid, to balance supply with demand.

The use of small amounts of intermittent power has little effect on grid operations. Using larger amounts of intermittent power may require upgrades or even a redesign of the grid infrastructure.

Terminology

Several key terms are useful for understanding the issue of intermittent power sources. These terms are not standardized, and variations may be used. Most of these terms also apply to traditional power plants.

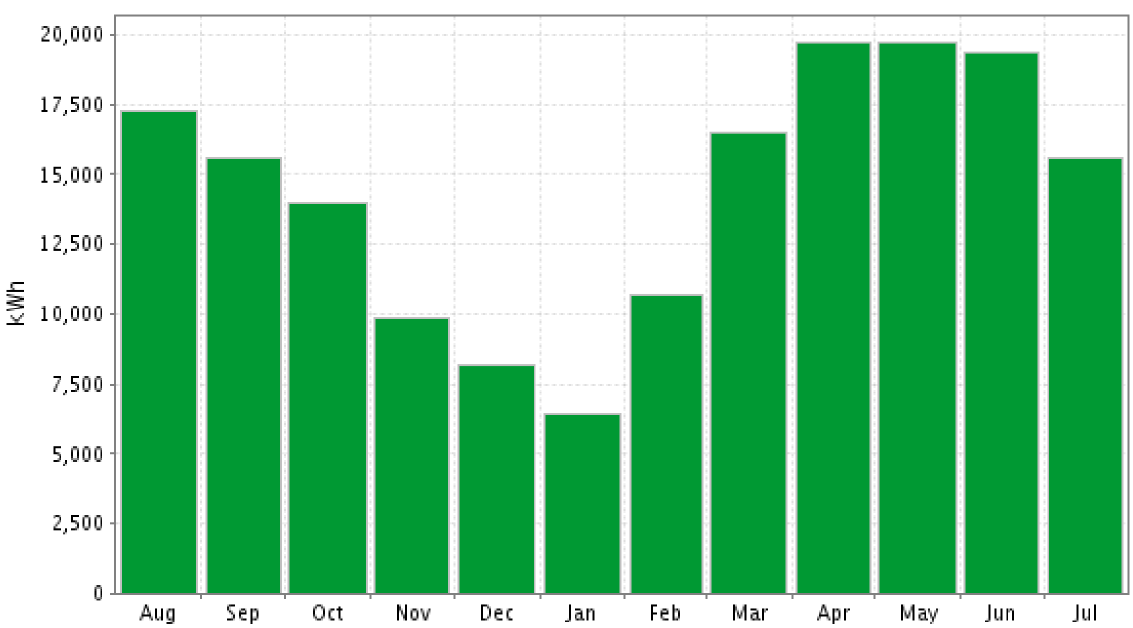
- **Intermittency** can mean the extent to which a power source is unintentionally stopped or unavailable, but intermittency is frequently used as though it were synonymous with **variability**.
- **Variability** is the extent to which a power source may exhibit undesired or uncontrolled changes in output.
- **Dispatchability** or **maneuverability** is the ability of a given power source to increase and/or decrease output quickly on demand. The concept is distinct from

intermittency; maneuverability is one of several ways grid operators match output (supply) to system demand.

- **Nominal** or **nameplate capacity**, or **maximum effect** refers to the normal maximum output of a generating source. This is the most common number used and is typically expressed in megawatts (MW).
- **Capacity factor**, **average capacity factor**, or **load factor** is the average expected output of a generator, usually over an annual period. Expressed as a percentage of the nameplate capacity or in decimal form (e.g. 30% or 0.30).
- **Capacity credit**: generally, the amount of output from a power source that may be statistically relied upon, expressed as a percentage.
- **Penetration** in this context is generally used to refer to the amount of energy generated as a percentage of annual consumption.

Intermittency of various power sources

Solar energy



Seasonal variation of the output of the solar panels at AT&T park in San Francisco.

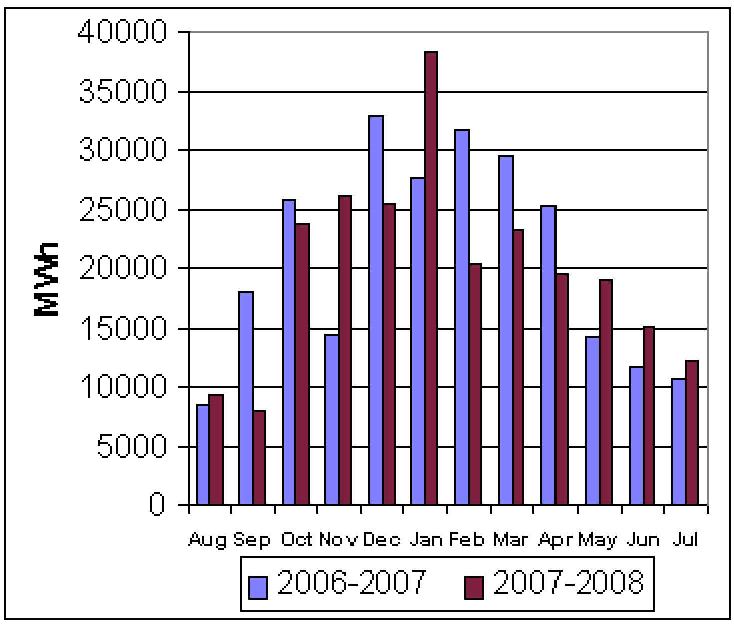
Intermittency inherently affects solar energy, as the production of electricity from solar sources depends on the amount of light energy in a given location. Solar output varies throughout the day and through the seasons, and is affected by cloud cover. These factors are fairly predictable, and some solar thermal systems make use of heat storage to produce power when the sun is not shining.

- **Intermittency:** In the absence of an energy storage system, solar does not produce power at night.

- **Capacity factor** Photovoltaic solar in Massachusetts 12-15%. Photovoltaic solar in Arizona 19% Thermal solar parabolic trough 56% Thermal solar power tower 73%

The extent to which the intermittency of solar-generated electricity is an issue will depend to some extent on the degree to which the generation profile of solar corresponds to demand. For example, solar thermal power plants such as Nevada Solar One are somewhat matched to summer peak loads in areas with significant cooling demands, such as the south-western United States. Thermal energy storage systems can improve the degree of match between supply and consumption. The increase in capacity factor of thermal systems does not represent an increase in efficiency, but rather a spreading out of the time over which the system generates power.

Wind energy



Erie Shores Wind Farm monthly output over a two year period

A wind farm in Muppandal, Tamil Nadu, India

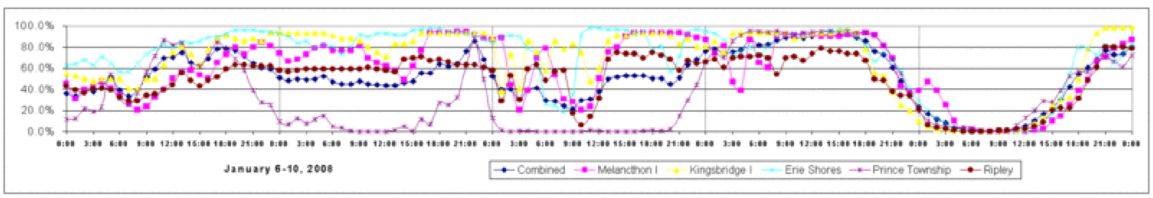
Wind-generated power is a variable resource, and the amount of electricity produced at any given point in time by a given plant will depend on wind speeds, air density, and turbine characteristics (among other factors). If wind speed is too low (less than about 2.5 m/s) then the wind turbines will not be able to make electricity, and if it is too high (more than about 25 m/s) the turbines will have to be shut down to avoid damage. While the output from a single turbine can vary greatly and rapidly as local wind speeds vary, as more turbines are connected over larger and larger areas the average power output becomes less variable.

- **Intermittence:** A single wind turbine is highly intermittent. Theoretical arguments often claim that a large wind farm spread over a geographically diverse area will as a whole rarely stop producing power altogether, however this is in contradiction to the observed variability in total power output of wind turbines installed in Ireland and Denmark.
- **Capacity Factor:** Wind power typically has a capacity factor of 20-40%.
- **Dispatchability:** Wind power is "highly non-dispatchable".
- **Capacity Credit:** At low levels of penetration, the capacity credit of wind is about the same as the capacity factor. As the concentration of wind power on the grid rises, the capacity credit percentage drops.
- **Variability:** Site dependent. Sea breezes are much more constant than land breezes.
- **Reliability:** A wind farm is highly reliable (although highly intermittent). That is, the output at any given time will only vary gradually due to falling wind speeds or storms (the latter necessitating shut downs). A typical wind farm is unlikely to have to shut down in less than half an hour at the extreme, whereas an equivalent sized power station can fail totally instantaneously and without warning. The total shut down of wind turbines is predictable via weather forecasting.

According to a study of wind in the United States, ten or more widely-separated wind farms connected through the grid could be relied upon for from 33 to 47% of their average output (15–20% of nominal capacity) as reliable, baseload power, as long as minimum criteria are met for wind speed and turbine height. When calculating the generating capacity available to meet peak demand, [ERCOT] (manages Texas grid) counts wind generation at 8.7% of nameplate capacity.

Because wind power is generated by large numbers of small generators, individual failures do not have large impacts on power grids. This feature of wind has been referred to as resiliency.

Wind power is affected by air temperature because colder air is more dense and therefore more effective at producing wind power. As a result, wind power is affected seasonally (more output in winter than summer) and by daily temperature variations. During the 2006 California heat storm output from wind power in California significantly decreased to an average of 4% of capacity for 7 days. A similar result was seen during the 2003 European heat wave, when the output of wind power in France, Germany, and Spain fell below 10% during peak demand times.



5 days of hourly output of five wind farms in Ontario

According to an article in EnergyPulse, "the development and expansion of well-functioning day-ahead and real time markets will provide an effective means of dealing with the variability of wind generation."

Nuclear power

Amory Lovins points out that *all* sources of electricity sometimes fail, differing only in how, when, and why. Even giant power plants are intermittent: "they fail unexpectedly in billion-watt chunks, often for long periods". For example in the United States, 132 nuclear plants were built, and 21% were permanently and prematurely closed due to reliability or cost problems, while another 27% have at least once completely failed for a year or more. The remaining U.S. nuclear plants produce approximately 90% of their full-time full-load potential, but even they must shut down (on average) for 39 days every 17 months for refueling and maintenance. To cope with such intermittence by nuclear (and centralized fossil-fuelled) power plants, utilities install a “reserve margin” of roughly 15% extra capacity spinning ready for instant use.

Lovins says that nuclear plants have an additional disadvantage: for safety, they must instantly shut down in a power failure, but for nuclear-physics reasons, they can’t be restarted quickly. For example, during the Northeast Blackout of 2003, nine perfectly operating U.S. nuclear units had to shut down and were later restarted. Lovins states that "twelve days of painfully slow restart later, their average capacity loss had exceeded 50 percent. For the first three days, just when they were most needed, their output was below 3% of normal".

Solving intermittency

Mark Z. Jacobson has studied how wind, water and solar technologies can be integrated to provide the majority of the world's energy needs. He advocates a "smart mix" of renewable energy sources to reliably meet electricity demand:

Because the wind blows during stormy conditions when the sun does not shine and the sun often shines on calm days with little wind, combining wind and solar can go a long way toward meeting demand, especially when geothermal provides a steady base and hydroelectric can be called on to fill in the gaps.

Technological solutions to mitigate large scale wind energy type intermittency exist such as increased interconnection (the European super grid), Demand response, load management, diesel generators (in National Grid), Frequency Response / National Grid Reserve Service type schemes, and use of existing power stations on standby. Studies by academics and grid operators indicate that the cost of compensating for intermittency is expected to be high at levels of penetration above the low levels currently in use today Large, distributed power grids are better able to deal with high levels of penetration than small, isolated grids. For a hypothetical European-wide power grid, analysis has shown that wind energy penetration levels as high as 70% are viable, and that the cost of the extra transmission lines would be only around 10% of the turbine cost, yielding power at around present day prices. Smaller grids may be less tolerant to high levels of penetration.

Matching power demand to supply is not a problem specific to intermittent power sources. Existing power grids already contain elements of uncertainty including sudden and large changes in demand and unforeseen power plant failures. Though power grids are already designed to have some capacity in excess of projected peak demand to deal with these problems, significant upgrades may be required to accommodate large amounts of intermittent power. The International Energy Agency (IEA) states: "In the case of wind power, operational reserve is the additional generating reserve needed to ensure that differences between forecast and actual volumes of generation and demand can be met. Again, it has to be noted that already significant amounts of this reserve are operating on the grid due to the general safety and quality demands of the grid. Wind imposes additional demands only inasmuch as it increases variability and unpredictability. However, these factors are nothing completely new to system operators. By adding another variable, wind power changes the degree of uncertainty, but not the kind..."

Denmark

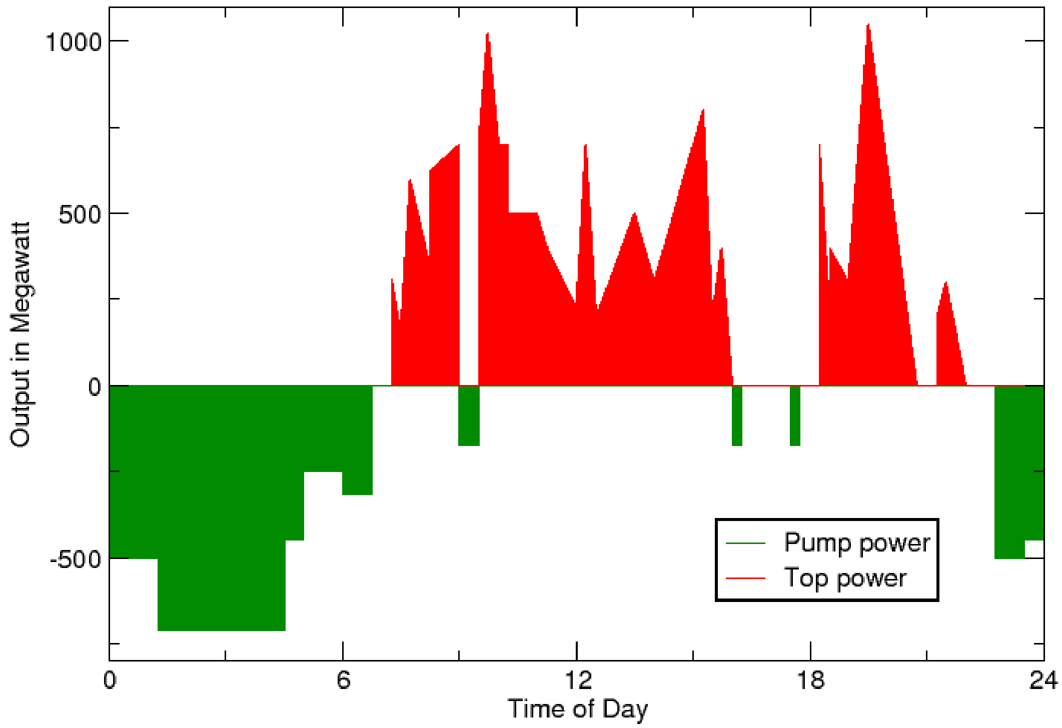
A November 2006 analysis found that "wind power may be able to cover more than 50% of the Danish electricity consumption in 2025" under conditions of high oil prices and higher costs for CO_2 allowances. Denmark's two grids (covering West Denmark and East Denmark separately) each incorporate high-capacity interconnectors to neighbouring grids where some of the variations from wind are absorbed.

Capacity credit, fuel saving and need for extra back-up

Many commentators concentrate on whether or not wind has any "capacity credit" without defining what they mean by this and its relevance. Wind does have a capacity credit, using a widely accepted and meaningful definition, equal to about 20% of its rated output (but this figure varies depending on actual circumstances). This means that reserve capacity on a system equal in MW to 20% of added wind could be retired when such wind is added without affecting system security or robustness.

UK academic commentator Graham Sinden, of Oxford University, argues that this issue of capacity credit is a "red herring" in that the value of wind generation is largely due to the value of displaced fuel, not any perceived capacity credit – it being well understood by the wind energy proponents that conventional capacity will be retained to "fill in" during periods of low or no wind. The main value of wind, (in the UK, 5 times the capacity credit value) is its fuel and CO_2 savings. Wind does not require any extra back-up, as is often wrongly claimed, since it uses the existing power stations, which are already built, as back-up, and which are started up during low wind periods, just as they are started up now, during the non availability of other conventional plant. More spinning reserve, of existing plant, is required, but this again is already built and has a low cost comparatively.

Hydroelectricity



Power output of a pumped-storage plant. Green areas show excess power being stored, and red areas show power being given back when needed.

Hydroelectric power is usually extremely dispatchable and more reliable than other renewable energy sources. Many dams can provide hundreds of megawatts within seconds of demand. The exact nature of the power availability depends on the type of plant.

In run-of-the-river hydroelectricity, power availability is highly dependent on the flow of the river, making this type of generation mostly suitable only at locations where flow levels are controlled by upstream dams.

In conventional hydroelectric plants, there is a reservoir and a one-way generator. The water flow through its turbines can be adjusted frequently to meet changing demand throughout the day by running the generator when demand is high and not running it when demand is low.

Pumped-storage hydroelectricity can make an even more significant contribution to peaking ability of the grid. These just move water between reservoirs and are powered by power *from* the grid when demand is low and put power back *into* the grid when demand is high. There also exist combined pump-storage plants that use river flow as well as extra pumping when demand is low, such as the 240 MW Lewiston Pump-Generating Plant.

Direct pumped-storage does not contribute any net generation to the grid, in fact, it increases the fuel used by other power plants because there is inefficiency in the turbine/generator. The economic benefit of pumped-storage plants lies only in increasing the capacity of the grid. This type of plant works well on a grid with many nuclear or renewable energy plants because the fuel is very cheap or essentially free, so it costs very little to keep them running at high power during the night when demand is low. Both pump-storage plants and natural flow hydro plants can help allow for intermittency of other plants by running at higher capacity for short times, but assistance is limited by the total capacity of the hydroelectric plant.

Conventional power stations

Once a conventional power station has come offline it may stay that way for more than a week.

Conventional power plants (as well as nuclear plants) use water for cooling, and water shortages during hot summer months have occasionally resulted in periods when output has had to be curtailed, notably in France in 2006.

Conventional power plant failures can remove large amounts of capacity from the grid suddenly, resulting in blackouts.

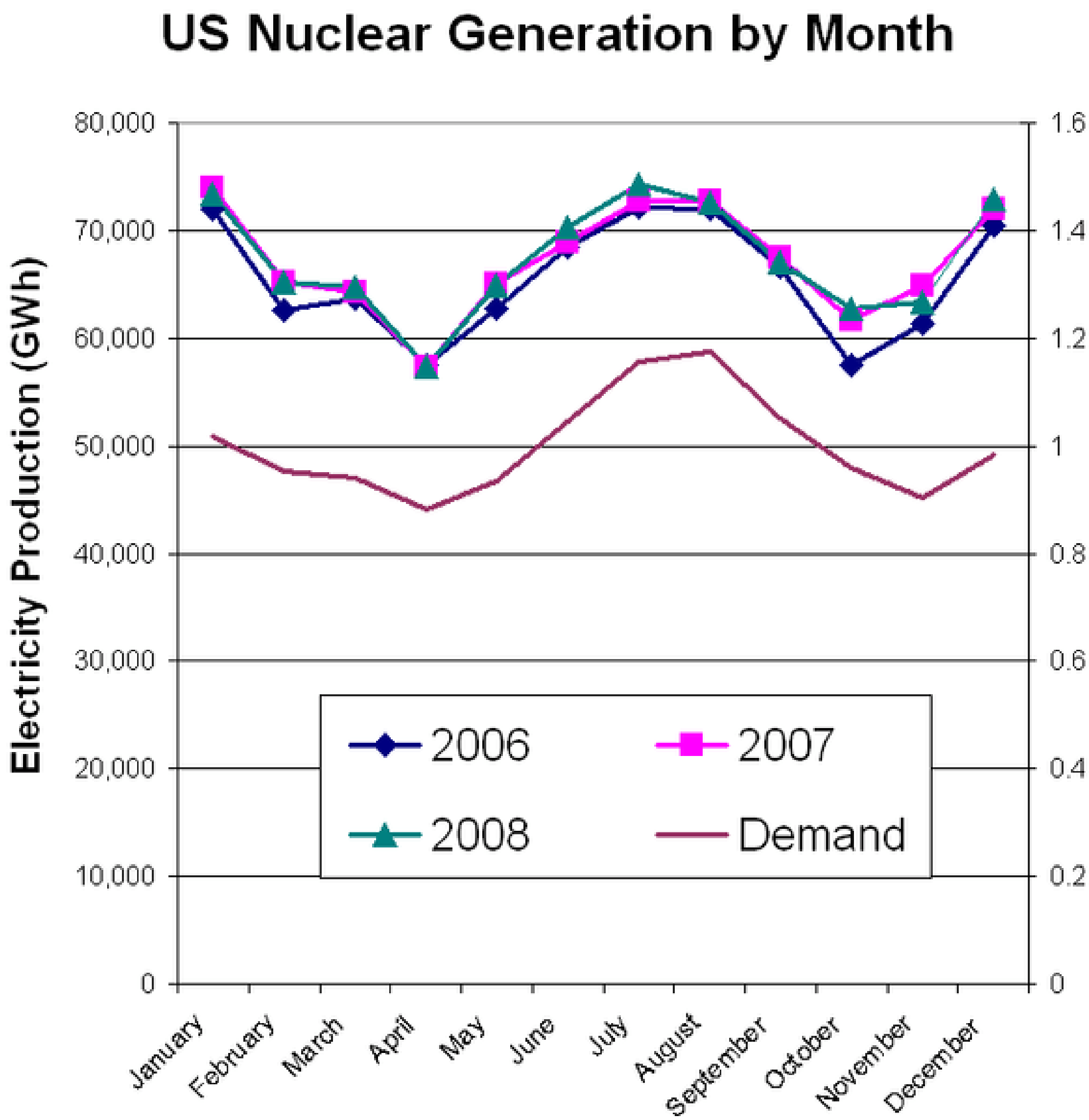
- **Capacity factor**: Base load coal plant 70–90%

Gas-fired generation

Gas-fired plants are typically very reliable and dispatchable. These kinds of plants also often have the ability to quickly vary their output to adjust to the frequent jumps and changes in consumer demand. Thus these are very good as peaking units. These benefits are weighted against the high price of gas when deployed in the grid.

- **Capacity factor**: about 60%.

Nuclear power



Seasonal variation in total nuclear power delivered to the grid in the United States compared to the demand cycle.

Nuclear power is considered a **base load** power source, in that its output is nearly constant and other types of plants are adjusted with changes in demand. This is done because output changes can only be made in small increments, and because of small fuel costs - there is little marginal cost between running at a low power and a high power, therefore it is cheapest for the system to run the nuclear plants at high power.

Every year or two (depending on the plant), the plant must be shut down for planned outages for about a month. This is typically done in the spring or autumn (fall) when electricity demand is lower, as such, on a national scale power output from nuclear increases corresponding with demand during the peak summer and winter months. This change in output commonly occurs on a yearly basis.

It is rare that nuclear power plants adjust their power output to correspond with demand on a daily basis because pressurized water reactors (PWR, which are the vast majority of nuclear power plants) use a chemical shim in the moderator–coolant to control their power level. (Boiling water reactors (BWR), however, can use a combination of control rods and recirculation water flow speed to control their power level, and so in markets such as Chicago, Illinois where half of the local utility's fleet is BWRs it is common to load-follow although less economic to do so.)

- **Intermittence**: Unplanned outages worldwide caused power losses varying from 3.1% and 1.4% of capacity between 1995 and 2005. Over that same period reactors worldwide encountered an average of 1.1 to 0.6 SCRAMs per 7,000 hours critical (about a year of operation.) An automatic SCRAM is a protective measure that shuts the reactor down suddenly for safety reasons.
- **Capacity factor**: U.S. average 92%. Worldwide average varied between about 81% to 87% between 1995 and 2005.

In the UK one of the key criteria for determining the amount of required spinning reserve is the possible loss of Sizewell B, a 1.2 GW nuclear power plant. At one point in the fall of 2007, out of 16 nuclear power stations in the UK, seven were offline due to a combination of planned and unplanned outages.

Diesel engine generation

Small high-speed diesels are very commonly used within large power grids throughout North America and Europe. France uses about 5 GW of such diesels to cover the intermittency of their nuclear stations; these are all in private hands - at small scales factories and the like - with their usage being triggered semi-randomly by a special tariff - EJP - which encourages these users to start their diesels.

In USA and UK these diesels have usually been purchased for other reasons e.g. for emergency standby, in water works, hotels, hospitals, etc. and in some cases for electricity substations - e.g. Cuyahoga Falls, USA (10 × 1.6 MW Caterpillar) and Tregarron Mid Wales UK (3 × 1.6 MW Caterpillar), but can be readily used to automatically synchronize and feed into the grid.

In the UK 500 MW of such plant is routinely started within a few minutes; this is perfectly acceptable to the engines' service life in a scheme operated by National Grid called National Grid Reserve Service. It has been established that there is 20 GW of such diesel plant in the UK and it has been pointed out that there is no technical reason why this quantity could not be brought into the Reserve Service scheme to assist handling very rapid changes in renewable output, whilst conventional plant is started or indeed stopped.

Compensating for variability

All sources of electrical power have some degree of unpredictability, and demand patterns routinely drive large swings in the amount of electricity that suppliers feed into the grid. Wherever possible, grid operations procedures are designed to match supply with demand at high levels of reliability, and the tools to influence supply and demand are well-developed. The introduction of large amounts of highly variable power generation may require changes to existing procedures and additional investments.

Operational reserve

All managed grids already have existing operational and "spinning" reserve to compensate for existing uncertainties in the power grid. The addition of intermittent resources such as wind does not require 100% "back-up" because operating reserves and balancing requirements are calculated on a system-wide basis, and not dedicated to a specific generating plant.

- Some coal, gas, or hydro power plants are partially loaded and then controlled to change as demand changes or to replace rapidly lost generation. The ability to change as demand changes is termed "response." The ability to quickly replace lost generation, typically within timescales of 30 seconds to 30 minutes, is termed "spinning reserve."
- Generally thermal plants running as peaking plants will be less efficient than if they were running as base load.
- Hydroelectric facilities with storage capacity (such as the traditional dam configuration) may be operated as base load or peaking plants.
- In practice, as the power output from wind varies, partially loaded conventional plants, which are already present to provide response and reserve, adjust their output to compensate.
- While low penetrations of intermittent power may utilize existing levels of response and spinning reserve, the larger overall variations at higher penetrations levels will require additional reserves or other means of compensation.

Demand reduction or increase

- Demand response refers to the use of communication and switching devices which can release deferrable loads quickly, or absorb additional energy to correct supply/demand imbalances. Incentives have been widely created in the American, British and French systems for the use of these systems, such as favorable rates or capital cost assistance, encouraging consumers with large loads to take them off line or to start diesels whenever there is a shortage of capacity, or conversely to increase load when there is a surplus.
- Load Control allows the power company to turn loads off remotely if insufficient power is available. In France large users such as CERN cut power usage as required by the System Operator - EDF under the encouragement of the EJP tarrif.

- Energy demand management refers to incentives to adjust use of electricity, such as higher rates during peak hours.

- Real-time variable electricity pricing can encourage users to adjust usage to take advantage of periods when power is cheaply available and avoid periods when it is more scarce and expensive.
- Instantaneous demand reduction. Most large systems also have a category of loads which instantly disconnect when there is a generation shortage, under some mutually beneficial contract. This can give instant load reductions (or increases).

- Diesel generators, originally or primarily installed for emergency power supply are often also connected to the National Grid in the UK to help deal with short term demand supply mismatches.

Storage and demand loading

At times of low or falling demand where wind output may be high or increasing, grid stability may require lowering the output of various generating sources or even increasing demand, possibly by using energy storage to time-shift output to times of higher demand. Such mechanisms can include:

- Pumped storage hydropower is the most prevalent existing technology used, and can substantially improve the economics of wind power. The availability of hydropower sites suitable for storage will vary from grid to grid. Typical round trip efficiency is 80%.
- Thermal energy storage stores heat or ice (or a similarly cold material). Stored heat can be used directly for heating needs or converted into electricity. Stored ice can be used as a source of air-conditioning during periods of high demand.
- Hydrogen can be created through electrolysis and stored for later use. NREL found that a kilogram of hydrogen (roughly equivalent to a gallon of gasoline) could be produced for between $5.55 in the near term and $2.27 in the long term.
- Rechargeable flow batteries can serve as a large capacity, rapid-response storage medium.
- Some loads such as desalination plants and electric boilers, are able to store their output (water and heat.) These "opportunistic loads" are able to take advantage of "burst electricity" when it is available.
- Various other potential applications are being considered, such as charging plug-in electric vehicles during periods of low demand and high production; such technologies are not widely used at this time.

Storage of electrical energy results in some lost energy because storage and retrieval are not perfectly efficient. Storage may also require substantial capital investment and space for storage facilities.

Geographic diversity

The variability of production from a single wind turbine can be high. Combining any additional number of turbines (for example, in a wind farm) results in lower statistical variation, as long as the correlation between the output of each turbine is imperfect, and the correlations are always imperfect due to the distance between each turbine. Similarly, geographically distant wind turbines or wind farms have lower correlations, reducing overall variability. Since wind power is dependent on weather systems, there is a limit to the benefit of this geographic diversity for any power system.

Multiple wind farms spread over a wide geographic area and gridded together produce power more constantly and with less variability than smaller installations. Wind output can be predicted with some degree of confidence using weather forecasts, especially from large numbers of turbines/farms. The ability to predict wind output is expected to increase over time as data is collected, especially from newer facilities.

Complementary power sources and matching demand

- Electricity produced from solar energy could be a counter balance to the fluctuating supplies generated from wind. In some locations, it tends to be windier at night and during cloudy or stormy weather, so there is likely to be more sunshine when there is less wind.
- In some locations, electricity demand may have a high correlation with wind output, particularly in locations where cold temperatures drive electric consumption (as cold air is denser and carries more energy).
- The allowable penetration may be further increased by increasing the amount of part-loaded generation available. Systems with existing high levels of hydroelectric generation may be able to incorporate substantial amounts of wind, although high hydro penetration may indicate that hydro is already a low-cost source of electricity; Norway, Quebec, and Manitoba all have high levels of existing hydroelectric generation (Quebec produces over 90% of its electricity from hydropower, and the local utility, Hydro-Québec, is the largest single hydropower producer in the world). The US Pacific Northwest has been identified as another region where wind energy is complemented well by existing hydropower, and there were "no fundamental technical barriers" to integrating up to 6,000 MW of wind capacity. Storage capacity in hydropower facilities will be limited by size of reservoir, and environmental and other considerations.
- The Institute for Solar Energy Supply Technology of the University of Kassel, Germany pilot-tested a combined power plant linking solar, wind, biogas and hydrostorage to provide load-following power around the clock, entirely from renewable sources.

Export & import arrangements with neighboring systems

- It is often feasible to export energy to neighboring grids at times of surplus, and import energy when needed. This practice is common in Western Europe and North America.
- Integration with other grids can lower the effective concentration of variable power. Denmark's 44% penetration, in the context of the German/Dutch/Scandinavian grids with which it has interconnections, is

considerably lower as a proportion of the total system. This effect is diminished if more neighboring grids also have high penetration levels of variable power.

- Integration of grids may decrease the overall variability of both supply and demand by increasing geographical diversity.
- Methods of compensating for power variability in one grid, such as peaking-plants or pumped-storage hydro-electricity, may be taken advantage of by importing variable power from another grid that is short on such capabilities.
- The capacity of power transmission infrastructure may have to be substantially upgraded to support export/import plans.
- Some energy is lost in transmission.
- The economic value of exporting variable power depends in part on the ability of the exporting grid to provide the importing grid with useful power at useful times for an attractive price.

Penetration

Penetration refers to the proportion of a power source on a system, expressed as a percentage. There are several ways that this can be calculated, with the different methods yielding different penetrations. It can be calculated either as :

- the nominal capacity of a power source divided by peak demand; or
- the nominal capacity of a power source divided by total capacity; or
- the average power generated by a power source, divided by the average system demand.

The level of penetration of intermittent variable sources is significant for the following reasons:

- As penetration increases, the variations in power produced for the grid become larger and the costs and complexity of compensating for these variations increases.
- Large, geographically distributed networks may accept a higher penetration of wind than small networks because fluctuations in supply and demand across the entire grid can be averaged out.
- Power grids with significant amounts pumped storage, hydropower or other peaking power plants such as natural gas-fired power plants are more inherently capable of accommodating fluctuations from intermittent power.
- If an intermittent source produces more power than can be used, stored, or exported at that time, then that excess power will be lost.
- Wind power generation tends to be higher in the winter and at night (due to higher air density) , so the appropriateness of wind power in high concentrations may crucially depend on the prevalence of air conditioning in a given jurisdiction. Wind power may be weakest in the hot summer months, and particularly during the day when air conditioning demand is highest. Conversely, systems where heat is electrical may be well-suited to higher penetration of wind power.

- Isolated, relatively small systems with only a few wind plants may only be stable and economic with a lower fraction of wind energy (e.g. Ireland), although mixed wind/diesel systems have been used in isolated communities with success at relatively high penetration levels.

The maximum proportion of intermittent power allowable in a power system will thus depend on many factors, including the size of the system, the attainable geographical diversity, the ability of the system to transmit power to where it is needed, storage capabilities, demand control capabilities, the conventional plant mix (coal, gas, nuclear, hydroelectric) and seasonal load factors (heating in winter, air-conditioning in summer) and their statistical correlation with power output.

There is no generally accepted maximum level of penetration, as each system's capacity to compensate for intermittency differs, and the systems themselves will change over time. Discussion of acceptable or unacceptable penetration figures should be treated and used with caution, as the relevance or significance will be highly dependent on local factors, grid structure and management, and existing generation capacity.

For most systems worldwide, existing penetration levels are significantly lower than practical or theoretical maximums; for example, a UK study found that "it is clear that intermittent generation need not compromise electricity system reliability at any level of penetration foreseeable in Britain over the next 20 years, although it may increase costs." As of 2006, Denmark has more than 40% penetration and at least two other countries (Portugal and Germany) have penetration levels (nominal to peak demand) of more than 20%.

Maximum penetration limits

There is no generally accepted maximum penetration of wind energy that would be feasible in any given grid. Rather, economic efficiency and cost considerations are more likely to dominate as critical factors; technical solutions may allow higher penetration levels to be considered in future, particularly if cost considerations are secondary.

High penetration scenarios may be feasible in certain circumstances:

- Power generation for periods of little or no wind generation can be provided by retaining the existing power stations. The cost of using existing power stations for this purpose may be low since fuel costs dominate the operating costs. The actual cost of paying to keep a power station idle, but usable at short notice, may be estimated from published spark spreads and dark spreads. As existing traditional plant ages, the cost of replacing or refurbishing these facilities will become part of the cost of high-penetration wind if they are used only to provide operational reserve.

- Automatic load shedding of large industrial loads and its subsequent automatic reconnection is established technology and used in the UK and US, and known as

Frequency Service contractors in the UK. Several GW are switched off and on each month in the UK in this way. Reserve Service contractors offer fast response gas turbines and even faster diesels in the UK, France and US to control grid stability.

- In a close-to-100% wind scenario, surplus wind power can be allowed for by increasing the levels of the existing Reserve and Frequency Service schemes and by extending the scheme to domestic-sized loads. Energy can be stored by advancing deferrable domestic loads such as storage heaters, water heaters, fridge motors, or even hydrogen production, and load can be shed by turning such equipment off.

- Alternatively or additionally, power can be exported to neighboring grids and re-imported later. HVDC cables are efficient with 3% loss per 1000 km and may be inexpensive in certain circumstances. For example an 8 GW link from UK to France would cost about £1 billion using high-voltage direct current cables. Under such scenarios, the amount of transmission capacity required may be many times higher than currently available.

Penetration Studies

Studies have been conducted to assess the viability of specific penetration levels in specific energy markets.

European super grid

A series of detailed modelling studies by Dr. Gregor Czisch, which looked at the European wide adoption of renewable energy and interlinking power grids the European super grid 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. This proposed large European power grid has been called a "super grid."

The model deals with intermittent power issues by using base-load renewables such as hydroelectric and biomass for a substantial portion of the remaining 30% and by heavy use of HVDC to shift power from windy areas to non-windy areas. The report states that "electricity transport proves to be one of the keys to an economical electricity supply" and underscores the importance of "international co-operation in the field of renewable energy use [and] transmission."

Dr. Czisch described the concept in an interview, saying "For example, if we look at wind energy in Europe. We have a winter wind region where the maximum production is in winter and in the Sahara region in northern Africa the highest wind production is in the summer and if you combine both, you come quite close to the needs of the people living in the whole area - let's say from northern Russia down to the southern part of the Sahara."

Grid study in Ireland

A study of the grid in Ireland indicates that it would be feasible to accommodate 42% (of demand) renewables in the electricity mix. This acceptable level of renewable penetration was found in what the study called Scenario 5, provided 47% of electrical capacity (different from demand) with the following mix of renewable energies:

- 6,000 MW wind
- 360 MW base load renewables
- 285 MW additional variable renewables (other intermittent sources)

The study cautions that various assumptions were made that "may have understated dispatch restrictions, resulting in an underestimation of operational costs, required wind curtailment, and CO_2 emissions" and that "The limitations of the study may overstate the technical feasibility of the portfolios analyzed..."

Scenario 6, which proposed renewables providing 59% of electrical capacity and 54% of demand had problems. Scenario 6 proposed the following mix of renewable energies:

- 8,000 MW wind
- 392 MW base load renewables
- 1,685 MW additional variable renewables (other intermittent sources)

The study found that for Scenario 6, "a significant number of hours characterized by extreme system situations occurred where load and reserve requirements could not be met. The results of the network study indicated that for such extreme renewable penetration scenarios, a system re-design is required, rather than a reinforcement exercise." The study declined to analyze the cost effectiveness of the required changes because "determination of costs and benefits had become extremely dependent on the assumptions made" and this uncertainty would have impacted the robustness of the results.

Canada

A study published in October, 2006, by the Ontario Independent Electric System Operator (IESO) found that "there would be minimal system operation impacts for levels of wind capacity up to 5,000 MW," which corresponds to a peak penetration of 17%

Economic impacts of variability

Estimates of the cost of wind energy may include estimates of the "external" costs of wind variability, or be limited to the cost of production. All electrical plant has costs that are separate from the cost of production, including, for example, the cost of any necessary transmission capacity or reserve capacity in case of loss of generating capacity. Many types of generation, particularly fossil fuel derived, will also have cost externalities such as pollution, greenhouse gas emission, and habitat destruction which are generally not directly accounted for. The magnitude of the economic impacts is debated and will vary by location, but is expected to rise with higher penetration levels. At low penetration levels, costs such as operating reserve and balancing costs are believed to be insignificant.

Intermittency may introduce additional costs that are distinct from or of a different magnitude than for traditional generation types. These may include:

- Transmission capacity: transmission capacity may be more expensive than for nuclear and coal generating capacity due to lower load factors. Transmission capacity will generally be sized to projected peak output, but average capacity for wind will be significantly lower, raising cost per unit of energy actually transmitted. However transmission costs are a low fraction of total energy costs.
- Additional operating reserve: if additional wind does not correspond to demand patterns, additional operating reserve may be required compared to other generating types, however this does not result in higher capital costs for additional plants since this is merely existing plants running at low output - spinning reserve. Contrary to statements that all wind must be backed by an equal amount of "back-up capacity", intermittent generators contribute to base capacity "as long as there is some probability of output during peak periods." Back-up capacity is not attributed to individual generators, as back-up or operating reserve "only have meaning at the system level."
- Balancing costs: to maintain grid stability, some additional costs may be incurred for balancing of load with demand. The ability of the grid to balance supply with demand will depend on the rate of change of the amount of energy produced (by wind, for example) and the ability of other sources to ramp production up or scale production down. Balancing costs have generally been found to be low.
- Storage, export and load management: at high penetrations (more than 30%), solutions (described below) for dealing with high output of wind during periods of low demand may be required. These may require additional capital expenditures, or result in lower marginal income for wind producers.

Analyses of costs

Studies have been performed to determine the costs of variability. RenewableUK states:

> “A review of integration studies, worldwide, suggests that the additional costs of integrating wind are around £2/MWh with 10% wind, rising to £3/MWh with 20% wind.”

Colorado - Separate reports by Xcel and UCS

An official at Xcel Energy claimed that at 20 percent penetration, additional standby generators to compensate for wind in Colorado would cost $8 per MWh, adding between 13% and 16% to the $50–$60 cost per MWh of wind energy.

The Union of Concerned Scientists conducted a study of the costs to increase the renewable penetration in Colorado to 10% and found that for an average residential bill "customers of municipal utilities and rural electric cooperatives that opt out of the solar energy requirement" would save 4 cents per month, but that for Xcel Energy customers there would be additional cost of about 10 cents per month. Total impact on all consumers would be $4.5 million or 0.01% over two decades.

UK Studies

A detailed study for UK National Grid (a private power company) states "We have estimated that for the case with 8,000 MW of wind needed to meet the 10% renewables target for 2010, balancing costs can be expected to increase by around £2 per MWh of wind production. This would represent an additional £40million per annum, just over 10% of existing annual balancing costs."

In evidence to the UK House of Lords Economic Affairs Select Committee, National Grid have quoted estimates of balancing costs for 40% wind and these lie in the range £500-1000M per annum. "These balancing costs represent an additional £6 to £12 per annum on average consumer electricity bill of around £390."

National Grid notes that "increasing levels of such renewable generation on the system would increase the costs of balancing the system and managing system frequency."

A 2003 report by Carbon Trust and the UK Department of Trade and Industry (DTI) found that the costs for reinforcement and new build of transmission and distribution systems to support 10% renewable electricity in the UK by 2010 would be £1.6 to £2.4 billion. The study classified "Intermittency" as "Not a significant issue" for the 2010 target. The same 2003 study found that achieving 20% renewable electricity in the UK by 2020 would cost £3.2bn to £4.5bn in transmission and distribution system construction and reinforcement. The study classified "Intermittency" as a "Significant Issue" for the 2020 target.

Minnesota

Minnesota study on wind penetration levels and found that "total integration operating cost for up to 25% wind energy" would be less than $0.0045 per kWh (additional).

Intermittency and renewable energy

There are differing views about some sources of renewable energy and intermittency. The World Nuclear Association argues that the sun, wind, tides and waves cannot be controlled to provide directly either continuous base-load power, or peak-load power when it is needed. Proponents of renewable energy use argue that the issue of intermittency of renewables is over-stated, and that practical experience demonstrates this. In any case, geothermal renewable energy has no intermittency.

Views of critics of high penetration renewable energy use

The World Nuclear Association states that:

"Obviously sun, wind, tides and waves cannot be controlled to provide directly either continuous base-load power, or peak-load power when it is needed,..." "In practical terms non-hydro renewables are therefore able to supply up to some 15–20% of the capacity of an electricity grid, though they cannot directly be applied as economic substitutes for most coal or nuclear power, however significant they become in particular areas with favourable conditions." "If the fundamental opportunity of these renewables is their abundance and relatively widespread occurrence, the fundamental challenge, especially for electricity supply, is applying them to meet demand given their variable and diffuse nature. This means either that there must be reliable duplicate sources of electricity beyond the normal system reserve, or some means of electricity storage." "Relatively few places have scope for pumped storage dams close to where the power is needed, and overall efficiency is less than 80%. Means of storing large amounts of electricity as such in giant batteries or by other means have not been developed."

On December 10, 2007 Patrick Moore, co-chair of the Clean & Safe Energy Coalition - a pro-nuclear group funded by the Nuclear Energy Institute - wrote:

> “Greenpeace is deliberately misleading the public into thinking that wind and solar energy, both of which are inherently intermittent and unreliable, can replace baseload power that is continuous and reliable. Only three technologies can produce large amounts of baseload power: fossil fuels, hydroelectric plants and nuclear power. Given that we want to reduce fossil fuels and that potential hydroelectric sites are becoming scarce, nuclear power is the main option... Over the past 10 years, Germany and Denmark have”

poured billions of taxpayers' euros into wind and solar energy in the vain hope that this would allow them to shut down fossil fuel and nuclear plants. They have not succeeded because every solar panel and every wind turbine must be backed up by reliable power when the sun isn't shining and the wind isn't blowing.

Mr. Moore is a co-founder and former leader of Greenpeace, but he has not been involved with Greenpeace since 1986.

Views of proponents of high penetration renewable energy use

The US Federal Energy Regulatory Commission (FERC) Chairman Jon Wellinghoff has stated that "baseload capacity is going to become an anachronism" and that no new nuclear or coal plants may ever be needed in the United States. This however is a minority viewpoint within President Obama's administration which via expanded federal loan guarantees in the proposed 2011 budget is supporting a nuclear renaissance.

Australian researchers at the University of New South Wales claim to have solved the energy storage problem for solar and wind power with the development of vanadium redox batteries. (U.S. patent issued in 1986).

Some renewable electricity sources have identical variability to coal-fired power stations, so they are base-load, and can be integrated into the electricity supply system without any additional back-up. Examples include:

- Bio-energy, based on the combustion of crops and crop residues, or their gasification followed by combustion of the gas.
- Hot dry rock geothermal power, which is being developed in Australia and the United States.
- Solar thermal electricity, with overnight heat storage in water or rocks, or a thermochemical store as with Nevada Solar One and Solar Tres.

Furthermore, supporters argue that the total electricity generated from a large-scale array of dispersed wind farms, located in different wind regimes, cannot be accurately described as intermittent, because it does not start up or switch off instantaneously at irregular intervals. With a small amount of supplementary peak-load plant, which operates infrequently, large-scale distributed wind power can substitute for some base-load power and be equally reliable.

Hydropower can be intermittent and/or dispatchable, depending on the configuration of the plant. Typical hydroelectric plants in the dam configuration may have substantial storage capacity, and be considered dispatchable. Run of the river hydroelectric generation will typically have limited or no storage capacity, and will be variable on a seasonal or annual basis (dependent on rainfall and snow melt).

Amory Lovins suggests a few basic strategies to deal with these issues:

> "The variability of sun, wind and so on, turns out to be a non-problem if you do several sensible things. One is to diversify your renewables by technology, so that weather conditions bad for one kind are good for another. Second, you diversify by site so they're not all subject to the same weather pattern at the same time because they're in the same place. Third, you use standard weather forecasting techniques to forecast wind, sun and rain, and of course hydro operators do this right now. Fourth, you integrate all your resources — supply side and demand side..."

Moreover, efficient energy use and energy conservation measures can reliably reduce demand for base-load and peak-load electricity.

Several studies have demonstrated the technical feasibility of integrating intermittent power at levels substantially higher than is common in most countries (from 15-30% penetration), and at least three countries have more than 20% wind penetration. Relatively few changes to large grids are normally required and the associated system costs are moderate. International groups are studying much higher penetrations (30-75%, corresponding to up to 20% of national electricity consumption) and preliminary conclusions are that these levels are also technically feasible. In the UK, one summary of other studies indicated that if assuming that wind power contributed less than 20% of UK power consumption, then the intermittency would cause only moderate cost.

Methods to manage wind power integration range from those that are commonly used at present (e.g. demand management) to potential new technologies for grid energy storage. Improved forecasting can also contribute as the daily and seasonal variations in wind and solar sources are to some extent predictable.

The Pembina Institute and the World Wide Fund for Nature state in the Renewable is Doable plan that resilience is a feature of renewable energy:

> “ Diversity and dispersal also add system security. If one wind turbine fails, the lights won't flicker. If an entire windfarm gets knocked out by a storm, only 40,000 people will lose power. If a single Darlington reactor goes down, 400,000 homes, or key industries, could face instant blackouts. To hedge this extra risk, high premiums have to be paid for decades to ensure large blocks of standby generation.

Chapter- 10

Electricity Market

In economic terms, electricity (both power and energy) is a commodity capable of being bought, sold and traded. An **electricity market** is a system for effecting purchases, through bids to buy; sales, through offers to sell; and short-term trades, generally in the form of financial or obligation swaps. Bids and offers use supply and demand principles to set the price. Long-term trades are contracts similar to power purchase agreements and generally considered private bi-lateral transactions between counterparties.

Wholesale transactions (bids and offers) in electricity are typically cleared and settled by the market operator or a special-purpose independent entity charged exclusively with that function. Market operators do not clear trades but often require knowledge of the trade in order to maintain generation and load balance. The commodities within an electric market generally consist of two types: Power and Energy. Power is the metered net electrical output of a generator at any given time and is measured in Megawatts (MW). Energy is electricity that flows through a metered point for a given time and is measured in Megawatt Hours (MWh).

Markets for power related commodities are net generation output for a number of intervals usually in increments of 5, 15 and 60 minutes. Markets for energy related commodities required by, managed by (and paid for by) market operators to ensure reliability, are considered Ancillary Services and include such names as spinning reserve, non-spinning reserve, operating reserves, responsive reserve, regulation up regulation down, and installed capacity.

In addition, for most major operators, there are markets for transmission congestion and electricity derivatives, such as electricity futures and options, which are actively traded. These markets developed as a result of the restructuring of electric power systems around the world. This process has often gone on in parallel with the restructuring of natural gas markets.

History

The earliest introduction of energy market concepts and privatization to electric power systems took place in Chile in the early 1980s, in parallel with other market-oriented reforms associated with the Chicago Boys. The Chilean model was generally perceived as successful in bringing rationality and transparency to power pricing, but it contemplated the continuing dominance of several large incumbents and suffered from the attendant structural problems. Argentina improved on the Chilean model by imposing strict limits on market concentration and by improving the structure of payments to units held in reserve to assure system reliability. One of the principal purposes of the introduction of market concepts in Argentina was to privatize existing generation assets (which had fallen into disrepair under the government-owned monopoly, resulting in frequent service interruptions) and to attract capital needed for rehabilitation of those assets and for system expansion. The World Bank was active in introducing a variety of hybrid markets in other Latin American nations, including Peru, Brazil, and Colombia, during the 1990s, with limited success.

A key event for electricity markets occurred in 1990 when the UK government under Margaret Thatcher privatised the UK electricity supply industry. The process followed by the British was then used as a model or at least a catalyst for the deregulation of several other Commonwealth countries, notably Australia and New Zealand, and regional markets such as Alberta. However, in many of these other instances the market deregulation occurred without the widespread privatisation that characterised the UK example.

In the USA the traditional model of the vertically integrated electric utility with a transmission system designed to serve its own customers worked extremely well for decades. As dependence on a reliable supply of electricity grew and electricity was transported over increasingly greater distances, power pools were formed and interconnections developed. Transactions were relatively few and generally planned well in advance.

However, in the last decade of the 20th century, some US policy makers and academics projected that the electrical power industry would ultimately experience deregulation and Independent System Operators (ISOs) and Regional Transmission Organizations (RTOs) were established. They were conceived as the way to handle the vastly increased number of transactions that take place in a competitive environment. About a dozen states decided to deregulate but some pulled back following the California electricity crisis of 2000 and 2001.

In different deregulation processes the institutions and market designs were often very different but many of the underlying concepts were the same. These are: separate the potentially competitive functions of generation and retail from the natural monopoly functions of transmission and distribution; and establish a **wholesale electricity market** and a **retail electricity market**. The role of the wholesale market is to allow trading between generators, retailers and other financial intermediaries both for short-term delivery of electricity and for future delivery periods.

Nature of the market

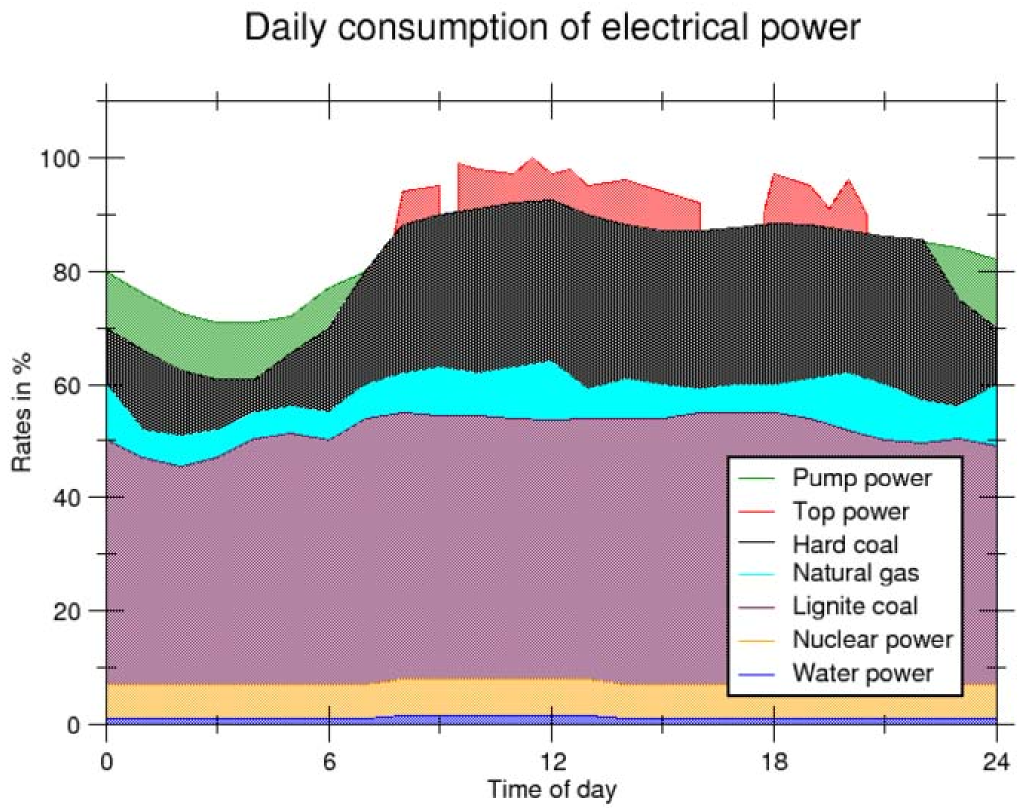
Electricity is by its nature difficult to store and has to be available on demand. Consequently, unlike other products, it is not possible, under normal operating conditions, to keep it in stock, ration it or have customers queue for it. Furthermore, demand and supply vary continuously.

There is therefore a physical requirement for a controlling agency, the transmission system operator, to coordinate the dispatch of generating units to meet the expected demand of the system across the transmission grid. If there is a mismatch between supply and demand the generators speed up or slow down causing the system frequency (either 50 or 60 hertz) to increase or decrease. If the frequency falls outside a predetermined range the system operator will act to add or remove either generation or load.

In addition, the laws of physics determine how electricity flows through an electricity network. Hence the extent of electricity lost in transmission and the level of congestion on any particular branch of the network will influence the economic dispatch of the generation units.

The scope of each electricity market consists of the transmission grid or network that is available to the wholesalers, retailers and the ultimate consumers in any geographic area. Markets may extend beyond national boundaries.

Wholesale electricity market



Typical daily consumption of electrical power in Germany

A **wholesale electricity market** exists when competing generators offer their electricity output to retailers. The retailers then re-price the electricity and take it to market. While wholesale pricing used to be the exclusive domain of large retail suppliers, increasingly markets like New England are beginning to open up to end-users. Large end-users seeking to cut out unnecessary overhead in their energy costs are beginning to recognize the advantages inherent in such a purchasing move. Consumers buying electricity directly from generators is a relatively recent phenomenon.

Buying wholesale electricity is not without its drawbacks (market uncertainty, membership costs, set up fees, collateral investment), however, the larger the end user's electrical load, the greater the benefit and incentive to make the switch.

For an economically efficient electricity wholesale market to flourish it is essential that a number of criteria are met. Professor William Hogan of Harvard University has identified these criteria. Central to his criteria is a coordinated spot market that has "bid-based, security-constrained, economic dispatch with nodal prices". Other academics such as Professors Shmuel Oren and Pablo Spiller of the University of California, Berkeley have proposed other criteria. Variants of Professor Hogan's model have largely been adopted in the US, Australia and New Zealand.

Bid-based, security-constrained, economic dispatch with nodal prices

The system price in the day-ahead market is, in principle, determined by matching offers from generators to bids from consumers at each node to develop a classic supply and demand equilibrium price, usually on an hourly interval, and is calculated separately for subregions in which the system operator's load flow model indicates that constraints will bind transmission imports.

The theoretical prices of electricity at each node on the network is a calculated "shadow price", in which it is assumed that one additional kilowatt-hour is demanded at the node in question, and the hypothetical incremental cost to the system that would result from the optimized redispatch of available units establishes the hypothetical production cost of the hypothetical kilowatt-hour. This is known as *locational marginal pricing* (LMP) or *nodal pricing* and is used in some deregulated markets, most notably in the PJM Interconnection, New York, and New England markets in the USA and in New Zealand.

In practice, the LMP algorithm described above is run, incorporating a security-constrained, least-cost dispatch calculation (see below) with supply based on the generators that submitted offers in the day-ahead market, and demand based on bids from load-serving entities draining supplies at the nodes in question.

While in theory the LMP concepts are useful and not evidently subject to manipulation, in practice system operators have substantial discretion over LMP results through the ability to classify units as running in "out-of-merit dispatch", which are thereby excluded from the LMP calculation. In most systems, units that are dispatched to provide reactive power to support transmission grids are declared to be "out-of-merit" (even though these are typically the same units that are located in constrained areas and would otherwise result in scarcity signals). System operators also normally bring units online to hold as "spinning-reserve" to protect against sudden outages or unexpectedly rapid ramps in demand, and declare them "out-of-merit". The result is often a substantial reduction in clearing price at a time when increasing demand would otherwise result in escalating prices.

Researches have noted that a variety of factors, including energy price caps set well below the putative scarcity value of energy, the impact of "out-of-merit" dispatch, the use of techniques such as voltage reductions during scarcity periods with no corresponding scarcity price signal, etc., results in a "missing money" problem. The consequence is that prices paid to suppliers in the "market" are substantially below the levels required to stimulate new entry. The markets have therefore been useful in bringing efficiencies to short-term system operations and dispatch, but have been a failure in what was advertised as a principal benefit: stimulating suitable new investment where it is needed, when it is needed.

In LMP markets, where constraints exist on a transmission network, there is a need for more expensive generation to be dispatched on the downstream side of the constraint.

Prices on either side of the constraint separate giving rise to congestion pricing and constraint rentals.

A constraint can be caused when a particular branch of a network reaches its thermal limit or when a potential overload will occur due to a contingent event (e.g., failure of a generator or transformer or a line outage) on another part of the network. The latter is referred to as a *security constraint*. Transmission systems are operated to allow for continuity of supply even if a contingent event, like the loss of a line, were to occur. This is known as a *security constrained system*.

In most systems the algorithm used is a "DC" model rather than an "AC" model, so constraints and redispatch resulting from thermal limits are identified/predicted, but constraints and redispatch resulting from reactive power deficiencies are not. Some systems take marginal losses into account. The prices in the real-time market are determined by the LMP algorithm described above, balancing supply from available units. This process is carried out for each 5-minute, half-hour or hour (depending on the market) interval at each node on the transmission grid. The hypothetical redispatch calculation that determines the LMP must respect security constraints and the redispatch calculation must leave sufficient margin to maintain system stability in the event of an unplanned outage anywhere on the system. This results in a spot market with "bid-based, security-constrained, economic dispatch with nodal prices".

Since the introduction of the market, New Zealand has experienced shortages in 2001 and 2003, high prices all through 2005 and even higher prices and the risk of a severe shortage in 2006 (as of April 2006). These problems arose because New Zealand is at risk from drought due to its high proportion of electricity generated from hydro. However, similar shortages arose during the 1970s before the electricity market was introduced and the absence of shortages during the 1980s appears to be due to the large increase in capacity as a result of the "Think Big" projects started during the 1970s. The difference the market has made is that now cuts in electricity demand are made voluntarily while in the 1970s cuts were imposed. If the users of electricity know more about what they prefer to cut than the government, this would have led to an increase in efficiency.

Many established markets do not employ nodal pricing, examples being the UK, Powernext and Nord Pool (Scandinavia and Finland).

Risk management

Financial risk management is often a high priority for participants in deregulated electricity markets due to the substantial price and volume risks that the markets can exhibit. A consequence of the complexity of a wholesale electricity market can be extremely high price volatility at times of peak demand and supply shortages. The particular characteristics of this price risk are highly dependent on the physical fundamentals of the market such as the mix of types of generation plant and relationship between demand and weather patterns. Price risk can be manifest by price "spikes" which are hard to predict and price "steps" when the underlying fuel or plant position changes for long periods.

"Volume risk" is often used to denote the phenomenon whereby electricity market participants have uncertain volumes or quantities of consumption or production. For example, a retailer is unable to accurately predict consumer demand for any particular hour more than a few days into the future and a producer is unable to predict the precise time that they will have plant outage or shortages of fuel. A compounding factor is also the common correlation between extreme price and volume events. For example, price spikes frequently occur when some producers have plant outages or when some consumers are in a period of peak consumption. The introduction of substantial amounts of intermittent power sources such as wind energy may have an impact on market prices.

Electricity retailers, who in aggregate buy from the wholesale market, and generators who in aggregate sell to the wholesale market, are exposed to these price and volume effects and to protect themselves from volatility, they will enter into "hedge contracts" with each other. The structure of these contracts varies by regional market due to different conventions and market structures. However, the two simplest and most common forms are simple fixed price forward contracts for physical delivery and contracts for differences where the parties agree a strike price for defined time periods. In the case of a contract for difference, if a resulting wholesale price index (as referenced in the contract) in any time period is higher than the "strike" price, the generator will refund the difference between the "strike" price and the actual price for that period. Similarly a retailer will refund the difference to the generator when the actual price is less than the "strike price". The actual price index is sometimes referred to as the "spot" or "pool" price, depending on the market.

Many other hedging arrangements, such as swing contracts, Virtual Bidding, Financial Transmission Rights, call options and put options are traded in sophisticated electricity markets. In general they are designed to transfer financial risks between participants.

Wholesale electricity markets

- Czech Republic / Europe - OTE - Czech electricity and gas market operator
- Western Australia - IMO the Independent Market Operator
- Australia - AEMO the Australian Market Administrator
- Austria - EXAA Energy Exchange
- Brazil - Eletric Energy Commercialization Chamber
- Canada - Independent Electricity System Operator (IESO) Ontario Market and Alberta Electric System Operator (AESO)
- Chile
- Scandinavia - Nord Pool Spot
- France, - Powernext
- Germany - European Energy Exchange EEX
- Great Britain - Elexon
- India - Indian Energy Exchange

- Ireland - SEMO
- Italy - GME
- Japan - Japan Electric Power Exchange (JEPX)
- Netherlands, UK, Belgium - APX-ENDEX
- New Zealand - New Zealand Electricity Market
- Philippines - Philippine Wholesale Electricity Spot Market
- Portugal - OMIP
- Russian Federation - Trade System Administrator (ATS)
- Singapore - Energy Market Authority, Singapore and Energy Market Company (EMC)
- Spain - OMEL Electricity Market
- USA (summarized here)
    - PJM
    - ERCOT Market,
    - New York Market,
    - Midwest Market,
    - California ISO,
    - New England Market

Retail electricity market

A **retail electricity market** exists when end-use customers can choose their supplier from competing electricity retailers; one term used in the United States for this type of consumer choice is 'energy choice'. A separate issue for electricity markets is whether or not consumers face real-time pricing (prices based on the variable wholesale price) or a price that is set in some other way, such as average annual costs. In many markets, consumers do not pay based on the real-time price, and hence have no incentive to reduce demand at times of high (wholesale) prices or to shift their demand to other periods. Demand response may use pricing mechanisms or technical solutions to reduce peak demand.

Generally, electricity retail reform follows from electricity wholesale reform. However, it is possible to have a single electricity generation company and still have retail competition. If a wholesale price can be established at a node on the transmission grid and the electricity quantities at that node can be reconciled, competition for retail customers within the distribution system beyond the node is possible. In the German market, for example, large, vertically integrated utilities compete with one another for customers on a more or less open grid.

Although market structures vary, there are some common functions that an electricity retailer has to be able to perform, or enter into a contract for, in order to compete effectively. Failure or incompetence in the execution of one or more of the following has led to some dramatic financial disasters:

- Billing
- Credit control

- Customer management via an efficient call centre
- Distribution use-of-system contract
- Reconciliation agreement
- "Pool" or "spot market" purchase agreement
- Hedge contracts - contracts for differences to manage "spot price" risk

The two main areas of weakness have been risk management and billing. In the USA in 2001, California's flawed regulation of retail competition led to the California electricity crisis and left incumbent retailers subject to high spot prices but without the ability to hedge against these. In the UK a retailer, Independent Energy, with a large customer base went bust when it could not collect the money due from customers.

New technology is available and has been piloted by the US Department of Energy that may be better suited to real-time market pricing. A potential use of event-driven SOA could be a virtual electricity market where home clothes dryers can bid on the price of the electricity they use in a real-time market pricing system. The real-time market price and control system could turn home electricity customers into active participants in managing the power grid and their monthly utility bills. Customers can set limits on how much they would pay for electricity to run a clothes dryer, for example, and electricity providers willing to transmit power at that price would be alerted over the grid and could sell the electricity to the dryer.

On one side, consumer devices can bid for power based on how much the owner of the device were willing to pay, set ahead of time by the consumer. On the other side, suppliers can enter bids automatically from their electricity generators, based on how much it would cost to start up and run the generators. Further, the electricity suppliers could perform real-time market analysis to determine return-on-investment for optimizing profitability or reducing end-user cost of goods.

Event-driven SOA software could allow homeowners to customize many different types of electricity devices found within their home to a desired level of comfort or economy. The event-driven software could also automatically respond to changing electricity prices, in as little as five-minute intervals. For example, to reduce the home owner's electricity usage in peak periods (when electricity is most expensive), the software could automatically lower the target temperature of the thermostat on the central heating system (in winter) or raise the target temperature of the thermostat on the central cooling system (in summer).

Electricity market experience

In the main, experience in the introduction of wholesale and retail competition has been mixed. Many regional markets have achieved some success and the ongoing trend continues to be towards deregulation and introduction of competition. However in 2000/2001 major failures such as the California electricity crisis and the Enron debacle caused a slow down in the pace of change and in some regions an increase in market regulation and reduction in competition. However, this trend is widely regarded as a temporary one against the longer term trend towards more open and competitive markets.

Notwithstanding the favorable light in which market solutions are viewed conceptually, the "missing money" problem has to date proved intractable. If electricity prices were to move to the levels needed to incent new merchant (i.e., market-based) transmission and generation, the costs to consumers would be politically difficult.

The increase in annual costs to consumers in New England alone were calculated at $3 billion during the recent FERC hearings on the NEPOOL market structure. Several mechanisms that are intended to incent new investment where it is most needed by offering enhanced capacity payments (but only in zones where generation is projected to be short) have been proposed for NEPOOL, PJM and NYPOOL, and go under the generic heading of "locational capacity" or LICAP (the PJM version currently [May 2006] under FERC review is called the "Reliability Pricing Model", or "RPM"). There is substantial doubt as to whether any of these mechanisms will in fact incent new investment, given the regulatory risk and chronic instability of the market rules in US systems, and there are substantial concerns that the result will instead be to increase revenues to incumbent generators, and costs to consumers, in the constrained areas.