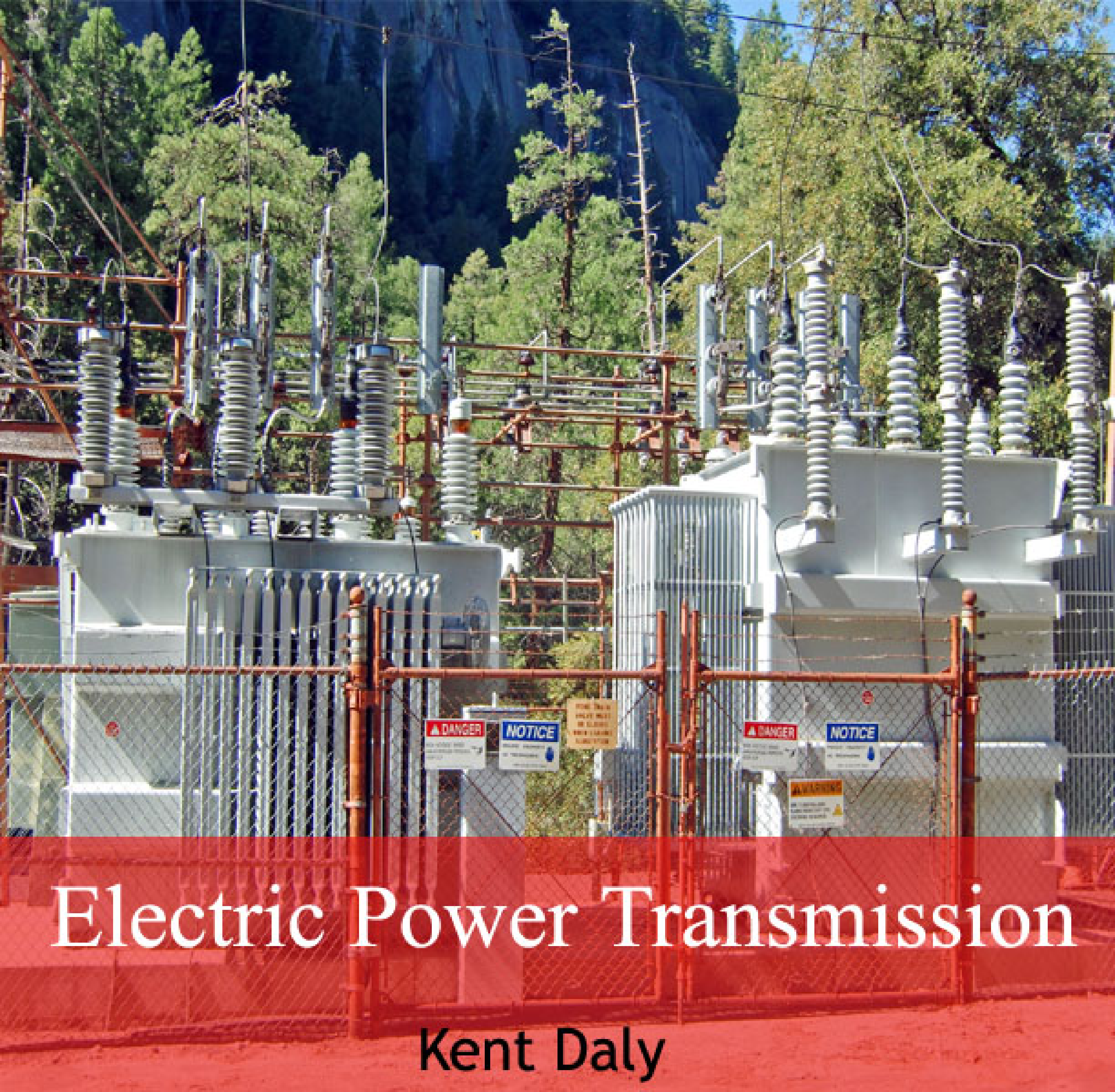


# Electric Power Transmission

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First Edition, 2012

ISBN 978-81-323-4128-4

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*Published by:*
**White Word Publications**
4735/22 Prakashdeep Bldg,
Ansari Road, Darya Ganj,
Delhi - 110002
Email: info@wtbooks.com

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## Chapter 1

# 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 just "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 liberalized the electricity market in ways 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 must be generated as 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.

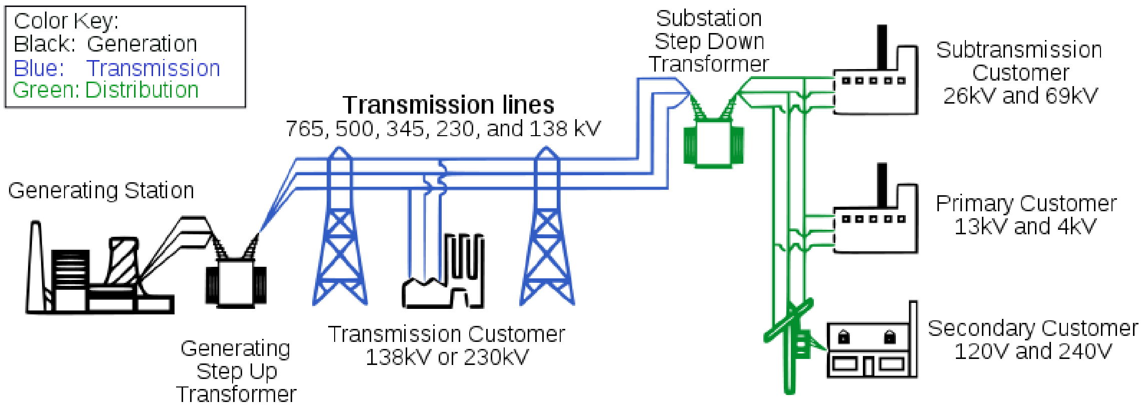
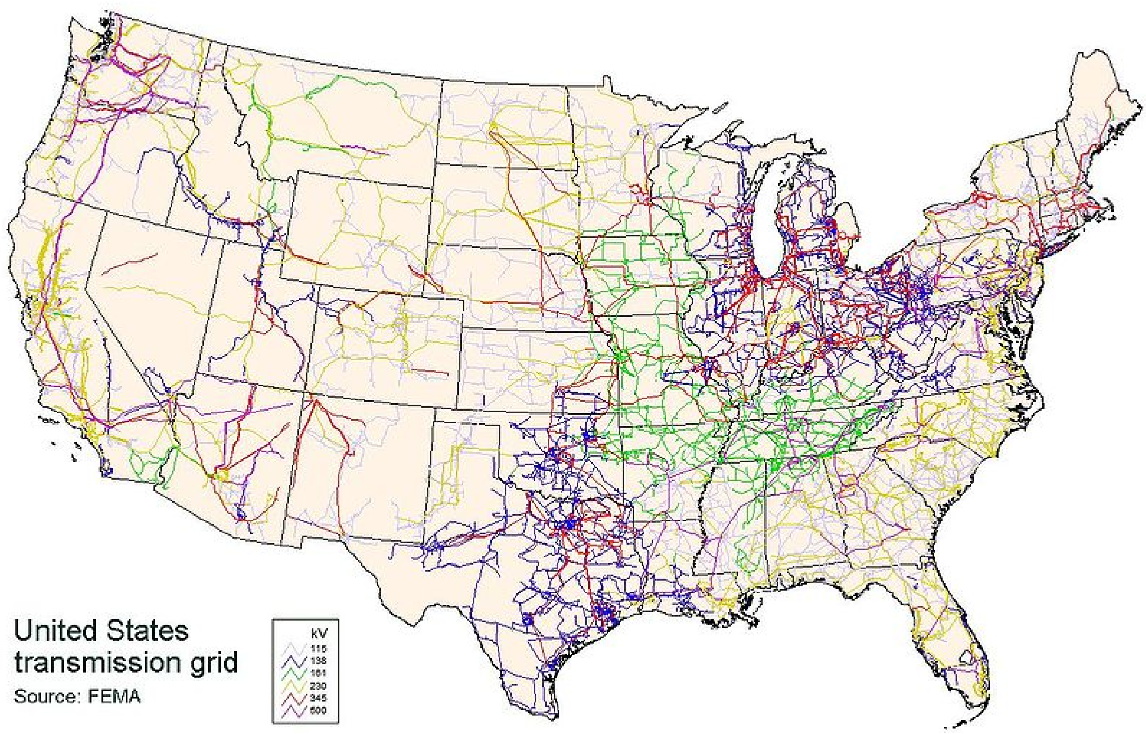



Diagram of an electrical system.

### ***Overhead transmission***




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

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 only marginally reduced 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.

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 subtransmission 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.

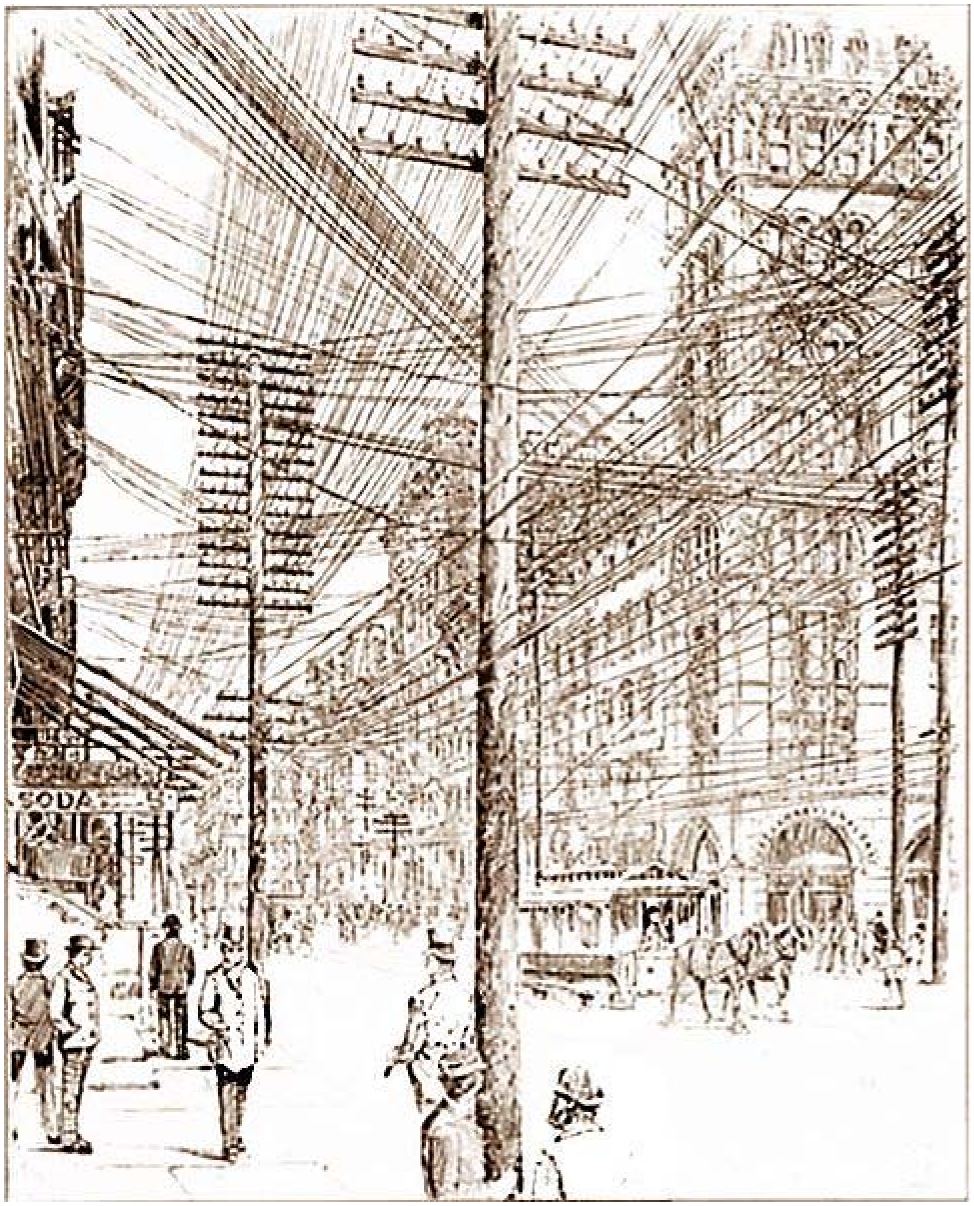
Since overhead transmission lines are uninsulated, design of these lines requires minimum clearances to be observed to maintain safety. Adverse weather conditions of high wind and low temperatures can lead to power outages: wind speeds as low as 23 knots (43 km/h) can permit conductors to encroach operating 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.

High Voltage Lines in Washington State

### *Underground transmission*

Electric power can also be transmitted by underground power cables instead of overhead power lines.

## *History*

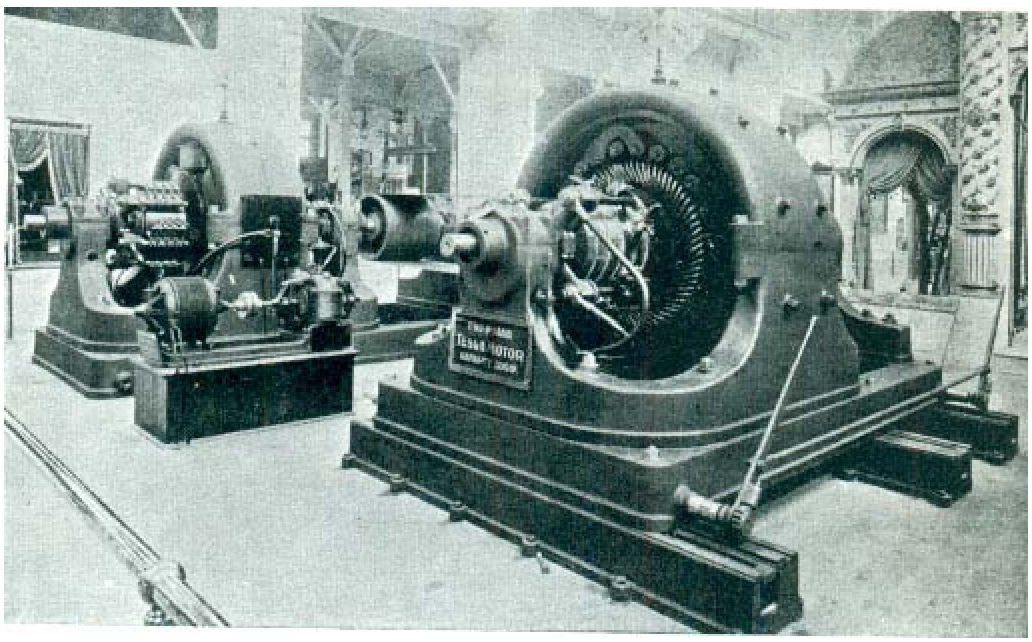



New York City streets in 1890. Besides telegraph lines, multiple electric lines were required for each class of device requiring different voltages.

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 (DC), 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 alternating current (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*

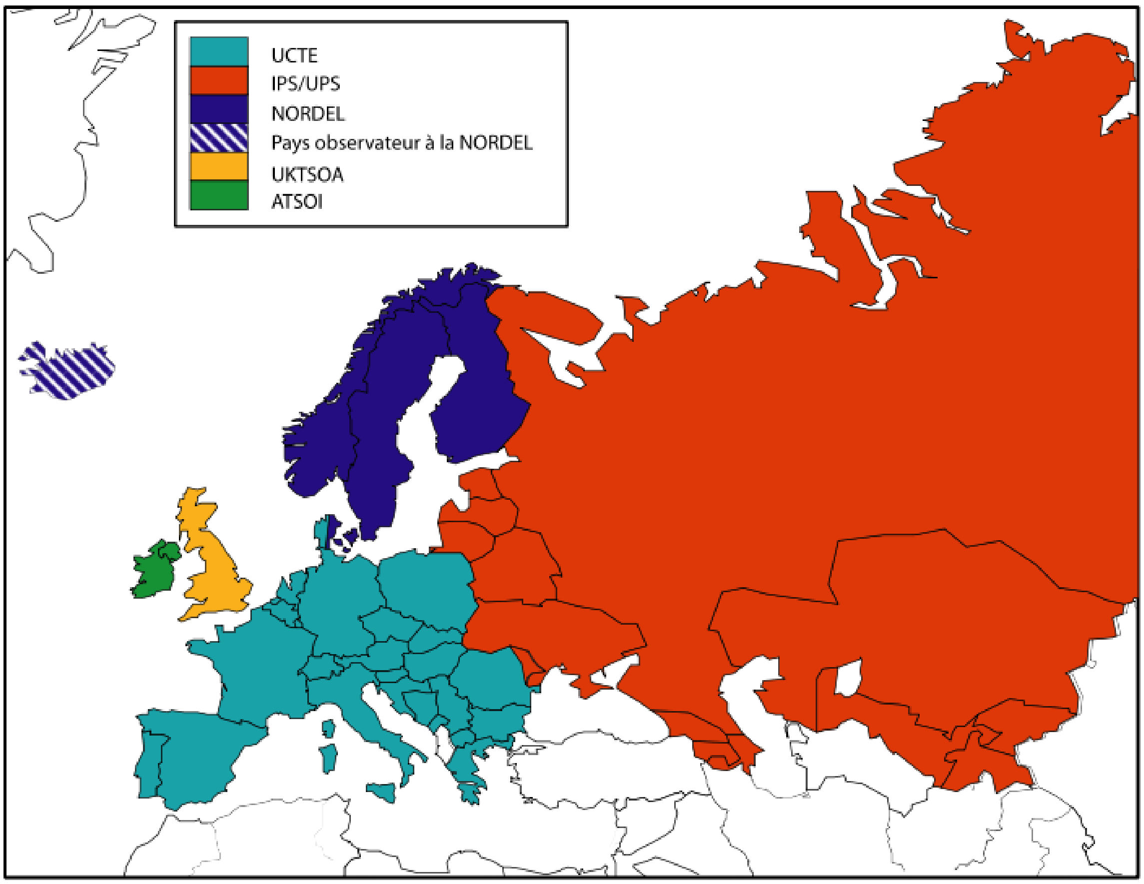
A transmission substation decreases the voltage of incoming electricity, allowing it to connect from long distance high voltage transmission, to local lower voltage distribution. It also reroutes power to other transmission lines that serve local markets. A transmission substation may include phase-shifting 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 $I^2R$ losses 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 $I^2R$ losses 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. Measures to reduce corona losses include conductors having large diameter; often hollow to save weight, , or bundles of two or more 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 DC electricity was 7,000 km (4,300 mi) (4,000 km (2,500 mi) for AC), 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.

### Subtransmission

*Subtransmission* is part of an electric power transmission system that runs at relatively lower voltages. It is uneconomical to connect all distribution substations to the high main transmission voltage, because the equipment is larger and more expensive. Typically, only larger substations connect with this high voltage. It is stepped down and sent to smaller substations in towns and neighborhoods. Subtransmission circuits are usually arranged in loops so that a single line failure does not cut off service to a large number of customers for more than a short time. While subtransmission circuits are usually carried on overhead lines, in urban areas buried cable may be used.

There is no fixed cutoff between subtransmission and transmission, or subtransmission and distribution. The voltage ranges overlap somewhat. Voltages of 69 kV, 115 kV and 138 kV are often used for substranmission in North America. As power systems evolved, voltages formerly used for transmission were used for subtransmission, and subtransmission voltages became distribution voltages. Like transmission, subtransmission moves relatively large amonts of power, and like distribution, subtransmission covers an area instead of just point to point.

### 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.

# Chapter 2

# History of Electric Power Transmission

The history of the technology of moving electricity far from where it was generated dates from the late 19th century. This includes movement of electricity in bulk (formally referred to as "transmission), and the delivery of electricity ("distribution") to individual customers. The distinction between the two terms did not exist in early years and were used interchangeably.

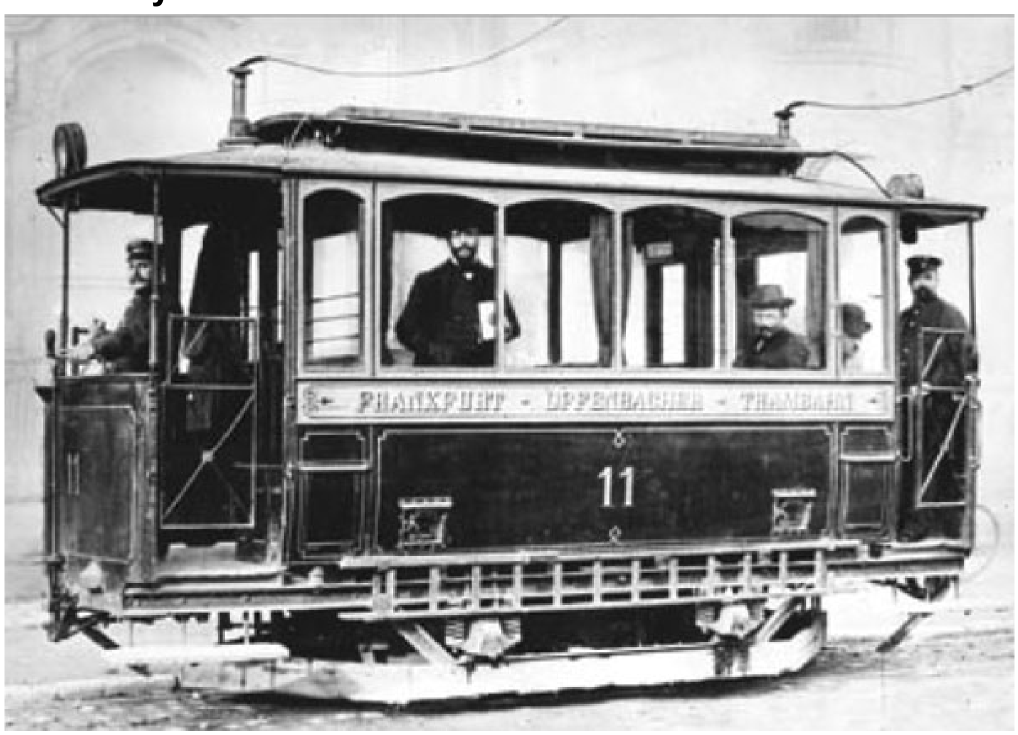
## *Early transmission*


Berlin, 1884. With double the brilliance of gaslight, arc lights were in high demand for stores and public areas but each required thousands of volts.

Prior to electricity, various systems have been used for transmission of power across large distances. Chief among them were telodynamic (cable in motion), pneumatic (pressurized air), and hydraulic (pressurized fluid) transmission. Cable cars were the most frequent example of telodynamic transmission, whose lines could extend for several miles for a single section. Pneumatic transmission was used for city power transmission systems in Paris, Birmingham, Rixdorf, Offenbach, Dresden and Buenos Aires at the beginning of the twentieth century. Cities in the 19th century also used hydraulic transmission using high pressure water mains to deliver power to factory motors. London's system delivered 7000 hp (5Megawatts) over a 180-mile (290 km) network of pipes carrying water at 800psi. These systems were replaced by cheaper and more versatile electrical systems, but by the end of the 19th century, city planners and financiers well aware of the benefits, economics, and process of establishing power transmission systems.

In the early days electric power usage, widespread transmission of electric power had two obstacles. Firstly, devices requiring different voltages required specialized generators with their own separate lines. Street lights, electric motors in factories, power for streetcars and lights in homes are examples of the diversity of devices with voltages requiring separate systems. Secondly, generators had to be relatively nearby their loads (a mile or less for low voltage devices). It was known that long distance transmission was possible the higher the voltage was raised, so both problems could be solved if transforming voltages could be cheaply performed from a single universal power line.

## Specialized systems

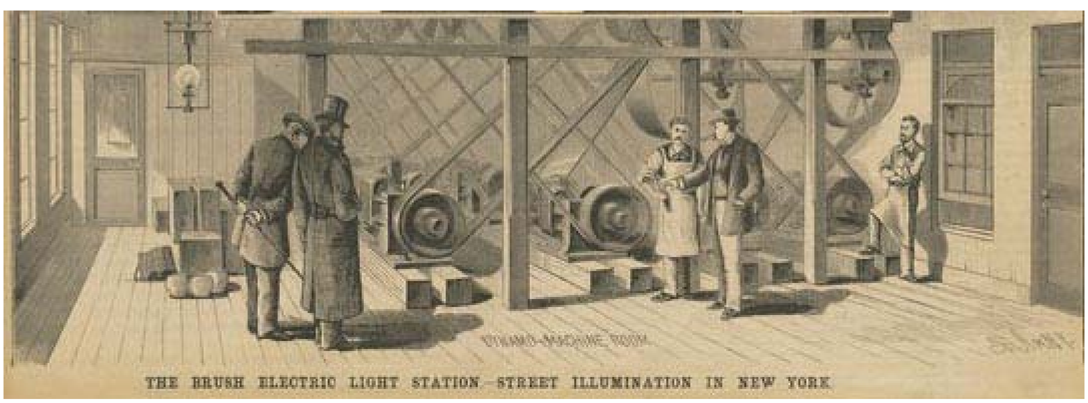



Streetcars created enormous demand for early electricity. This Siemens Tram from 1884 required 500 volt direct current, which was typical.

Much of early electricity was direct current, which could not easily be increased or decreased in voltage either for long-distance transmission or for sharing a common line to be used with multiple types of electric devices. Companies simply ran different lines for the different classes of loads their inventions required, for example, Charles Brush's New York voltaic arc lights required up to 10,000 volts, Edison's incandescent lights used 110 volts, streetcars built by Siemens or Sprague required large motors in the 500 volt range, whereas industrial motors in factories used still other voltages. Due to this specialization of lines and because transmission was so inefficient that generators needed to be close by 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.

## Early high voltage and commercial systems

High voltage was of interest to early researchers working on the problem of transmission over distance. They know from elementary electricity principle that the same amount of power could be transferred on a cable by doubling the voltage and halving the current. Due to Joule's Law, they also knew that the capacity of a wire is proportionate to the square of the current traveling on it, regardless the voltage, and so by doubling the voltage, the same cable would be capable of transmitting the same amount of power four times the distance. At the Paris Exposition of 1878, electric arc lighting had been installed along the Avenue de l'Opera and the Place de l'Opera, using electric Yablochkov arc lamps, powered by Zénobe Gramme alternating current dynamos. Yablochkov candles required high voltage, and it was not long before experimenters reported that the arc lights could be powered on a 7-mile (11 km) circuit. Within a decade scores of cities would have lighting systems using a central power plant that provided electricity to multiple customers via electrical transmission lines. These systems were in direct competition with the dominant gaslight utilities of the period.




Brush Electric Company's central power plant dynamos powered arc lamps for public lighting in New York. Beginning operation in December 1880 at 133 West Twenty-Fifth Street, it powered a 2-mile (3.2 km) long circuit.

The idea of investing in a central plant and a network to deliver energy produced to customers who pay a recurring fee for service was familiar business model for investors: it was identical to the lucrative gaslight business, or the hydraulic and pneumatic power transmission systems. The only difference was the stuff being delivered was electricity not gas, and the "pipes" doing the delivering were flexible. The California Electric

Company (now PG&E) in San Francisco in 1879 used two direct current generators from Charles Brush's company to supply multiple customers with power for their arc lights. This San Francisco system was the first case of a utility selling electricity from a central plant to multiple customers via transmission lines. The California Electric Company (now PG&E) purchased three generators from Charles Brush's company in 1879 and soon opened a second plant with 4 additional generators. Service charges for light from sundown to midnight was $10 per lamp per week. In December 1880, Brush Electric Company set up a central station to supply a 2-mile (3.2 km) length of Broadway with arc lighting. By the end of 1881, New York, Boston, Philadelphia, Baltimore, Montreal, Buffalo, San Francisco, Cleveland and other cities had Brush arc light systems, producing public light well into the 20th century. By 1893 there were 1500 arc lights illuminating New York streets.

The first electricity system supplying incandescent lights was built by Edison Electric Illuminating Company in lower Manhattan eventually serving one square mile with 6 "jumbo dynamos" housed at Pearl Street Station. When service began in September 1882, there were 85 customers with 400 light bulbs. Each dynamo produced 100 kW- enough for 1200 incandescent lights, and transmission was at 110 volts via underground conduits. The system cost $300,000 to build with installation of the 100,000 feet (30,000 m) of underground conduits one of the most expensive parts of the project. Operating expenses exceeded income in the first two years and fire destroyed the plant in 1890. Edison's lights were cheaper, provided light that was warmer and operated at much lower voltages than the arc lights. Further, Edison had a three wire system so that either 110 volts or 220 volts could be supplied to power some motors.

## Availability of large scale generation

Availability of large amounts of power from diverse locations would become possible after Charles Parsons' production of turbogenerators beginning 1889. Turbogenerator output quickly jumped from 100 kW to 25 megawatts in two decades. Prior to efficient turbogenerators, hydroelectric projects were a significant source of large amounts of power requiring transmission infrastructure.

## Induction coils advantage of alternating current

When George Westinghouse became interested in electricity, he quickly and correctly concluded that Edison's low voltages were too inefficient to be scaled up for transmission needed for large systems. He further understood that long-distance transmission needed high voltage and that inexpensive conversion technology only existed for alternating current. Transformers would play the decisive role in the victory of alternating current over direct current for transmission and distribution systems. In 1876, Pavel Yablochkov patented his mechanism of using induction coils to served as a step up transformer prior to the Paris Exposition demonstrating his arc lights. Lucien Gaulard and John Dixon Gibbs later developed more efficient, less expensive AC transformers.

**The birth of the first transformer**

Between 1884 and 1885, Hungarian engineers Zipernowsky, Bláthy and Déri from the Ganz company in Budapest created the efficient "Z.B.D." closed-core coils, as well as the modern electric distribution system. The three had discovered that all former coreless or open-core devices were incapable of regulating voltage, and were therefore impracticable. Their joint patent described two versions of a design with no poles: the "closed-core transformer" and the "shell-core transformer". Ottó Bláthy suggested the use of closed-cores, Károly Zipernowsky the use of shunt connections, and Miksa Déri performed the experiments.

In the closed-core transformer the iron core is a closed ring around which the two coils are wound. In the shell type transformer, the windings are passed through the core. In both designs, the magnetic flux linking the primary and secondary windings travels almost entirely within the iron core, with no intentional path through air. The core consists of iron strands or sheets. These revolutionary design elements would finally make it technically and economically feasible to provide electric power for lighting in homes, businesses and public spaces. Zipernowsky, Bláthy and Déri also discovered the transformer formula, $V_s/V_p = N_s/N_p$. Electrical and electronic systems the world over rely on the principles of the original Ganz transformers. The inventors are also credited with the first use of the word "transformer" to describe a device for altering the EMF of an electric current.

The concept that is the basis of modern transmission using inexpensive step up and step down transformers was first implemented by Westinghouse, Stanley and Franklin Leonard Pope in 1886 in Great Barrington, Massachusetts. There were still problems with efficient generators and high voltage transformers. 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 alternating currents. Westinghouse needed Telsa's better step up transformer technology and bought patents for it along with the highly efficient and inexpensive polyphase design for AC generators and motors used today. The utter simplicity of polyphase generators and motors meant that besides their efficiency they could be manufactured cheaply, compactly and would required little attention to maintain. Simple economics would drive the expensive, balky and mechanically complex DC dynamos to their ultimate extinction. As it turned out, the deciding factor in the War of Currents was the availability of low cost step up and step down transformers that meant that all customers regardless of their specialized voltage requirements could be served at minimal cost of conversion. This "universal system" is today regarded as one of the most influential innovations for the use of electricity.

## High voltage direct current transmission

The case for alternating current was not clear at the turn of the century and high voltage direct current transmission systems were successfully installed without the benefit of transformers. Rene Thury who had spent six months at Edison's Menlo park facility understood his problem with transmission and was convinced that moving electricity over great distances was possible using direct current. He was familiar with the work of Marcel Deprez, who did early work on high voltage transmission after being inspired by the capability of arc light generators to support lights over great distances. Deprez avoided transformers by placing generators and loads in series as arc light systems of Charles F. Brush did. Thury developed this idea into the first commercial system for high-voltage DC transmission. Like Brush's dynamos, current is kept constant, and when increasing load demands more pressure, voltage is increased. The Thury System was successfully used on several DC transmission projects from Hydro generators. The first in 1885 was a low voltage system in Bözingen, and the first high voltage system went into service in 1889 in Genoa, Italy by the *Acquedotto de Ferrari-Galliera* company. This system transmitted 630 kW at 14 kV DC over a circuit 120 km long. The largest Thury System was the Lyon Moutiers project that was 230 km in length, eventually delivering 20 Megawatts, at 125kV.

## Victory for AC

Ultimately, the versatility of the Thury system was hampered the fragility of series distribution, and the lack of a reliable DC conversion technology that would not show up until the 1940s with improvements in mercury arc valves. The AC "universal system" won by force of numbers, proliferating systems with transformers both to couple generators to high-voltage transmission lines, and to connect transmission to local distribution circuits. 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 load to be served by local conversion where needed. Even generating stations and loads using different frequencies could also 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, allowing for a lower cost of energy to 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 kilometers long, connected Lauffen on the Neckar and Frankfurt.

Initially transmission lines were supported by porcelain pin-and-sleeve insulators similar to those used for telegraphs and telephone lines. However, these had a practical limit of 40 kV. In 1907, the invention of the disc insulator by Harold W. Buck of the Niagara

Falls Power Corporation and Edward M. Hewlett of General Electric allowed practical insulators of any length to be constructed for higher voltages.

The first large scale hydroelectric generators in the USA were installed in 1895 at Niagara Falls and provided electricity to Buffalo, New York via power transmission lines. A statue of Tesla stands at Niagara Falls today in tribute to his contributions.

### Modern Period

Voltages used for electric power transmission increased throughout the 20th century. The first electric power transmission line in North America operated at 4000V. It was constructed in 1889 between the generating station at Willamette Falls in Oregon City, Oregon, and downtown Portland, Oregon, a distance of around 13 miles. By 1914 fifty-five transmission systems operating at more than 70,000 V were in service, and the highest voltage then used was 150,000 volts. The first three-phase alternating current power transmission at 110 kV took place in 1907 between Croton and Grand Rapids, Michigan. Voltages of 100 kV and more where not established technology until around 5 years later, with for example the first 110 kV line in Europe between Lauchhammer and Riesa, Germany in 1912.

In the early 1920s the Pit River – Cottonwood – Vaca-Dixon line was built for 220 kV transporting power from hydroelectric plants in the Sierra Nevada to the San Francisco Bay Area, at the same time the Big Creek - Los Angeles lines where upgraded to the same voltage. Both of those systems entered commercial service in 1923. On April 17, 1929 the first 220 kV line in Germany was completed, running from Brauweiler near Cologne, over Kelsterbach near Frankfurt, Rheinau near Mannheim, Ludwigsburg–Hoheneck near Austria. This line comprises the North-South interconnect, at the time one of the world's largest power systems. The masts of this line were designed for eventual upgrade to 380 kV. However the first transmission at 380 kV in Germany was on October 5, 1957 between the substations in Rommerskirchen and Ludwigsburg–Hoheneck.

The world's first 380 kV power line was built in Sweden, the 952 km Harsprånget - Hallsberg line in 1952. In 1965, the first extra-high-voltage transmission at 735 kV took place on a Hydro-Québec transmission line. In 1982 the first transmission at 1200 kV was in the Soviet Union.

The rapid industrialization in the 20th century made electrical transmission lines and grids a critical part of the economic 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 load through long-distance transmission.

Small municipal electrical utilities did not necessarily desire to reduce the cost of each unit of electricity sold; to some extent, especially during the period 1880–1890, electrical lighting was considered a luxury product and electric power was not substituted for steam power. Engineers such as Samuel Insull in the United States and Sebastian Z. De Ferranti in the United Kingdom were instrumental in overcoming technical, economic, regulatory and political difficulties in development of long-distance electric power transmission. By introduction of electric power transmission networks, in the city of London the cost of a kilowatt-hour was reduced to one-third in a ten-year period.

In 1926 electrical networks in the United Kingdom began to be interconnected in the National Grid, initially operating at 132,000 volts.

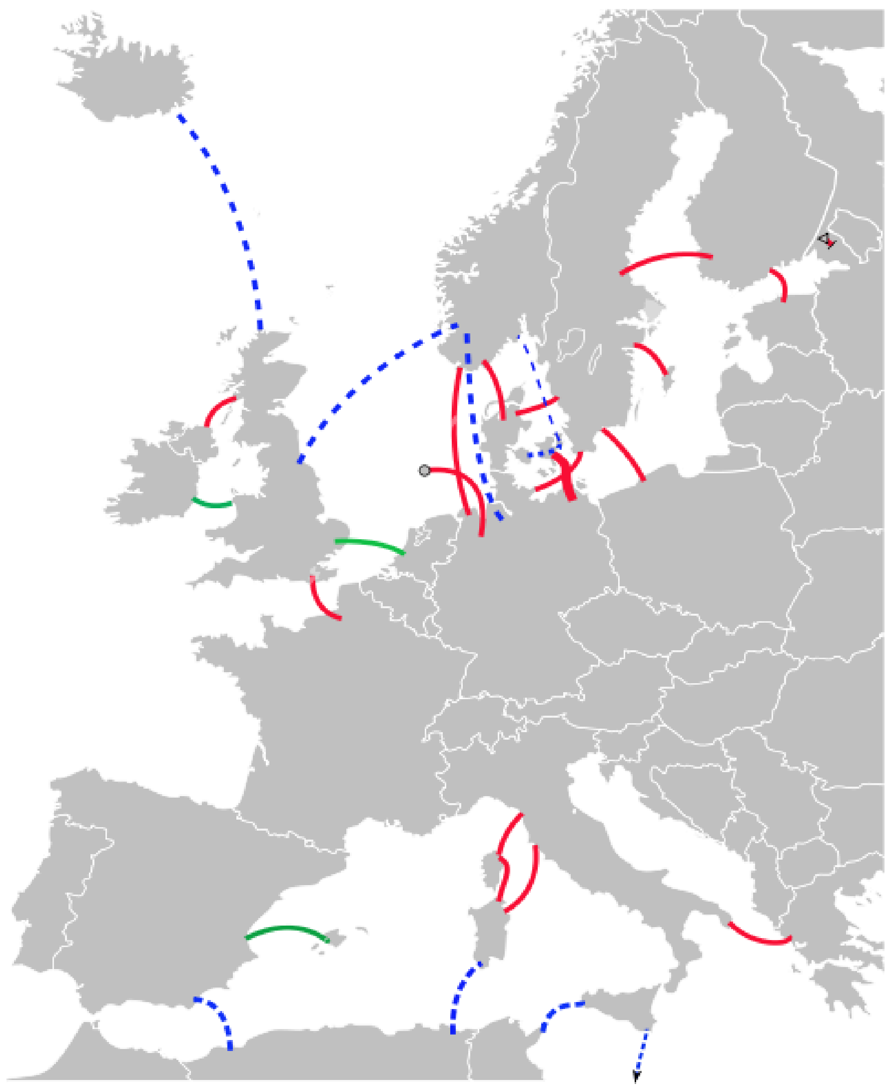
# Chapter 3

# High-Voltage Direct Current

Long distance HVDC lines carrying hydroelectricity from Canada's Nelson river to this station where it is converted to AC for use in Winnipeg's local grid

A **high-voltage, direct current** (**HVDC**) electric power transmission system uses direct current for the bulk transmission of electrical power, in contrast with the more common alternating current systems. For long-distance transmission, HVDC systems may be less expensive and suffer lower electrical losses. For shorter distances, the higher cost of DC conversion equipment compared to an AC system may be warranted where other benefits of direct current links are useful.

The modern form of HVDC transmission uses technology developed extensively in the 1930s in Sweden at ASEA. Early commercial installations included one in the Soviet Union in 1951 between Moscow and Kashira, and a 10-20 MW system between Gotland and mainland Sweden in 1954. The longest HVDC link in the world is currently the Xiangjiaba-Shanghai 2,071 km (1,287 mi) 6400 MW link connecting the Xiangjiaba Dam to Shanghai, in the People's Republic of China. In 2012, the longest HVDC link will be the Rio Madeira link connecting the Amazonas to the São Paulo area and the length of the DC line is over 2,500 km (1,600 mi).



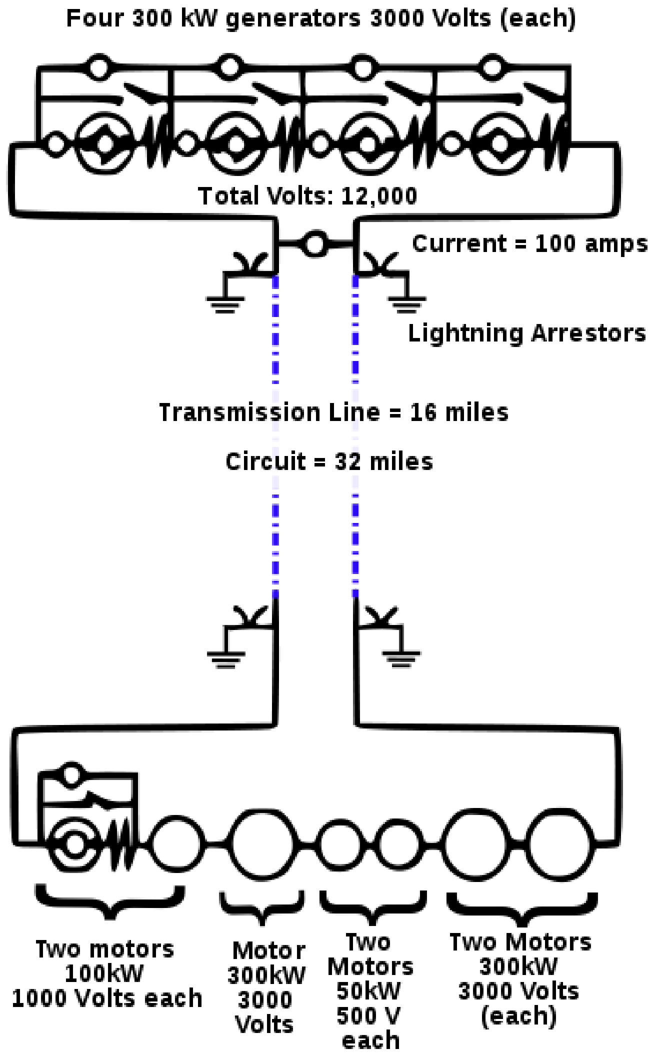
Existing links
Under construction
Proposed
Many of these transfer power from renewable sources such as hydro and wind.

### *High voltage transmission*

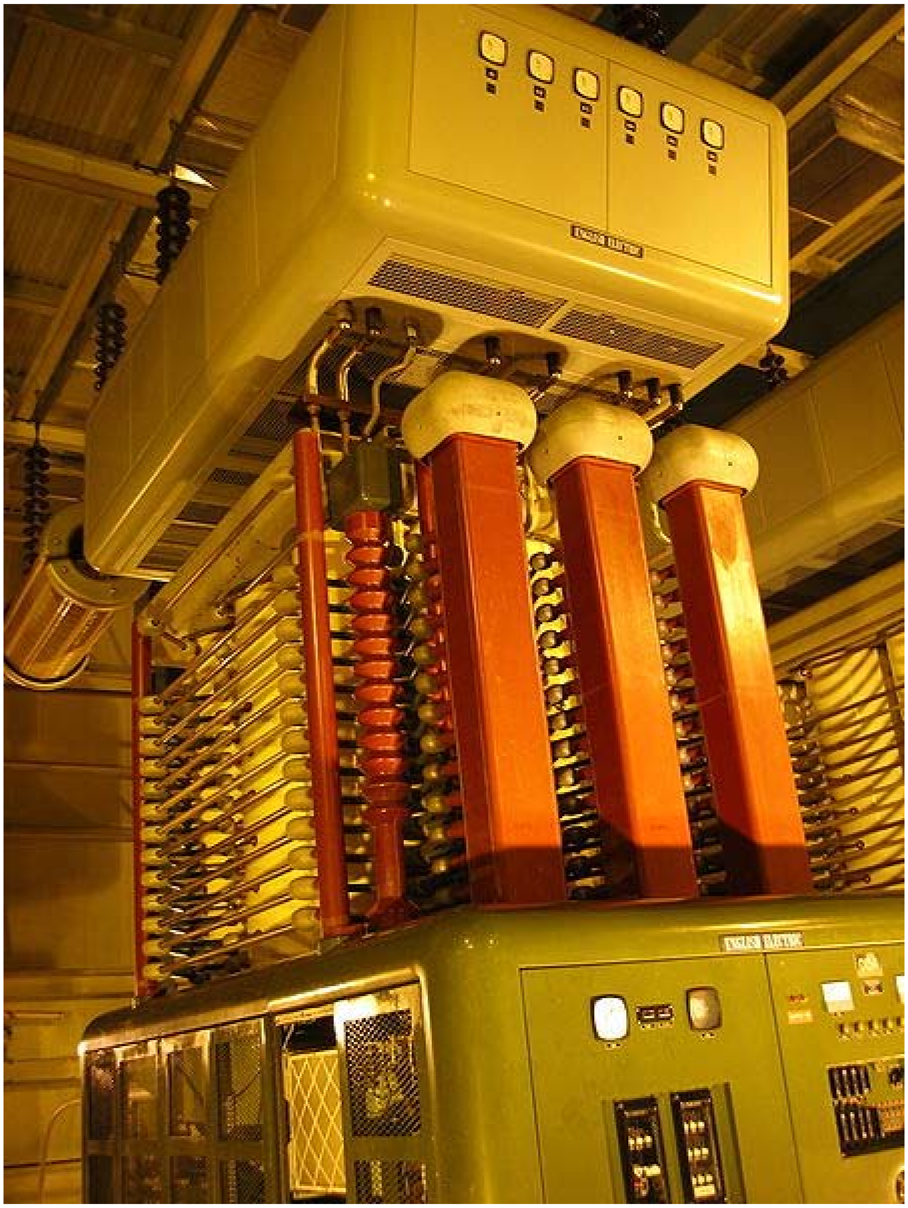
High voltage is used for electric power transmission to reduce the energy lost in the resistance of the wires. For a given quantity of power transmitted, higher voltage reduces the transmission power loss. The power lost as heat in the wires is proportional to the square of the current. So if a given power is transmitted at higher voltage and lower current, power loss in the wires is reduced. Power loss can also be reduced by reducing resistance, for example by increasing the diameter of the conductor, but larger conductors are heavier and more expensive.

High voltages cannot easily be used for lighting and motors, and so transmission-level voltages must be reduced to values compatible with end-use equipment. Transformers are used to change the voltage level in alternating current (AC) transmission circuits. The competition between the direct current (DC) of Thomas Edison and the AC of Nikola Tesla and George Westinghouse was known as the War of Currents, with AC becoming dominant. Practical manipulation of DC voltages became possible with the development of high power electronic devices such as mercury arc valves and, more recently, semiconductor devices such as thyristors, insulated-gate bipolar transistors (IGBTs), high power MOSFETs and gate turn-off thyristors (GTOs).

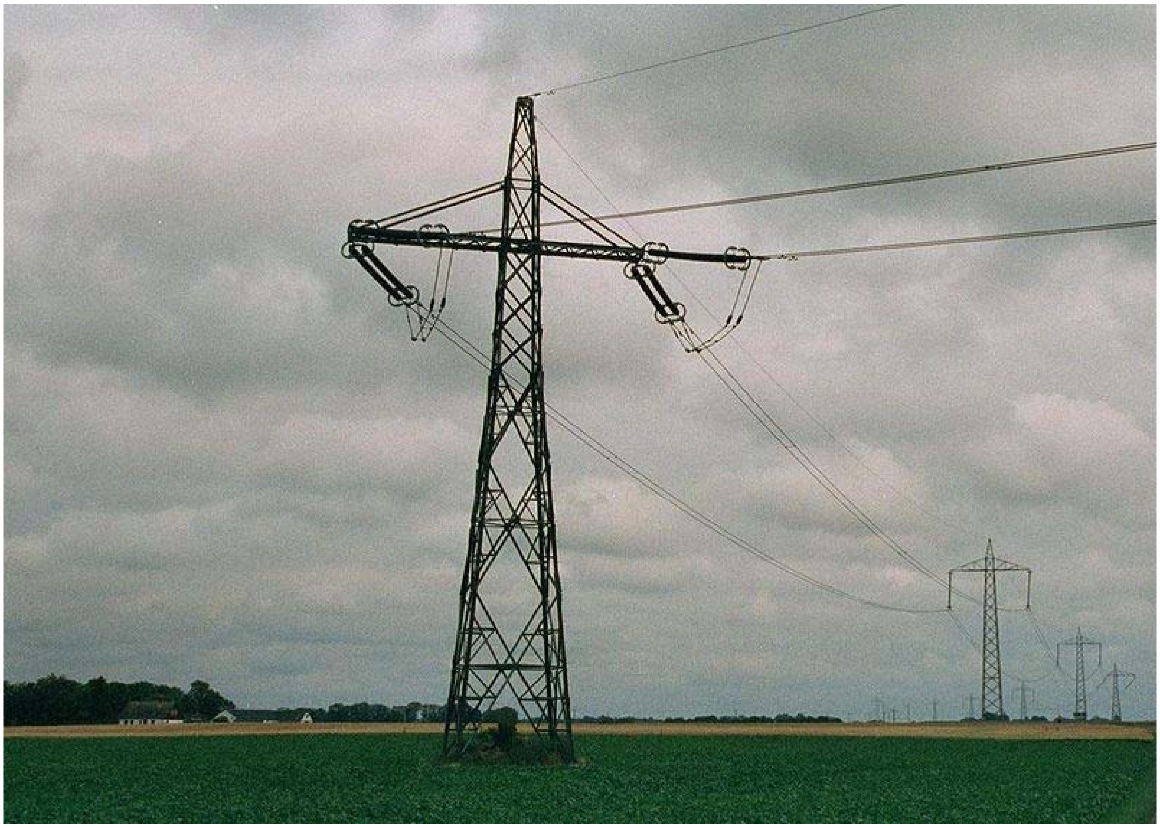
### *History of HVDC transmission*




Schematic diagram of a Thury HVDC transmission system



HVDC in 1971: this 150 kV mercury arc valve converted AC hydropower voltage for transmission to distant cities from Manitoba Hydro generators.



Bipolar system pylons of the Baltic-Cable-HVDC in Sweden

The first long-distance transmission of electric power was demonstrated using direct current in 1882 at the Miesbach-Munich Power Transmission, but only 2.5 kW was transmitted. An early method of high-voltage DC transmission was developed by the Swiss engineer René Thury and his method was put into practice by 1889 in Italy by the *Acquedotto De Ferrari-Galliera* company. This system used series-connected motor-generator sets to increase voltage. Each set was insulated from ground and driven by insulated shafts from a prime mover. The line was operated in constant current mode, with up to 5,000 volts on each machine, some machines having double commutators to reduce the voltage on each commutator. This system transmitted 630 kW at 14 kV DC over a distance of 120 km. The Moutiers-Lyon system transmitted 8,600 kW of hydroelectric power a distance of 124 miles, including 6 miles of underground cable. The system used eight series-connected generators with dual commutators for a total voltage of 150,000 volts between the poles, and ran from about 1906 until 1936. Fifteen Thury systems were in operation by 1913  Other Thury systems operating at up to 100 kV DC operated up to the 1930s, but the rotating machinery required high maintenance and had high energy loss. Various other electromechanical devices were tested during the first half of the 20th century with little commercial success.

One conversion technique attempted for conversion of direct current from a high transmission voltage to lower utilization voltage was to charge series-connected batteries, then connect the batteries in parallel to serve distribution loads. While at least two commercial installations were tried around the turn of the 20th century, the technique was not generally useful owing to the limited capacity of batteries, difficulties in switching between series and parallel connections, and the inherent energy inefficiency of a battery charge/discharge cycle.

The grid controlled mercury arc valve became available for power transmission during the period 1920 to 1940. Starting in 1932, General Electric tested mercury-vapor valves and a 12 kV DC transmission line, which also served to convert 40 Hz generation to serve 60 Hz loads, at Mechanicville, New York. In 1941, a 60 MW, +/-200 kV, 115 km buried cable link was designed for the city of Berlin using mercury arc valves (Elbe-Project), but owing to the collapse of the German government in 1945 the project was never completed. The nominal justification for the project was that, during wartime, a buried cable would be less conspicuous as a bombing target. The equipment was moved to the Soviet Union and was put into service there.

Introduction of the fully static mercury arc valve to commercial service in 1954 marked the beginning of the modern era of HVDC transmission. A HVDC-connection was constructed by ASEA between the mainland of Sweden and the island Gotland. Mercury arc valves were common in systems designed up to 1975, but since then, HVDC systems use only solid-state devices. From 1975 to 2000, line-commutated converters (LCC) using thyristor valves were relied on. According to senior engineer Dr Vijay Sood, the next 25 years may well be dominated by force commutated converters, beginning with capacitor commutated converters (CCC) followed by self commutating converters which have largely supplanted LCC use. Since use of semiconductor commutators, hundreds of HVDC sea-cables have been laid and worked with high reliability, usually better than 96% of the time.

## *Advantages of HVDC over AC transmission*

The advantage of HVDC is the ability to transmit large amounts of power over long distances with lower capital costs and with lower losses than AC. Depending on voltage level and construction details, losses are quoted as about 3% per 1,000 km. High-voltage direct current transmission allows efficient use of energy sources remote from load centers.

In a number of applications HVDC is more effective than AC transmission. Examples include:

- Undersea cables, where high capacitance causes additional AC losses. (e.g., 250 km Baltic Cable between Sweden and Germany, the 600 km NorNed cable between Norway and the Netherlands, and 290 km Basslink between the Australian mainland and Tasmania)
- Endpoint-to-endpoint long-haul bulk power transmission without intermediate 'taps', for example, in remote areas
- Increasing the capacity of an existing power grid in situations where additional wires are difficult or expensive to install

- Power transmission and stabilization between unsynchronised AC distribution systems
- Connecting a remote generating plant to the distribution grid, for example Nelson River Bipole
- Stabilizing a predominantly AC power-grid, without increasing prospective short circuit current
- Reducing line cost. HVDC needs fewer conductors as there is no need to support multiple phases. Also, thinner conductors can be used since HVDC does not suffer from the skin effect
- Facilitate power transmission between different countries that use AC at differing voltages and/or frequencies
- Synchronize AC produced by renewable energy sources

Long undersea / underground high voltage cables have a high electrical capacitance, since the conductors are surrounded by a relatively thin layer of insulation and a metal sheath while the extensive length of the cable multiplies the area between the conductors. The geometry is that of a long co-axial capacitor. Where alternating current is used for cable transmission, this capacitance appears in parallel with load. Additional current must flow in the cable to charge the cable capacitance, which generates additional losses in the conductors of the cable. Additionally, there is a dielectric loss component in the material of the cable insulation, which consumes power.

When, however, direct current is used, the cable capacitance is charged only when the cable is first energized or when the voltage is changed; there is no steady-state additional current required. For a long AC undersea cable, the entire current-carrying capacity of the conductor could be used to supply the charging current alone. The cable capacitance issue limits the length and power carrying capacity of AC cables. DC cables have no such limitation, and are essentially bound by only Ohm's Law. Although some DC leakage current continues to flow through the dielectric insulators, this is very small compared to the cable rating and much less than with AC transmission cables.

HVDC can carry more power per conductor because, for a given power rating, the constant voltage in a DC line is lower than the peak voltage in an AC line. The power delivered is defined by the root mean square (RMS) of an AC voltage, but RMS is only about 71% of the peak voltage. The peak voltage of AC determines the actual insulation thickness and conductor spacing. Because DC operates at a constant maximum voltage, this allows existing transmission line corridors with equally sized conductors and insulation to carry more power into an area of high power consumption than AC, which can lower costs.

Because HVDC allows power transmission between unsynchronized AC distribution systems, it can help increase system stability, by preventing cascading failures from propagating from one part of a wider power transmission grid to another. Changes in load that would cause portions of an AC network to become unsynchronized and separate would not similarly affect a DC link, and the power flow through the DC link would tend to stabilize the AC network. The magnitude and direction of power flow through a DC link can be directly commanded, and changed as needed to support the AC networks at either end of the DC link. This has caused many power system operators to contemplate wider use of HVDC technology for its stability benefits alone.

### *Disadvantages*

The disadvantages of HVDC are in conversion, switching, control, availability and maintenance.

HVDC is less reliable and has lower availability than AC systems, mainly due to the extra conversion equipment. Single pole systems have availability of about 98.5%, with about a third of the downtime unscheduled due to faults. Fault redundant bipole systems provide high availability for 50% of the link capacity, but availability of the full capacity is about 97% to 98%.

The required static inverters are expensive and have limited overload capacity. At smaller transmission distances the losses in the static inverters may be bigger than in an AC transmission line. The cost of the inverters may not be offset by reductions in line construction cost and lower line loss. With two exceptions, all former mercury rectifiers worldwide have been dismantled or replaced by thyristor units. Pole 1 of the HVDC scheme between the North and South Islands of New Zealand still uses mercury arc rectifiers, as does Pole 1 of the Vancouver Island link in Canada. Both are currently being replaced - in New Zealand by a new thyristor pole and in Canada by a three-phase AC link.

In contrast to AC systems, realizing multiterminal systems is complex, as is expanding existing schemes to multiterminal systems. Controlling power flow in a multiterminal DC system requires good communication between all the terminals; power flow must be actively regulated by the inverter control system instead of the inherent impedance and phase angle properties of the transmission line. Multi-terminal lines are rare. One is in operation at the Hydro Québec - New England transmission from Radisson to Sandy Pond. Another example is the Sardinia-mainland Italy link which was modified in 1989 to also provide power to the island of Corsica.

High voltage DC circuit breakers are difficult to build because some mechanism must be included in the circuit breaker to force current to zero, otherwise arcing and contact wear would be too great to allow reliable switching.

Operating a HVDC scheme requires many spare parts to be kept, often exclusively for one system as HVDC systems are less standardized than AC systems and technology changes faster.

## *Costs of high voltage DC transmission*

Normally manufacturers such as Alstom, Siemens and ABB do not state specific cost information of a particular project since this is a commercial matter between the manufacturer and the client.

Costs vary widely depending on the specifics of the project such as power rating, circuit length, overhead vs. underwater route, land costs, and AC network improvements required at either terminal. A detailed evaluation of DC vs. AC cost may be required where there is no clear technical advantage to DC alone and only economics drives the selection.

However some practitioners have given out some information that can be reasonably well relied upon:

For an 8 GW 40 km link laid under the English Channel, the following are approximate primary equipment costs for a 2000 MW 500 kV bipolar conventional HVDC link (exclude way-leaving, on-shore reinforcement works, consenting, engineering, insurance, etc.)

- Converter stations ~£110M
- Subsea cable + installation ~£1M/km

So for an 8 GW capacity between England and France in four links, little is left over from £750M for the installed works. Add another £200–300M for the other works depending on additional onshore works required.

An April, 2010 announcement for a 2,000 MW line, 64 km, between Spain and France, is 700 million euros; this includes the cost of a tunnel through the Pyrenees.

### *Rectifying and inverting*

#### Components

Two of three thyristor valve stacks used for long distance transmission of power from Manitoba Hydro dams

Most of the HVDC systems in operation today are based on *Line-Commutated Converters*. Early static systems used mercury arc rectifiers, which were unreliable. Two HVDC systems using mercury arc rectifiers are still in service (As of 2008). The thyristor valve was first used in HVDC systems in the 1960s. The thyristor is a solid-state semiconductor device similar to the diode, but with an extra control terminal that is used to switch the device on at a particular instant during the AC cycle. The insulated-gate bipolar transistor (IGBT) is now also used, forming a *Voltage Sourced Converter*, and offers simpler control, reduced harmonics and reduced valve cost.

Because the voltages in HVDC systems, up to 800 kV in some cases, exceed the breakdown voltages of the semiconductor devices, HVDC converters are built using large numbers of semiconductors in series.

The low-voltage control circuits used to switch the thyristors on and off need to be isolated from the high voltages present on the transmission lines. This is usually done optically. In a hybrid control system, the low-voltage control electronics sends light pulses along optical fibres to the *high-side* control electronics. Another system, called *direct light triggering*, dispenses with the high-side electronics, instead using light pulses from the control electronics to switch light-triggered thyristors (LTTs).

A complete switching element is commonly referred to as a *valve*, irrespective of its construction.

## Rectifying and inverting systems

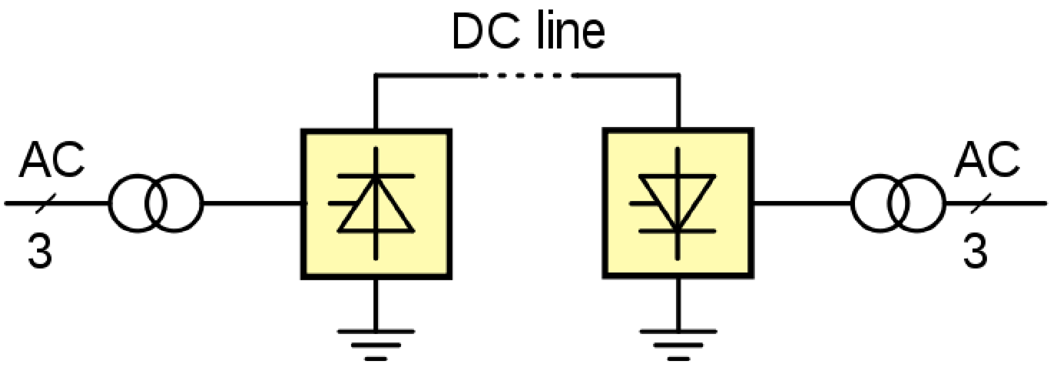
Rectification and inversion use essentially the same machinery. Many substations (*Converter Stations*) are set up in such a way that they can act as both rectifiers and inverters. At the AC end a set of transformers, often three physically separated single-phase transformers, isolate the station from the AC supply, to provide a local earth, and to ensure the correct eventual DC voltage. The output of these transformers is then connected to a bridge rectifier formed by a number of valves. The basic configuration uses six valves, connecting each of the three phases to each of the two DC rails. However, with a phase change only every sixty degrees, considerable harmonics remain on the DC rails.

An enhancement of this configuration uses 12 valves (often known as a **twelve-pulse system**). The AC is split into two separate three phase supplies before transformation. One of the sets of supplies is then configured to have a star (wye) secondary, the other a delta secondary, establishing a thirty degree phase difference between the two sets of three phases. With twelve valves connecting each of the two sets of three phases to the two DC rails, there is a phase change every 30 degrees, and harmonics are considerably reduced.

In addition to the conversion transformers and valve-sets, various passive resistive and reactive components help filter harmonics out of the DC rails.

## *Configurations*

### Monopole and earth return




Block diagram of a monopole system with earth return

In a common configuration, called monopole, one of the terminals of the rectifier is connected to earth ground. The other terminal, at a potential high above or below ground, is connected to a transmission line. The earthed terminal may be connected to the corresponding connection at the inverting station by means of a second conductor.

If no metallic conductor is installed, current flows in the earth between the earth electrodes at the two stations. Therefore it is a type of single wire earth return. The issues surrounding earth-return current include:

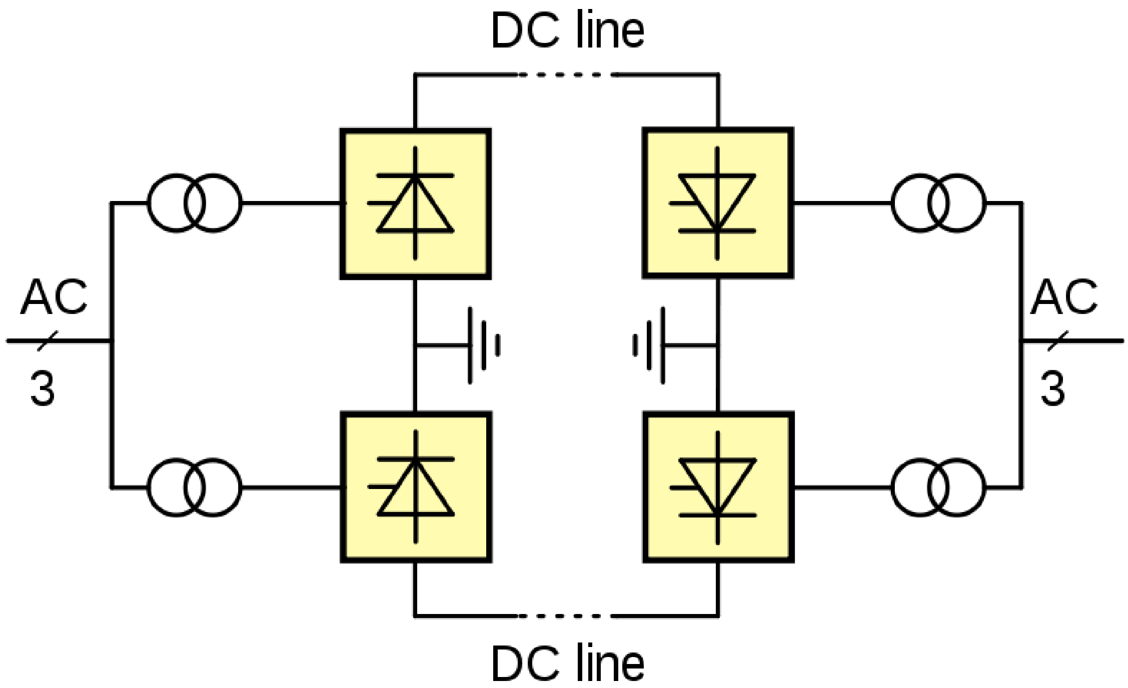
- Electrochemical corrosion of long buried metal objects such as pipelines
- Underwater earth-return electrodes in seawater may produce chlorine or otherwise affect water chemistry.
- An unbalanced current path may result in a net magnetic field, which can affect magnetic navigational compasses for ships passing over an underwater cable.

These effects can be eliminated with installation of a metallic return conductor between the two ends of the monopolar transmission line. Since one terminal of the converters is connected to earth, the return conductor need not be insulated for the full transmission voltage which makes it less costly than the high-voltage conductor. Use of a metallic return conductor is decided based on economic, technical and environmental factors.

Modern monopolar systems for pure overhead lines carry typically 1,500 MW. If underground or underwater cables are used, the typical value is 600 MW.

Most monopolar systems are designed for future bipolar expansion. Transmission line towers may be designed to carry two conductors, even if only one is used initially for the monopole transmission system. The second conductor is either unused, used as electrode line or connected in parallel with the other (as in case of Baltic-Cable).

**Bipolar**



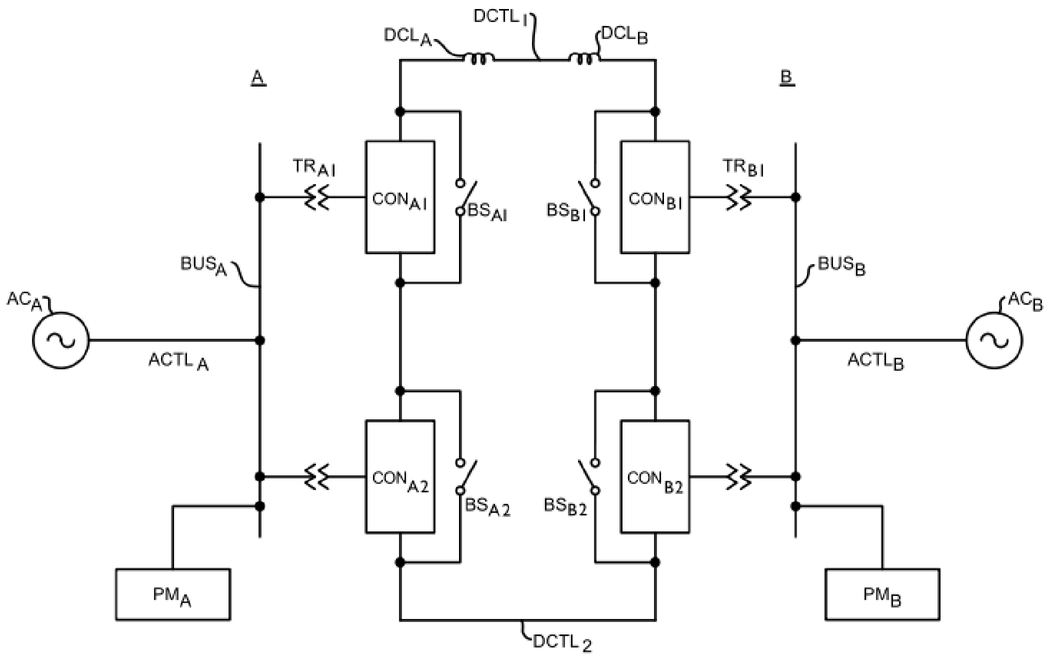

Block diagram of a bipolar system that also has an earth return

In bipolar transmission a pair of conductors is used, each at a high potential with respect to ground, in opposite polarity. Since these conductors must be insulated for the full voltage, transmission line cost is higher than a monopole with a return conductor. However, there are a number of advantages to bipolar transmission which can make it the attractive option.

- Under normal load, negligible earth-current flows, as in the case of monopolar transmission with a metallic earth-return. This reduces earth return loss and environmental effects.
- When a fault develops in a line, with earth return electrodes installed at each end of the line, approximately half the rated power can continue to flow using the earth as a return path, operating in monopolar mode.
- Since for a given total power rating each conductor of a bipolar line carries only half the current of monopolar lines, the cost of the second conductor is reduced compared to a monopolar line of the same rating.
- In very adverse terrain, the second conductor may be carried on an independent set of transmission towers, so that some power may continue to be transmitted even if one line is damaged.

A bipolar system may also be installed with a metallic earth return conductor.

Bipolar systems may carry as much as 3,200 MW at voltages of +/-600 kV. Submarine cable installations initially commissioned as a monopole may be upgraded with additional cables and operated as a bipole.




A block diagram of a bipolar HVDC transmission system, between two stations designated A and B. AC - represents an alternating current network CON - represents a converter valve, either rectifier or inverter, TR represents a power transformer, DCTL is the direct-current transmission line conductor, DCL is a direct-current filter inductor, BP represents a bypass switch, and PM represent power factor correction and harmonic filter networks required at both ends of the link. The DC transmission line may be very short in a back-to-back link, or extend hundreds of miles (km) overhead, underground or underwater. One conductor of the DC line may be replaced by connections to earth ground.

A bipolar scheme can be implemented so that the polarity of one or both poles can be changed. This allows the operation as two parallel monopoles. If one conductor fails, transmission can still continue at reduced capacity. Losses may increase if ground electrodes and lines are not designed for the extra current in this mode. To reduce losses in this case, intermediate switching stations may be installed, at which line segments can be switched off or parallelized. This was done at Inga–Shaba HVDC.

## Back to back

A **back-to-back station** (or B2B for short) is a plant in which both static inverters and rectifiers are in the same area, usually in the same building. The length of the direct current line is kept as short as possible. HVDC back-to-back stations are used for

- coupling of electricity mains of different frequency (as in Japan; and the GCC interconnection between UAE [50 Hz] and Saudi Arabia [60 Hz] under construction in ±2009-2011)
- coupling two networks of the same nominal frequency but no fixed phase relationship (as until 1995/96 in Etzenricht, Dürnrohr, Vienna, and the Vyborg HVDC scheme).
- different frequency and phase number (for example, as a replacement for traction current converter plants)

The DC voltage in the intermediate circuit can be selected freely at HVDC back-to-back stations because of the short conductor length. The DC voltage is as low as possible, in order to build a small valve hall and to avoid series connections of valves. For this reason at HVDC back-to-back stations valves with the highest available current rating are used.

## Systems with transmission lines

The most common configuration of an HVDC link is two inverter/rectifier stations connected by an overhead power line. This is also a configuration commonly used in connecting unsynchronised grids, in long-haul power transmission, and in undersea cables.

Multi-terminal HVDC links, connecting more than two points, are rare. The configuration of multiple terminals can be series, parallel, or hybrid (a mixture of series and parallel). Parallel configuration tends to be used for large capacity stations, and series for lower capacity stations. An example is the 2,000 MW Quebec - New England Transmission system opened in 1992, which is currently the largest multi-terminal HVDC system in the world.

## Tripole: current-modulating control

A scheme patented in 2004 (Current modulation of direct current transmission lines) is intended for conversion of existing AC transmission lines to HVDC. Two of the three circuit conductors are operated as a bipole. The third conductor is used as a parallel monopole, equipped with reversing valves (or parallel valves connected in reverse polarity). The parallel monopole periodically relieves current from one pole or the other, switching polarity over a span of several minutes. The bipole conductors would be loaded to either 1.37 or 0.37 of their thermal limit, with the parallel monopole always carrying +/- 1 times its thermal limit current. The combined RMS heating effect is as if each of the conductors is always carrying 1.0 of its rated current. This allows heavier currents to be carried by the bipole conductors, and full use of the installed third conductor for energy transmission. High currents can be circulated through the line conductors even when load demand is low, for removal of ice.

As of 2005, no tri-pole conversions are in operation, although a transmission line in India has been converted to bipole HVDC.

Cross-Skagerrak consists of 3 poles, from which 2 are switched in parallel and the third uses an opposite polarity with a higher transmission voltage. A similar arrangement is HVDC Inter-Island, but it consists of 2 parallel-switched inverters feeding in the same pole and a third one with opposite polarity and higher operation voltage.

## *Corona discharge*

Corona discharge is the creation of ions in a fluid (such as air) by the presence of a strong electric field. Electrons are torn from neutral air, and either the positive ions or the electrons are attracted to the conductor, while the charged particles drift. This effect can cause considerable power loss, create audible and radio-frequency interference, generate toxic compounds such as oxides of nitrogen and ozone, and bring forth arcing.

Both AC and DC transmission lines can generate coronas, in the former case in the form of oscillating particles, in the latter a constant wind. Due to the space charge formed around the conductors, an HVDC system may have about half the loss per unit length of a high voltage AC system carrying the same amount of power. With monopolar transmission the choice of polarity of the energized conductor leads to a degree of control over the corona discharge. In particular, the polarity of the ions emitted can be controlled, which may have an environmental impact on particulate condensation. (particles of different polarities have a different mean-free path.) Negative coronas generate considerably more ozone than positive coronas, and generate it further *downwind* of the power line, creating the potential for health effects. The use of a *positive* voltage will reduce the ozone impacts of monopole HVDC power lines.

## *Applications*

### Overview

The controllability of current-flow through HVDC rectifiers and inverters, their application in connecting unsynchronized networks, and their applications in efficient submarine cables mean that HVDC cables are often used at national boundaries for the exchange of power (in North America, HVDC connections divide much of Canada and the United States into several electrical regions that cross national borders, although the purpose of these connections is still to connect unsynchronized AC grids to each other). Offshore windfarms also require undersea cables, and their turbines are unsynchronized. In very long-distance connections between just two points, for example around the remote communities of Siberia, Canada, and the Scandinavian North, the decreased line-costs of HVDC also makes it the usual choice.

### AC network interconnections

AC transmission lines can interconnect only synchronized AC networks that oscillate at the same frequency and in phase. Many areas that wish to share power have unsynchronized networks. The power grids of the UK, Northern Europe and continental Europe are not united into a single synchronized network. Japan has 50 Hz and 60 Hz networks. Continental North America, while operating at 60 Hz throughout, is divided into regions which are unsynchronised: East, West, Texas, Quebec, and Alaska. Brazil and Paraguay, which share the enormous Itaipu Dam hydroelectric plant, operate on 60 Hz and 50 Hz respectively. However, HVDC systems make it possible to interconnect unsynchronized AC networks, and also add the possibility of controlling AC voltage and reactive power flow.

A generator connected to a long AC transmission line may become unstable and fall out of synchronization with a distant AC power system. An HVDC transmission link may make it economically feasible to use remote generation sites. Wind farms located off-shore may use HVDC systems to collect power from multiple unsynchronized generators for transmission to the shore by an underwater cable.

In general, however, an HVDC power line will interconnect two AC regions of the power-distribution grid. Machinery to convert between AC and DC power adds a considerable cost in power transmission. The conversion from AC to DC is known as rectification, and from DC to AC as inversion. Above a certain break-even distance (about 50 km for submarine cables, and perhaps 600–800 km for overhead cables), the lower cost of the HVDC electrical conductors outweighs the cost of the electronics.

The conversion electronics also present an opportunity to effectively manage the power grid by means of controlling the magnitude and direction of power flow. An additional advantage of the existence of HVDC links, therefore, is potential increased stability in the transmission grid.

### Renewable electricity superhighways

Two HVDC lines cross near Wing, North Dakota.

A number of studies have highlighted the potential benefits of very wide area super grids based on HVDC since they can mitigate the effects of intermittency by averaging and smoothing the outputs of large numbers of geographically dispersed wind farms or solar farms. Czisch's study concludes that a grid covering the fringes of Europe could bring 100% renewable power (70% wind, 30% biomass) at close to today's prices. There has been debate over the technical feasibility of this proposal and the political risks involved in energy transmission across a large number of international borders.

The construction of such green power superhighways is advocated in a white paper that was released by the American Wind Energy Association and the Solar Energy Industries Association

In January 2009, the European Commission proposed €300 million to subsidize the development of HVDC links between Ireland, Britain, the Netherlands, Germany, Denmark, and Sweden, as part of a wider €1.2 billion package supporting links to offshore wind farms and cross-border interconnectors throughout Europe. Meanwhile the recently founded Union of the Mediterranean has embraced a Mediterranean Solar Plan to import large amounts of concentrating solar power into Europe from North Africa and the Middle East.

## Voltage Sourced Converters (VSC)

The development of insulated gate bipolar transistors (IGBT) and gate turn-off thyristors (GTO) has made smaller HVDC systems economical. These may be installed in existing AC grids for their role in stabilizing power flow without the additional short-circuit current that would be produced by an additional AC transmission line. The manufacturer ABB calls this concept "HVDC Light", while Siemens calls a similar concept "HVDC PLUS" (Power Link Universal System). They have extended the use of HVDC down to blocks as small as a few tens of megawatts and lines as short as a few score kilometres of overhead line. There are several different variants of Voltage-Sourced Converter (VSC) technology: most "HVDC Light" installations use pulse width modulation but the most recent installations, along with "HVDC PLUS", are based on multilevel switching.

## Chapter 4

# Overhead Power Line

Transmission lines in Lund, Sweden

Overhead lines in Japan

High and medium voltage power lines in Łomża, Poland

An **overhead power line** is an electric power transmission line suspended by towers or utility poles. Since most of the insulation is provided by air, overhead power lines are generally the lowest-cost method of transmission for large quantities of electric energy. Towers for support of the lines are made of wood (as-grown or laminated), steel (either lattice structures or tubular poles), concrete, aluminium, and occasionally reinforced plastics. The bare wire conductors on the line are generally made of aluminium (either plain or reinforced with steel or sometimes composite materials), though some copper wires are used in medium-voltage distribution and low-voltage connections to customer premises. A major goal of overhead power line design is to maintain adequate clearance between energized conductors and the ground so as to prevent dangerous contact with the line.

The invention of the strain insulator was a critical factor in allowing higher voltages to be used. At the end of the 19th century, the limited electrical strength of telegraph-style pin insulators limited the voltage to no more than 69,000 volts. Today overhead lines are routinely operated at voltages exceeding 765,000 volts between conductors, with even higher voltages possible in some cases.

Overhead power transmission lines are classified in the electrical power industry by the range of voltages:

- Low voltage – less than 1000 volts, used for connection between a residential or small commercial customer and the utility.
- Medium Voltage (Distribution) – between 1000 volts (1 kV) and to about 33 kV, used for distribution in urban and rural areas.
- High Voltage (subtransmission less than 100 kV; subtransmission or transmission at voltage such as 115 kV and 138 kV), used for sub-transmission and transmission of bulk quantities of electric power and connection to very large consumers.
- Extra High Voltage (transmission) – over 230 kV, up to about 800 kV, used for long distance, very high power transmission.
- Ultra High Voltage – higher than 800 kV.

## *Structures*

Structures for overhead lines take a variety of shapes depending on the type of line. Structures may be as simple as wood poles directly set in the earth, carrying one or more cross-arm beams to support conductors, or "armless" construction with conductors supported on insulators attached to the side of the pole. Tubular steel poles are typically used in urban areas. High-voltage lines are often carried on lattice-type steel towers or pylons. For remote areas, aluminium towers may be placed by helicopters. Concrete poles have also been used. Poles made of reinforced plastics are also available, but their high cost restricts application.

Each structure must be designed for the loads imposed on it by the conductors. A large transmission line project may have several types of towers, with "tangent" ("suspension" or "line" towers, UK) towers intended for most positions and more heavily constructed towers used for turning the line through an angle, dead-ending (terminating) a line, or for important river or road crossings. Depending on the design criteria for a particular line, semi-flexible type structures may rely on the weight of the conductors to be balanced on both sides of each tower. More rigid structures may be intended to remain standing even if one or more conductors is broken. Such structures may be installed at intervals in power lines to limit the scale of cascading tower failures.

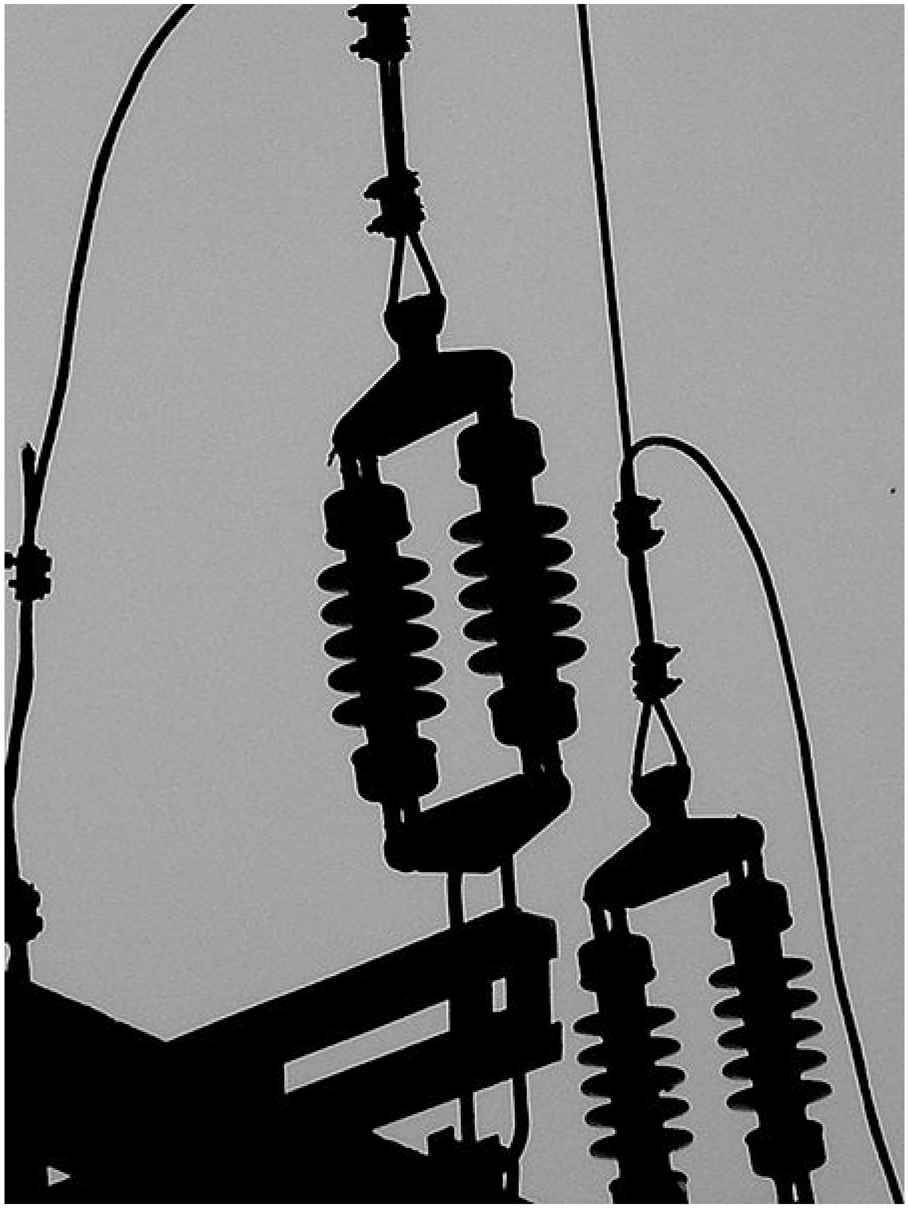
Foundations for tower structures may be large and costly, particularly if the ground conditions are poor, such as in wetlands. Each structure may be stabilized considerably by the use of guy wires to counteract some of the forces applied by the conductors.

Power lines and supporting structures can be a form of visual pollution. In some cases the lines are buried to avoid this, but this "undergrounding" is more expensive and therefore not common.

For a single wood utility pole structure, a pole is placed in the ground, then three crossarms extend from this, either staggered or all to one side. The insulators are attached to the crossarms. 1For an "H"-type wood pole structure, two poles are placed in the ground, then a crossbar is placed on top of these, extending to both sides. The insulators are attached at the ends and in the middle. Lattice tower structures have two common forms. One has a pyramidal base, then a vertical section, where three crossarms extend out, typically staggered. The strain insulators are attached to the crossarms. Another has a pyramidal base, which extends to four support points. On top of this a horizontal truss-like structure is placed. The insulators are attached to this.

### *Insulators*

Insulators must support the conductors and withstand both the normal operating voltage and surges due to switching and lightning. Insulators are broadly classified as either pin-type, which support the conductor above the structure, or suspension type, where the conductor hangs below the structure. Up to about 33 kV (69 kV in North America) both types are commonly used. At higher voltages only suspension-type insulators are common for overhead conductors. Insulators are usually made of wet-process porcelain or toughened glass, with increasing use of glass-reinforced polymer insulators. However, with rising voltage levels and changing climatic conditions, polymer insulators (silicone rubber based) are seeing increasing usage. China has already developed polymer insulators having a highest system voltage of 1100kV and India is currently developing a 1200kV (highest system voltage) line which will initially be charged with 400kV to be upgraded to a 1200kV line.



Ceramic insulators

Suspension insulators are made of multiple units, with the number of unit insulator disks increasing at higher voltages. The number of disks is chosen based on line voltage, lightning withstand requirement, altitude, and environmental factors such as fog, pollution, or salt spray. Longer insulators, with longer creepage distance for leakage current, are required in these cases. Strain insulators must be strong enough mechanically to support the full weight of the span of conductor, as well as loads due to ice accumulation, and wind.

Porcelain insulators may have a semi-conductive glaze finish, so that a small current (a few milliamperes) passes through the insulator. This warms the surface slightly and reduces the effect of fog and dirt accumulation. The semiconducting glaze also ensures a more even distribution of voltage along the length of the chain of insulator units.

Polymer insulators by nature have hydrophobic characteristics providing for improved wet performance. Also, studies have shown that the specific creepage distance required in polymer insulators is much lower than that required in porcelain or glass. Additionally, the mass of polymer insulators (espicially in higher voltages) is approximately 50% to 30% less than that of a comparative porcelain or glass string. Better pollution and wet performance is leading to the increased use of such insulators.

Insulators for very high voltages, exceeding 200 kV, may have grading rings installed at their terminals. This improves the electric field distribution around the insulator and makes it more resistant to flash-over during voltage surges.

## *Conductors*

Aluminium conductors reinforced with steel (known as ACSR) are primarily used for medium and high voltage lines and may also be used for overhead services to individual customers. Aluminium conductors are used as it has the advantage of better resistivity/weight than copper, as well as being cheaper. Some copper cable is still used, especially at lower voltages and for grounding.

While larger conductors may lose less energy due to lower electrical resistance, they are more costly than smaller conductors. An optimization rule called *Kelvin's Law* states that the optimum size of conductor for a line is found when the cost of the energy wasted in the conductor is equal to the annual interest paid on that portion of the line construction cost due to the size of the conductors. The optimization problem is made more complex due to additional factors such as varying annual load, varying cost of installation, and by the fact that only definite discrete sizes of cable are commonly made.

Since a conductor is a flexible object with uniform weight per unit length, the geometric shape of a conductor strung on towers approximates that of a catenary. The sag of the conductor (vertical distance between the highest and lowest point of the curve) varies depending on the temperature. A minimum overhead clearance must be maintained for safety. Since the temperature of the conductor increases with increasing heat produced by the current through it, it is sometimes possible to increase the power handling capacity (uprate) by changing the conductors for a type with a lower coefficient of thermal expansion or a higher allowable operating temperature.

### Bundle conductors

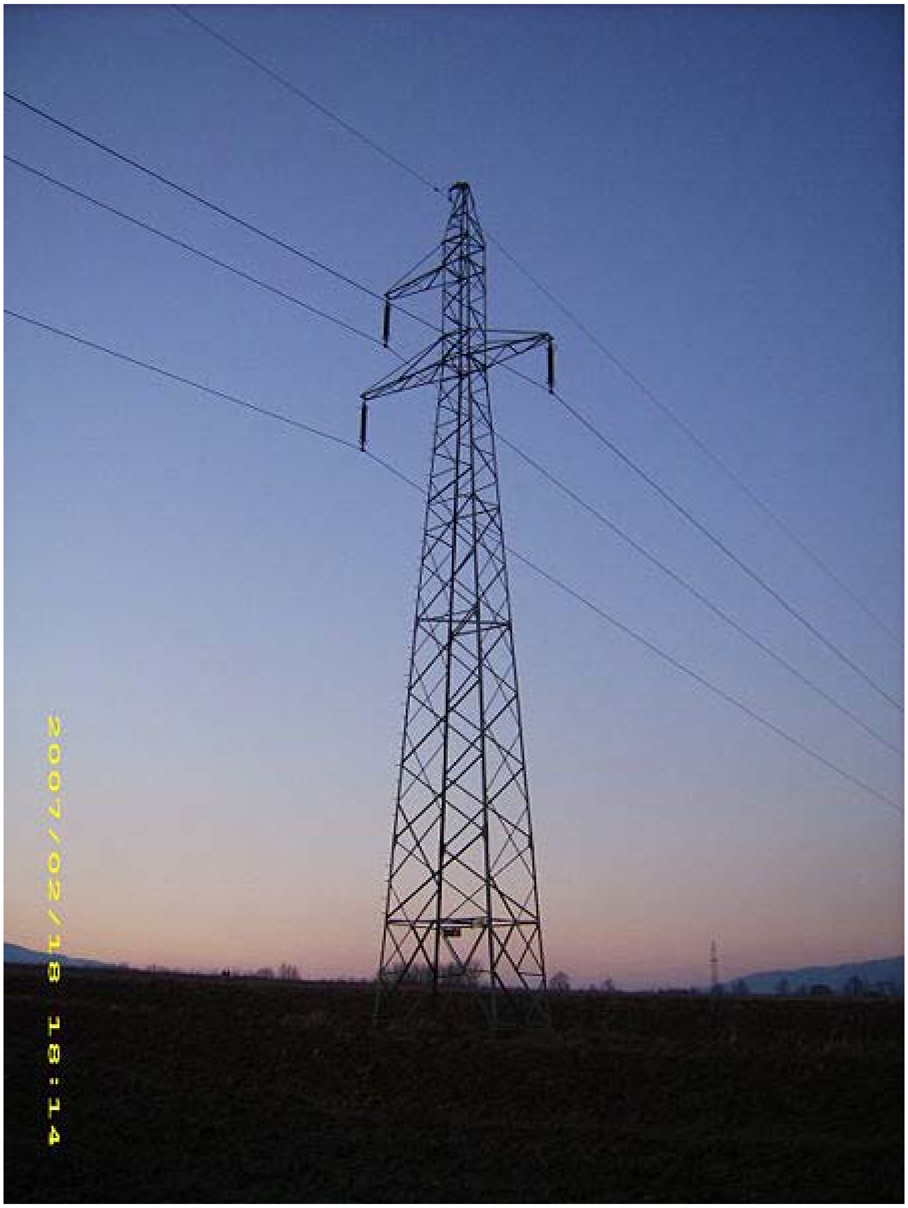
Bundle conductors are used to reduce corona losses and audible noise. Bundle conductors consist of several conductor cables connected by non-conducting spacers. For 220 kV lines, two-conductor bundles are usually used, for 380 kV lines usually three or even four. American Electric Power is building 765 kV lines using six conductors per phase in a bundle. Spacers must resist the forces due to wind, and magnetic forces during a short-circuit.

Bundle conductors are used to increase the amount of current that may be carried in a line. Due to the skin effect, ampacity of conductors is not proportional to cross section, for the larger sizes. Therefore, bundle conductors may carry more current for a given weight.

A bundle conductor results in lower reactance, compared to a single conductor. It reduces corona discharge loss at EHV (extra high voltage) and interference with communication systems. It also reduces voltage gradient in that range of voltage.

As a disadvantage, the bundle conductors have higher wind loading.

### Circuits




Single 3-phase circuit carried by electricity pylon, with ground wire

A *single-circuit transmission line* carries conductors for only one circuit. For a three-phase system, this implies that each tower supports three conductors.

Typical double-circuit line

A *double-circuit transmission line* has two circuits. For three-phase systems, each tower supports and insulates six conductors. Single phase AC-powerlines as used for traction current have four conductors for two circuits. Usually both circuits operate at the same voltage.

In HVDC systems typically two conductors are carried per line, but rarely only one pole of the system is carried on a set of towers.

In some countries like Germany most powerlines with voltages above 100 kV are implemented as double, quadruple or in rare cases even hexuple powerline as rights of way are rare. Sometimes all conductors are installed with the erection of the pylons; often some circuits are installed later. A disadvantage of double circuit transmission lines is that maintenance works can be more difficult, as either work in close proximity of high voltage or switch-off of 2 circuits is required. In case of failure, both systems can be affected.

The largest double-circuit transmission line is the Kita-Iwaki Powerline.

## Ground wires

Overhead power lines are often equipped with a ground conductor (shield wire or overhead earth wire). A ground conductor is a conductor that is usually grounded (earthed) at the top of the supporting structure to minimise the likelihood of direct lightning strikes to the phase conductors. The ground wire is also a parallel path with the earth for fault currents in earthed neutral circuits. Very high-voltage transmission lines may have two ground conductors. These are either at the outermost ends of the highest cross beam, at two V-shaped mast points, or at a separate cross arm. Older lines may use surge arrestors every few spans in place of a shield wire; this configuration is typically found in the more rural areas of the United States. By protecting the line from lightning, the design of apparatus in substations is simplified due to lower stress on insulation. Shield wires on transmission lines may include optical fibers (OPGW), used for communication and control of the power system.

Medium-voltage distribution lines may have the grounded conductor strung below the phase conductors to provide some measure of protection against tall vehicles or equipment touching the energized line, as well as to provide a neutral line in Wye wired systems.

## Insulated conductors

While overhead lines are usually bare conductors, rarely overhead insulated cables are used, usually for short distances (less than a kilometer). Insulated cables can be directly fastened to structures without insulating supports. An overhead line with bare conductors insulated by air is typically less costly than a cable with insulated conductors.

A more common approach is "covered" line wire. It is treated as bare cable, but often is safer for wildlife, as the insulation on the cables increases the likelihood of a large wing-span raptor to survive a brush with the lines, and reduces the overall danger of the lines slightly. These types of lines are often seen in the eastern United States and in heavily wooded areas, where tree-line contact is likely. The only pitfall is cost, as insulated wire is often costlier than its bare counterpart. Many utility companies implement covered line wire as jumper material where the wires are often closer to each other on the pole, such as an underground riser/Pothead, and on reclosers, cutouts and the like.

## *Low voltage*


Aerial bundled cable in Old Coulsdon, Surrey

Low voltage overhead lines may use either bare conductors carried on glass or ceramic insulators or an aerial bundled cable system. The number of conductors may be anywhere between four (three phase plus a combined earth/neutral conductor - a TN-C earthing system) up to as many as six (three phase conductors, separate neutral and earth plus street lighting supplied by a common switch).

### *Train power*

Overhead lines or overhead wires are used to transmit electrical energy to trams, trolleybuses or trains. Overhead line is designed on the principle of one or more overhead wires situated over rail tracks. Feeder stations at regular intervals along the overhead line supply power from the high voltage grid. For some cases low-frequency AC is used, and distributed by a special traction current network.

### *Further applications*

Overhead lines are also occasionally used to supply transmitting antennas, especially for efficient transmission of long, medium and short waves. For this purpose a staggered array line is often used. Along a staggered array line the conductor cables for the supply of the earth net of the transmitting antenna are attached on the exterior of a ring, while the conductor inside the ring, is fastened to insulators leading to the high voltage standing feeder of the antenna.

### *Usage of area under overhead power lines*

Use of the area below an overhead line is restricted because objects must not come too close to the energized conductors. Overhead lines and structures may shed ice, creating a hazard. Radio reception can be impaired under a power line, due both to shielding of a receiver antenna by the overhead conductors, and by partial discharge at insulators and sharp points of the conductors which creates radio noise.

In the area surrounding overhead lines it is dangerous to risk interference; e.g. flying kites or balloons, using ladders or operating machinery.

Overhead distribution and transmission lines near airfields are often marked on maps, and the lines themselves marked with conspicuous plastic reflectors, to warn pilots of the presence of conductors.

Construction of overhead power lines, especially in wilderness areas, may have significant environmental effects. Environmental studies for such projects may consider the effect of brush clearing, changed migration routes for migratory animals, possible access by predators and humans along transmission corridors, disturbances of fish habitat at stream crossings, and other effects.

### *History*

The first transmission of electrical impulses over an extended distance was demonstrated on July 14, 1729 by the physicist Stephen Gray, in order to show that one can transfer electricity by that method. The demonstration used damp hemp cords suspended by silk threads (the low resistance of metallic conductors not being appreciated at the time).

However the first practical use of overhead lines was in the context of telegraphy. By 1837 experimental commercial telegraph systems ran as far as 13 miles (20 km). Electric power transmission was accomplished in 1882 with the first high voltage transmission between Munich and Miesbach. 1891 saw the construction of the first three-phase alternating current overhead line on the occasion of the International Electricity Exhibition in Frankfurt, between Lauffen and Frankfurt.

In 1912 the first 110 kV-overhead power line entered service followed by the first 220 kV-overhead power line in 1923. In the 1920s RWE AG built the first overhead line for this voltage and in 1926 built a Rhine crossing with the pylons of Voerde, two masts 138 meters high.

In Germany in 1957 the first 380 kV overhead power line was commissioned (between the transformer station and Rommerskirchen). In the same year the overhead line traversing of the Strait of Messina went into service in Italy, whose pylons served the Elbe crossing 1. This was used as the model for the building of the Elbe crossing 2 in the second half of the 1970s which saw the construction of the highest overhead line pylons of the world. Starting from 1967 in Russia, and also in the USA and Canada, overhead lines for voltage of 765 kV were built. In 1982 overhead power lines were built in Russia between Elektrostal and the power station at Ekibastusz, this was a three-phase alternating current line at 1150 kV (Powerline Ekibastuz-Kokshetau). In 1999, in Japan the first powerline designed for 1000 kV with 2 circuits were built, the Kita-Iwaki Powerline. In 2003 the building of the highest overhead line commenced in China, the Yangtze River Crossing.

### *Similar constructions*

- Aerial cable
- Antenna (Some antennas for lower frequencies are similar to overhead power lines)
- Electric fence
- Overhead cable
- Overhead line
- Radio masts and towers
- Third rail

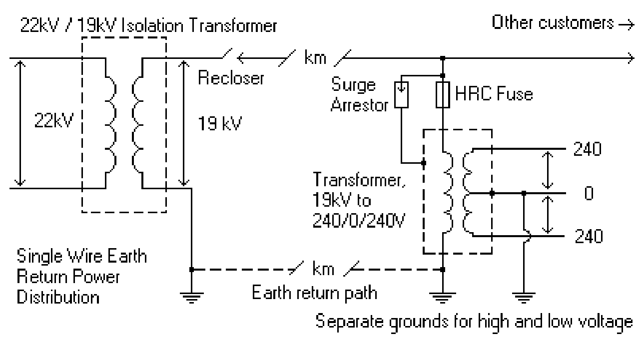
# Chapter 5

# 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 from an electrical grid to remote areas at low cost. Its distinguishing feature is that the earth (or sometimes a body of water) is used as the return path for the current, to avoid the need for a second wire (or *neutral wire*) to act as a return path. 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.

## Description

SWER is a good choice for a distribution system when conventional return current wiring would cost more than SWER's isolation transformers and small power losses. Power engineers experienced with both SWER and conventional power lines rate SWER as equally safe, more reliable, less costly, but with slightly lower efficiency than conventional lines.




Power is supplied to the SWER line by an isolating transformer of up to 300kVa. This transformer isolates the grid from ground or earth, and changes the grid voltage (typically 22 kilovolts line to line) to the SWER voltage (typically 12.7 or 19.1 kilovolts line to earth).

The SWER line is a single conductor that may stretch for tens or even hundreds of kilometres, with a number of distribution transformers along its length. At each transformer, such as a customer's premises, current flows from the line, through the primary coil of a step-down isolation transformer, to earth through an earth stake. From the earth stake, the current eventually finds its way back to the main step-down transformer at the head of the line, completing the circuit. SWER is therefore a practical example of a phantom loop.

In areas with high-resistance soil, SWER burns up grounding rods or may fail to reset breakers. In Australia, locations with very dry soils need the grounding rods to be extra deep. Experience in Alaska shows that SWER needs to be grounded below permafrost, which is high-resistance.

The secondary winding of the local transformer will supply the customer with either single ended single phase (N-0) or split phase (N-0-N) power in the region’s standard appliance voltages, with the 0 volt line connected to a safety earth that does not normally carry an operating current.

A large SWER line may feed as many as 80 distribution transformers. The transformers are usually rated at 5 kVA, 10 kVA and 25 kVA. The load densities are usually below 0.5 kVA per kilometer (0.8 kVA per mile) of line. Any single customer’s maximum demand will typically be less than 3.5 kVA, but larger loads up to the capacity of the distribution transformer can also be supplied.

Some SWER systems in the USA are conventional distribution feeders that were built without a continuous neutral (some of which were obsoleted transmission lines that were refitted for rural distribution service). The substation feeding such lines has a grounding rod on each pole within the substation; then on each branch from the line, the span between the pole next to and the pole carrying the transformer would have a grounded conductor (giving each transformer two grounding points for safety reasons).

## *History*

Lloyd Mandeno fully developed SWER in New Zealand around 1925 for rural electrification. Although he termed it “Earth Working Single Wire Line” it was often called “Mandeno’s Clothesline”. More than 200,000 kilometres have now been installed in Australia and New Zealand. It is considered safe, reliable and low cost, provided that safety features and earthing are correctly installed. The Australian standards are widely used and cited. It has been applied in the Canadian province of Saskatchewan, Brazil, Africa, portions of the United States' Upper Midwest, and SWER interties have been proposed for Alaska and prototyped.

## *Characteristics*

### Safety

SWER's safety is assured because transformers isolate the ground from both the generator and user. Most electrical systems use a metallic neutral connected directly to the generator or a shared ground. Certain groups claim that stray voltages from SWER can injure livestock.

Grounding is critical. Significant currents on the order of 8 amperes flow through the ground near the earth points. A good-quality earth connection is needed to prevent risk of electric shock due to earth potential rise near this point. Separate grounds for power and safety are also used. Duplication of the ground points assures that the system is still safe if either of the grounds is damaged.

A good earth connection is normally a 6 m stake of copper-clad steel driven vertically into the ground, and bonded to the transformer earth and tank. A good ground resistance is 5–10 ohms. SWER systems are designed to limit the voltage in the earth to 20 volts per meter to avoid shocking people and animals that might be in the area.

Other standard features include automatic reclosing circuit breakers (reclosers). Most faults (overcurrent) are transient. Since the network is rural, most of these faults will be cleared by the recloser. Each service site needs a rewirable drop out fuse for protection and switching of the transformer. The transformer secondary should also be protected by a standard high-rupture capacity (HRC) fuse or low voltage circuit breaker. A surge arrestor (spark gap) on the high voltage side is common, especially in lightning-prone areas.

The official investigation into the Black Saturday bushfires in Victoria, Australia, disclosed that a broken SWER conductor that comes in contact with a return path entry point with resistance similar to the circuit's normal load (such as a tree) can cause large amounts of current to flow to ground without a fault indication. This presents a danger in fire-prone areas where a conductor may snap and current may arc through trees or dry grass.

Bare-wire or ground-return telecommunications can be compromised by the ground-return current if the grounding area is closer than 100 m or sinks more than 10 A of current. Modern radio, optic fibre channels and cell phone systems are unaffected.

### Cost advantage

SWER’s main advantage is its low cost. It is often used in sparsely populated areas where the cost of building an isolated distribution line cannot be justified. Capital costs are roughly 50% of an equivalent two-wire single-phase line. They can cost 70% less than 3-wire three-phase systems. Maintenance costs are roughly 50% of an equivalent line.

SWER also reduces the largest cost of a distribution network, the number of poles. Conventional 2-wire or 3-wire distribution lines have a higher power transfer capacity, but can require seven poles per kilometre, with spans of 100 to 150 metres. SWER’s high line voltage and low current also permits the use of low-cost galvanized steel wire. Steel’s greater strength permits spans of 400 metres or more, reducing the number of poles to 2.5 per kilometre.

Reinforced concrete poles have been traditionally used in SWER lines because of their low cost, low maintenance, and resistance to water damage, termites and fungi. Local labor can produce them in most areas, further lowering costs. In New Zealand however, metal poles are also common (often being former rails from a railway line).

If the poles also carry optical fiber cable for telecommunications (metal conductors may not be used), capital expenditures by the power company may be further reduced.

## Reliability strengths

SWER can be used in a grid or loop, but is usually arranged in a linear or radial layout to save costs. In the customary linear form, a single-point failure in a SWER line causes all customers further down the line to lose power. However, since it has fewer components in the field, SWER has less to fail. For example, since there is only one line, winds can’t cause lines to clash, removing a source of damage, as well as a source of rural brush fires.

Since the line can't clash in the wind, and the bulk of the transmission line has low resistance attachments to earth, excessive ground currents from shorts and geomagnetic storms are far more rare than in conventional metallic-return systems. So, SWER has fewer ground-fault circuit-breaker openings to interrupt service.

## Power quality weakness

SWER lines tend to be long, with high impedance, so the voltage drop along the line is often a problem, causing poor regulation. Variations in demand cause variation in the delivered voltage. To combat this, some installations have automatic variable transformers at the customer site to keep the received voltage within legal specifications.

SWER combined with distributed generation is substantially more efficient than a single-ended system. For example, some rural installations can offset line losses and charging currents with local solar power, wind power, small hydro or other local generation. This can be an excellent value for the electrical distributor, because it reduces the need for more lines.

After some years of experience, the inventor advocated a capacitor in series with the ground of the main isolation transformer to counteract the inductive reactance of the transformers, wire and earth return path. The plan was to improve the power factor, reduce losses and improve voltage performance due to reactive power flow. Though theoretically sound, this is not standard practice.

### *Networks and circuits*

As demand grows, a well-designed SWER line can be substantially upgraded without new poles. The first step may be to replace the steel wire with more expensive copper-clad or aluminum-clad steel wire.

It may be possible to increase the voltage. Some distant SWER lines now operate at voltages as high as 35 kV. Normally this requires changing the insulators and transformers, but no new poles are needed.

If more capacity is needed, a second SWER line can be run on the same poles to provide two SWER lines 180 degrees out of phase. This requires more insulators and wire, but doubles the power without doubling the poles. Many standard SWER poles have several bolt holes to support this upgrade. This configuration causes most ground currents to cancel, reducing shock hazards and interference with communication lines.

Two phase service is also possible with a two-wire upgrade: Though less reliable, it is more efficient. As more power is needed the lines can be upgraded to match the load, from single wire SWER to two wire, single phase and finally to three wire, three phase. This ensures a more efficient use of capital and makes the initial installation more affordable.

Customer equipment installed before these upgrades will all be single phase, and can be reused after the upgrade. If small amounts of three-phase power are needed, it can be economically synthesized from two-phase power with on-site equipment.

### *Regulatory issues*

Many national electrical regulations (notably the U.S.) require a metallic return line from the load to the generator. In these jurisdictions, each SWER line must be approved by exception.

### *Use in interties*

In 1981 a high-power 8.5 mile prototype SWER intertie was successfully installed from a coal plant in Bethel to Napakiak in Alaska, United States. It operates at 80 kV, and has special lightweight fiberglass poles forming an A-frame. The poles can be carried on lightweight snow machines, and most poles can be installed with hand tools on permafrost without extensive digging. Erection of “anchoring” poles still required heavy machinery, but the cost savings were dramatic.

Researchers at the University of Alaska Fairbanks, United States estimate that a network of such interties, combined with coastal wind turbines, could substantially reduce rural Alaska’s dependence on increasingly expensive diesel fuel for power generation. Alaska’s state economic energy screening survey advocated further study of this option to use more of the state’s underutilized power sources.

## *Use by developing nations*

At present, certain developing nations have adopted SWER systems as their mains electricity systems, notably Laos and South Africa. SWER is also used extensively in Brazil where it is termed "Redes Monofilares com Retorno por Terra" or "MRT". There are detailed standards and drawings available in Brazilian Portuguese that would be transferable to other Portuguese speaking countries such as Angola and Mozambique.

## *Use for HVDC systems*

Many high-voltage direct current systems using submarine power cables are single wire earth return systems. Bipolar systems with both positive and negative cables may also retain a seawater grounding electrode, used when one pole has failed. To avoid electrochemical corrosion, the ground electrodes of such systems are situated apart from the converter stations and not near the transmission cable.

The electrodes can be situated in the sea or on land. Bare copper wires can be used for cathodes, and graphite rods buried in the ground, or titanium grids in the sea are used for anodes. To avoid electrochemical corrosion (and passivation of titanium surfaces) the current density at the surface of the electrodes must be small, and therefore large electrodes are required.

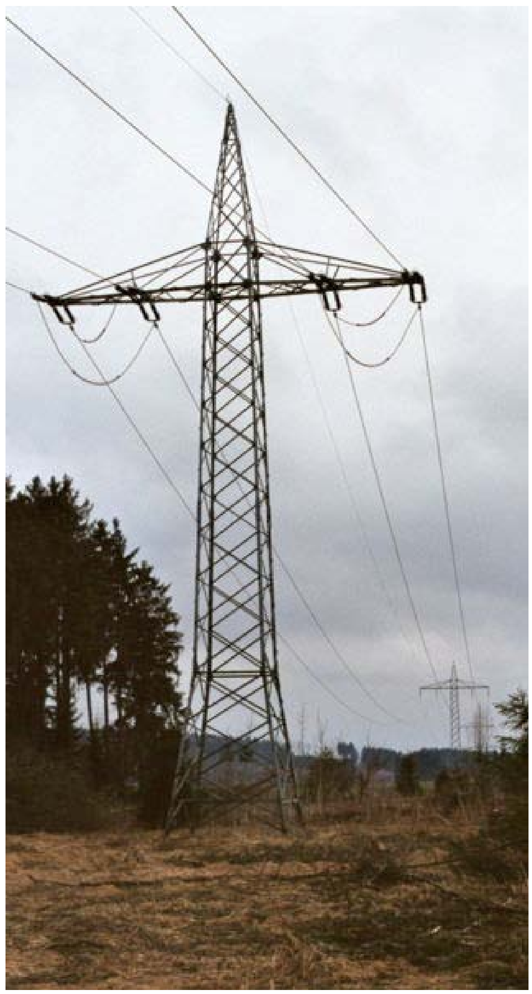
The advantage of such schemes is eliminating the cost of a second conductor, since salt water is an excellent conductor. Some ecologists claim that electrochemical reactions caused by the earth return can affect wildlife. However, these reactions do not occur on very large underwater electrodes.

### Examples of HVDC systems with single wire earth return

- Baltic Cable
- Kontek
- Basslink

## Chapter 6

# Traction Power Network



Twisting pylon of power line for single-phase AC traction current (110 kV, 16⅔ Hz) near Bartholomä in Germany.

A **traction network** or **traction power network** is an electricity grid for the supply of electrified rail networks. The installation of a separate traction network generally is only done if the railway in question uses alternating current (AC) with a frequency lower than that of the national grid, such as in Germany, Austria and Switzerland.

Alternatively, the three-phase alternating current of the power grid can be converted in substations by rotary transformers or static inverters into the voltage and type of current required by the trains. For railways which run on direct current (DC), this method is always used, as well as for railways which run on single-phase AC of decreased frequency, as in Mecklenburg-Western Pomerania, Saxony-Anhalt, Norway and Sweden. In these areas there are no **traction current networks**.

## *History*

Separate power for traction apart from industrial power always has historic roots. There is no reason today to apply different frequencies or current types than for transmission and for industrial usage. However, the advantage with DC traction was the easier transmission with single copper wires to the feeder points. The advantage with AC traction is the easier transmission over long distances to the feeder points. Beyond these parameters and securing former investment, no evidence exists to stay with different current schemes in networks.

## *Applications*

Dedicated traction current lines are used when railways are supplied with low frequency alternating current. The traction current supply line is connected to substations along the line of the railway and is usually run separately from the overhead catenary wire from which the locomotives are fed.

In countries in which the electric trains run with direct current or with single phase AC current with the frequency of the general power grid, the required conversion of the current is performed in the substations, so again no traction current lines are required.

Traction current supply lines are not usually laid parallel to the railway line, in order to allow a shorter line length and to avoid unnecessary influences to the electrical system near the railway line; this also is applied to the current supply of some rapid-transit railways operating with alternating current in Germany.

It is also possible to lay out the traction current supply on special cross beams right on the overhead wire pylons above the catenary wire. Because the overhead line pylons have a smaller cross section than traction current supply masts the cross beams cannot be too wide, so the standard arrangement of four conductor cables in one level cannot be used. In this case a two-level arrangement is used, or with two electric circuits for double-railed lines the overhead line pylons for both directions are equipped with cross beams for their own traction current system of two conductor cables each.

In densely populated areas there are pylons, which carry circuits for both traction current and for three-phase alternating current for general power. Such lines are found where right of ways are rare. In particular the parallel route of 110 kV and 220 kV three-phase AC is common. The use of 380 kV-power lines on the same pylon requires 220 kV insulators for the traction current line, because in case the 380 kV line fails, voltage spikes can occur along the traction current line, which the 110 kV insulators cannot handle.

As a rule traction current lines use single conductors, however for the supply of railways with high traffic and in particular for the supply of high speed railway lines, two bundle conductors are used.

## *Around the World*

### Austria

The Mariazeller railway in Lower Austria operates on single phase AC at a 25 Hz utility frequency. The railway has its own traction current lines with an operating voltage of 27 kV. These lines are mounted on the pylons of the overhead wire over the catenary wire.

### Germany

In Germany, single conductors are usually used for traction current lines but, for the ICE train, two bundle conductors are used. The traction current supply lines from the nuclear power station Neckarwestheim to the traction current switching station at Neckarwestheim and from there to the central substation in Stuttgart, Zazenhausen are implemented as a four-bundle conductor circuit.

### Scandinavia

In Sweden, Norway and some areas of the former German Democratic Republic, three phase AC-current is converted into single phase AC current with a frequency of 16.7 cycles per second at the substations. Unlike in Germany, there are no dedicated power plants for railway electricity. All power comes from general electricity suppliers. Although in this regions there is, in principle, no requirement for traction power lines, there is a 132 kV-single AC power grid for railway power supply in Central Sweden. In Norway, there is a small 55 kV single phase AC network for power supply of trains in the South, fed by Hakavik Power Station. A further power station, at Kjofossen feeds single phase AC directly in the overhead wire. In Denmark and Finland, 50 Hz is used for the main lines (if electrified) and the electricity comes from general suppliers. As such, much simpler equipment than in Sweden and Norway is needed for conversion.

### South Africa

In the Republic of South Africa there are extensive AC and DC traction schemes, including 50 kV and 25 kV AC single phase systems. Electrification in Natal was stimulated by the takeover of the South African Railways' system by the Electricity Supply Commission (now Eskom) based on the Colenso power station.

### United Kingdom

In the United Kingdom, the Network Rail 750 V DC electrification system in the southeast of England is supplied with power from an extensive 33 kV power distribution network.

## *Areas with traction power networks*

- United Kingdom
- Germany (except Mecklenburg-Western Pomerania and Saxony-Anhalt), total length 7959 km
- Switzerland
- Austria (separate traction power network for the Mariazeller Bahn)
- Central Sweden
- Southern Norway east of Oslo
- USA (in New York and Washington DC area for railway lines running with single phase 25 Hz AC)
- South Africa
- Melbourne, Australia (dedicated high voltage transmission wires between former Newport A Power Station and traction substations. However these lines are operated with three phase AC)

# Chapter 7

# Wireless Energy Transfer

**Wireless energy transfer** or **wireless power** is the transmission of electrical energy from a power source to an electrical load without interconnecting wires. Wireless transmission is useful in cases where interconnecting wires are inconvenient, hazardous, or impossible. The problem of wireless power transmission differs from that of wireless telecommunications, such as radio. In the latter, the proportion of energy received becomes critical only if it is too low for the signal to be distinguished from the background noise. With wireless power, efficiency is the more significant parameter. A large part of the energy sent out by the generating plant must arrive at the receiver or receivers to make the system economical.

The most common form of wireless power transmission is carried out using direct induction followed by resonant magnetic induction. Other methods under consideration include electromagnetic radiation in the form of microwaves or lasers.

## *Electric energy transfer*

An electric current flowing through a conductor carries electrical energy. When an electric current passes through a circuit there is an electric field in the dielectric surrounding the conductor; magnetic field lines around the conductor and lines of electric force radially about the conductor.

In a direct current circuit, if the current is continuous, the fields are constant; there is a condition of stress in the space surrounding the conductor, which represents stored electric and magnetic energy, just as a compressed spring or a moving mass represents stored energy. In an alternating current circuit, the fields also alternate; that is, with every half wave of current and of voltage, the magnetic and the electric field start at the conductor and run outwards into space with the velocity of light. Where these alternating fields impinge on another conductor a voltage and a current are induced.

Any change in the electrical conditions of the circuit, whether internal or external involves a readjustment of the stored magnetic and electric field energy of the circuit, that is, a so-called transient. A transient is of the general character of a condenser discharge through an inductive circuit. The phenomenon of the condenser discharge through an inductive circuit therefore is of the greatest importance to the engineer, as the foremost cause of high-voltage and high-frequency troubles in electric circuits.

Electromagnetic induction is proportional to the intensity of the current and voltage in the conductor which produces the fields and to the frequency. The higher the frequency the more intense the induction effect. Energy is transferred from a conductor that produces the fields (the primary) to any conductor on which the fields impinge (the secondary). Part of the energy of the primary conductor passes inductively across space into secondary conductor and the energy decreases rapidly along the primary conductor. A high frequency current does not pass for long distances along a conductor but rapidly transfers its energy by induction to adjacent conductors. Higher induction resulting from the higher frequency is the explanation of the apparent difference in the propagation of high frequency disturbances from the propagation of the low frequency power of alternating current systems. The higher the frequency the more preponderant become the inductive effects that transfer energy from circuit to circuit across space. The more rapidly the energy decreases and the current dies out along the circuit, the more local is the phenomenon.

The flow of electric energy thus comprises phenomena inside of the conductor and phenomena in the space outside of the conductor—the electric field—which, in a continuous current circuit, is a condition of steady magnetic and dielectric stress, and in an alternating current circuit is alternating, that is, an electric wave launched by the conductor to become far-field electromagnetic radiation traveling through space with the velocity of light.

In electric power transmission and distribution, the phenomena inside of the conductor are of main importance, and the electric field of the conductor is usually observed only incidentally. Inversely, in the use of electric power for *radio* telecommunications it is only the electric and magnetic fields outside of the conductor, that is electromagnetic radiation, which is of importance in transmitting the message. The phenomenon in the conductor, the current in the launching structure, is not used.

The electric charge displacement in the conductor produces a magnetic field and resultant lines of electric force. The magnetic field is a maximum in the direction concentric, or approximately so, to the conductor. That is, a ferromagnetic body tends to set itself in a direction at right angles to the conductor. The electric field has a maximum in a direction radial, or approximately so, to the conductor. The electric field component tends in a direction radial to the conductor and dielectric bodies may be attracted or repelled radially to the conductor.

The electric field of a circuit over which energy flows has three main axes at right angles with each other:

1. The *magnetic field*, concentric with the conductor.
2. The *lines of electric force*, radial to the conductor.
3. The *power gradient*, parallel to the conductor.

Where the electric circuit consists of several conductors, the electric fields of the conductors superimpose upon each other, and the resultant magnetic field lines and lines of electric force are not concentric and radial respectively, except *approximately in the immediate neighborhood* of the conductor. Between parallel conductors they are conjugate of circles. Neither the power consumption in the conductor, nor the magnetic field, nor the electric field, are proportional to the flow of energy through the circuit. However, the product of the intensity of the magnetic field and the intensity of the electric field is proportional to the flow of energy or the power, and the power is therefore resolved into a product of the two components **i** and **e**, which are chosen proportional respectively to the intensity of the magnetic field and of the electric field. The component called the current is defined as that factor of the electric power which is proportional to the magnetic field, and the other component, called the voltage, is defined as that factor of the electric power which is proportional to the electric field.

In *radio* telecommunications the electric field of the transmit antenna propagates through space as a radio wave and impinges upon the receive antenna where it is observed by its magnetic and electric effect. Radio waves, microwaves, infrared radiation, visible light, ultraviolet radiation, X rays and gamma rays are shown to be the same electromagnetic radiation phenomenon, differing one from the other only in frequency of vibration.

### Electromagnetic induction

Energy transfer by electromagnetic induction is typically magnetic but capacitive coupling can also be achieved.

## Electrodynamic induction method

The electrodynamic induction wireless transmission technique is near field over distances up to about one-sixth of the wavelength used. Near field energy itself is non-radiative but some radiative losses do occur. In addition there are usually resistive losses. With electrodynamic induction, electric current flowing through a primary coil creates a magnetic field that acts on a secondary coil producing a current within it. Coupling must be tight in order to achieve high efficiency. As the distance from the primary is increased, more and more of the magnetic field misses the secondary. Even over a relatively short range the inductive coupling is grossly inefficient, wasting much of the transmitted energy.

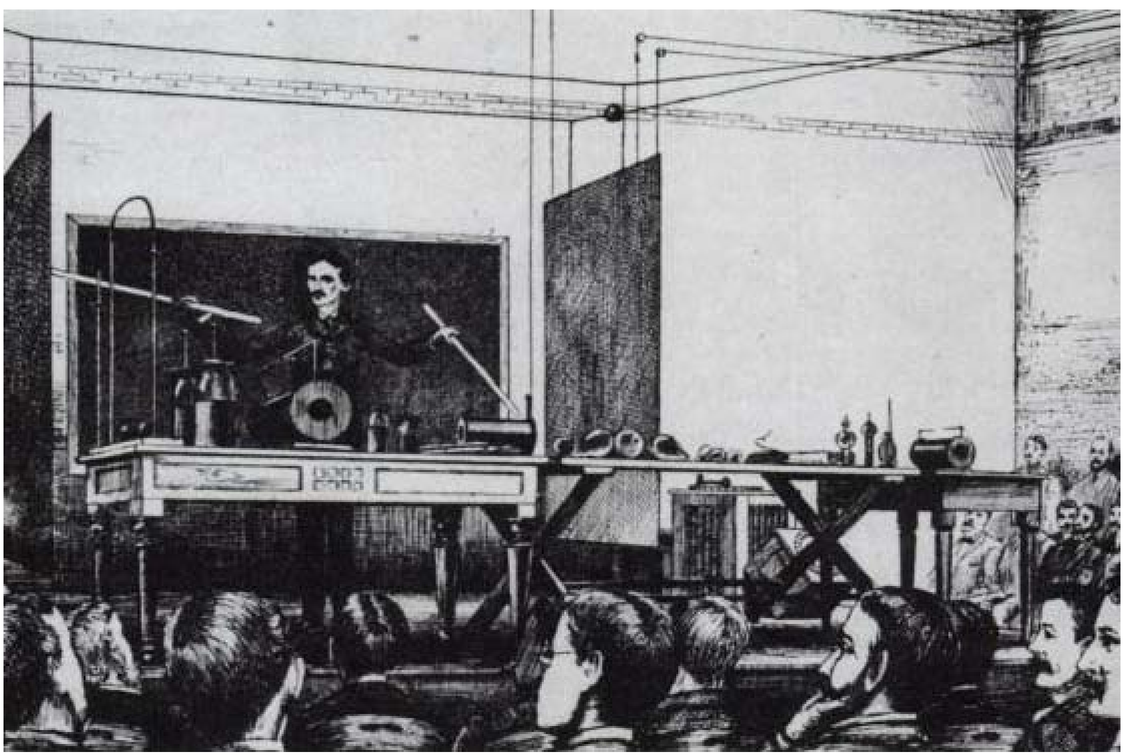
This action of an electrical transformer is the simplest form of wireless power transmission. The primary and secondary circuits of a transformer are not directly connected. Energy transfer takes place through a process known as mutual induction. Principal functions are stepping the primary voltage either up or down and electrical isolation. Mobile phone and electric toothbrush battery chargers, and electrical power distribution transformers are examples of how this principle is used. Induction cookers use this method. The main drawback to this basic form of wireless transmission is short range. The receiver must be directly adjacent to the transmitter or induction unit in order to efficiently couple with it.

The application of resonance improves the situation somewhat. When resonant coupling is used the transmitter and receiver inductors are tuned to a mutual frequency and the drive current is modified from a sinusoidal to a nonsinusoidal transient waveform. Pulse power transfer occurs over multiple cycles. In this way significant power may be transmitted over a distance of up to a few times the size of the primary coil. Transmitting and receiving coils are usually single layer solenoids or flat spirals with series capacitors, which, in combination, allow the receiving element to be tuned to the transmitter frequency.

Common uses of resonance-enhanced electrodynamic induction are charging the batteries of portable devices such as laptop computers and cell phones, medical implants and electric vehicles. A localized charging technique  selects the appropriate transmitting coil in a multilayer winding array structure. Resonance is used in both the wireless charging pad (the transmitter circuit) and the receiver module (embedded in the load) to maximize energy transfer efficiency. This approach is suitable for universal wireless charging pads for portable electronics such as mobile phones. It has been adopted as part of the Qi wireless charging standard.

It is also used for powering devices having no batteries, such as RFID patches and contactless smartcards, and to couple electrical energy from the primary inductor to the helical resonator of Tesla coil wireless power transmitters.

## Electrostatic induction method



The **Tesla effect**. is the illumination of two exhausted tubes by means of a powerful, rapidly alternating electrostatic field created between two vertical metal sheets suspended from the ceiling on insulating cords. It exploits the physics of electrostatic induction.

Electrostatic or capacitive coupling is the passage of electrical energy through a dielectric. In practice it is an electric field gradient or differential capacitance between two or more insulated terminals, plates, electrodes, or nodes that are elevated over a conducting ground plane. The electric field is created by an alternating current of high potential and high frequency. The capacitance between fixed plates and the powered device form a voltage divider.

The electric energy transmitted through the atmosphere can be utilized by receiving devices. Tesla demonstrated the illumination of wireless lamps by energy that was coupled to them through an alternating electric field.

"Instead of depending on *electrodynamic induction* at a distance to light the tube . . . [the] ideal way of lighting a hall or room would . . . be to produce such a condition in it that an illuminating device could be moved and put anywhere, and that it is lighted, no matter where it is put and without being electrically connected to anything. I have been able to produce such a condition by creating in the room a powerful, *rapidly alternating electrostatic field*. For this purpose I suspend a sheet of metal a distance from the ceiling on insulating cords and connect it to one terminal of the induction coil, the other terminal being preferably connected to the ground. Or else I suspend two sheets . . . each sheet being connected with one of the terminals of the coil, and their size being carefully determined. An exhausted tube may then be carried in the hand anywhere between the sheets or placed anywhere, even a certain distance beyond them; it remains always luminous."

The principle of electrostatic induction is applicable to the electrical conduction wireless transmission method.

## Electromagnetic radiation

Far field methods achieve longer ranges, often multiple kilometer ranges, where the distance is much greater than the diameter of the device(s). The main reason for longer ranges with radio wave and optical devices is the fact that electromagnetic radiation in the far-field can be made to match the shape of the receiving area (using high directivity antennas or well-collimated Laser Beam) thereby delivering almost all emitted power at long ranges. The maximum directivity for antennas is physically limited by diffraction.

## Beamed power, size, distance, and efficiency

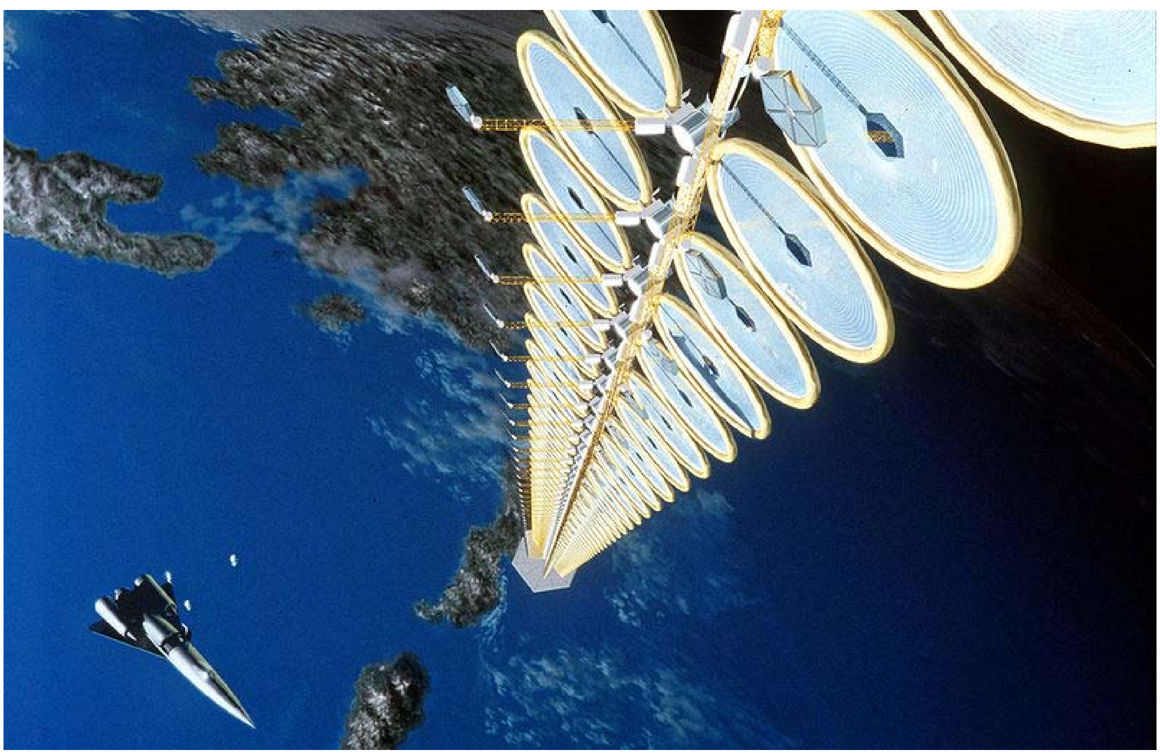
The size of the components may be dictated by the distance from transmitter to receiver, the wavelength and the Rayleigh criterion or diffraction limit, used in standard radio frequency antenna design, which also applies to lasers. In addition to the Rayleigh criterion Airy's diffraction limit is also frequently used to determine an approximate spot size at an arbitrary distance from the aperture.

The Rayleigh criterion dictates that any radio wave, microwave or laser beam will spread and become weaker and diffuse over distance; the larger the transmitter antenna or laser aperture compared to the wavelength of radiation, the tighter the beam and the less it will spread as a function of distance (and vice versa). Smaller antennae also suffer from excessive losses due to side lobes. However, the concept of laser aperture considerably differs from an antenna. Typically, a laser aperture much larger than the wavelength induces multi-moded radiation and mostly collimators are used before emitted radiation couples into a fiber or into space.

Ultimately, beamwidth is physically determined by diffraction due to the dish size in relation to the wavelength of the electromagnetic radiation used to make the beam. Microwave power beaming can be more efficient than lasers, and is less prone to atmospheric attenuation caused by dust or water vapor losing atmosphere to vaporize the water in contact.

Then the power levels are calculated by combining the above parameters together, and adding in the gains and losses due to the antenna characteristics and the transparency and dispersion of the medium through which the radiation passes. That process is known as calculating a link budget.

## Microwave method



An artist's depiction of a solar satellite that could send electric energy by microwaves to a space vessel or planetary surface.

Power transmission via radio waves can be made more directional, allowing longer distance power beaming, with shorter wavelengths of electromagnetic radiation, typically in the microwave range. A rectenna may be used to convert the microwave energy back into electricity. Rectenna conversion efficiencies exceeding 95% have been realized. Power beaming using microwaves has been proposed for the transmission of energy from orbiting solar power satellites to Earth and the beaming of power to spacecraft leaving orbit has been considered.

Power beaming by microwaves has the difficulty that for most space applications the required aperture sizes are very large due to diffraction limiting antenna directionality. For example, the 1978 NASA Study of solar power satellites required a 1-km diameter transmitting antenna, and a 10 km diameter receiving rectenna, for a microwave beam at 2.45 GHz. These sizes can be somewhat decreased by using shorter wavelengths, although short wavelengths may have difficulties with atmospheric absorption and beam blockage by rain or water droplets. Because of the "thinned array curse," it is not possible to make a narrower beam by combining the beams of several smaller satellites.

For earthbound applications a large area 10 km diameter receiving array allows large total power levels to be used while operating at the low power density suggested for human electromagnetic exposure safety. A human safe power density of 1 $mW/cm^2$ distributed across a 10 km diameter area corresponds to 750 megawatts total power level. This is the power level found in many modern electric power plants.

Following World War II, which saw the development of high-power microwave emitters known as cavity magnetrons, the idea of using microwaves to transmit power was researched. By 1964 a miniature helicopter propelled by microwave power had been demonstrated.

Japanese researcher Hidetsugu Yagi also investigated wireless energy transmission using a directional array antenna that he designed. In February 1926, Yagi and Uda published their first paper on the tuned high-gain directional array now known as the Yagi antenna. While it did not prove to be particularly useful for power transmission, this beam antenna has been widely adopted throughout the broadcasting and wireless telecommunications industries due to its excellent performance characteristics.

Wireless high power transmission using microwaves is well proven. Experiments in the tens of kilowatts have been performed at Goldstone in California in 1975 and more recently (1997) at Grand Bassin on Reunion Island. These methods achieve distances on the order of a kilometer.

## Laser method

In the case of electromagnetic radiation closer to visible region of spectrum (10s of microns (um) to 10s of nm), power can be transmitted by converting electricity into a laser beam that is then pointed at a solar cell receiver. This mechanism is generally known as "powerbeaming" because the power is beamed at a receiver that can convert it to usable electrical energy.

Advantages of laser based energy transfer compared with other wireless methods are:

1. collimated monochromatic wavefront propagation allows narrow beam cross-section area for energy transmission over large ranges.
2. compact size of solid state lasers-photovoltaics semiconductor diodes fit into into small products.
3. no radio-frequency interference to existing radio communication such as Wi-fi and cell phones.
4. control of access; only receivers illuminated by the laser receive power.

Its drawbacks are:

1. Conversion to light, such as with a laser, is inefficient
2. Conversion back into electricity is inefficient, with photovoltaic cells achieving 40%-50% efficiency. (Note that conversion efficiency is rather higher with monochromatic light than with insolation of solar panels).
3. Atmospheric absorption causes losses.
4. As with microwave beaming, this method requires a direct line of sight with the target.

The laser "powerbeaming" technology has been mostly explored in military weapons and aerospace applications and is now being developed for commercial and consumer electronics Low-Power applications. Wireless energy transfer system using laser for consumer space has to satisfy Laser safety requirements standardized under IEC 60825.

To develop an understanding of the trade-offs of Laser ("a special type of light wave"-based system):

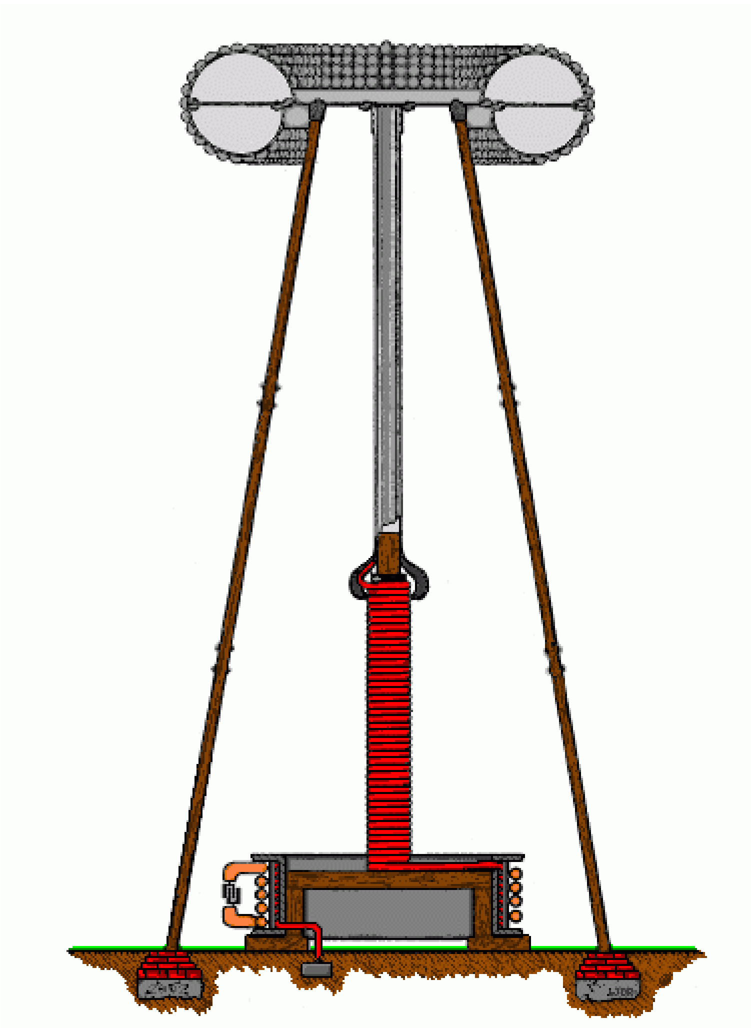
1. Propagation of a laser beam (on how Laser beam propagation is much less affected by diffraction limits)
2. Coherence and the range limitation problem (on how spatial and spectral coherence characteristics of Lasers allows better distance-to-power capabilities )
3. Airy disk (on how wavelength fundamentally dictates the size of a disk with distance)
4. Applications of laser diodes (on how the laser sources are utilized in various industries and their sizes are reducing for better integration)

Geoffrey Landis is one of the pioneers of solar power satellite and laser-based transfer of energy especially for space and lunar missions. The continuously increasing demand for safe and frequent space missions has resulted in serious thoughts on a futuristic space elevator that would be powered by lasers. NASA's space elevator would need wireless power to be beamed to it for it to climb a tether.

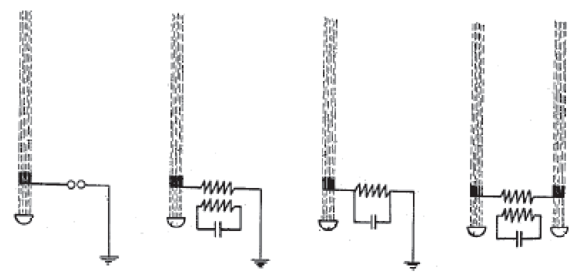
NASA's Dryden Flight Research Center has demonstrated flight of a lightweight unmanned model plane powered by a laser beam. This proof-of-concept demonstrates the feasibility of periodic recharging using the laser beam system and the lack of need to return to ground.

"Lasermotive" demonstrated laser powerbeaming at one kilometer during NASA's 2009 powerbeaming contest. Also "Lighthouse DEV" (a spin off of NASA Power Beaming Team) along with "University of Maryland" is developing an eye safe laser system to power a small UAV. Since 2006, "PowerBeam" which originally invented the eye-safe technology and holds all crucial patents in this technology space, is developing commercially ready units for various consumer and industrial electronic products.

## Electrical conduction



The Tesla coil wireless power transmitter **U.S. Patent 1,119,732**



Means for long conductors of electricity forming part of an electric circuit and electrically connecting said ionized beam to an electric circuit. Hettinger 1917 -(U.S. Patent 1,309,031)

## Disturbed charge of ground and air method

Single wire with Earth return electrical power transmission systems rely on current flowing through the earth plus a single wire insulated from the earth to complete the circuit. In emergencies high-voltage direct current power transmission systems can also operate in the 'single wire with earth return' mode. Elimination of the raised insulated wire, and transmission of high-potential, high-frequency alternating current through the earth with an atmospheric return circuit has been investigated as a method of wireless electrical power transmission. Transmission of electrical energy through the earth alone, eliminating the second conductor is also being investigated.

Low frequency alternating current can be transmitted through the inhomogeneous earth with low loss because the net resistance between earth antipodes is considerably less than 1 ohm. The electrical displacement takes place predominantly by electrical conduction through the oceans, and metallic ore bodies and similar subsurface structures. The electrical displacement is also by means of electrostatic induction through the more dielectric regions such as quartz deposits and other non-conducting minerals.

Alternating current can be transmitted through atmospheric strata having a barometric pressure of less than 135 millimeters of mercury. Current flows by means of electrostatic induction through the lower atmosphere up to about two or three miles above the plants (this is the middle part in a three-space model) and the flow of ions, that is to say, electrical conduction through the ionized region above three miles. Intense vertical beams of ultraviolet light may be used to ionize the atmospheric gasses directly above the two elevated terminals resulting in the formation of plasma high-voltage electrical transmission lines leading up to the conducting atmospheric strata. The end result is a flow electrical current between the two elevated terminals by a path up to and through the troposphere and back down to the other facility. Electrical conduction through atmospheric strata is made possible by the creation of capacitively coupled discharge plasma through the process of atmospheric ionization.

#### Terrestrial transmission line with atmospheric return

Tesla discovered that electrical energy can be transmitted through the earth and the atmosphere. In the course of his research he successfully lit lamps at moderate distances and was able to detect the transmitted energy at much greater distances. The Wardenclyffe Tower project was a commercial venture for trans-Atlantic wireless telephony and proof-of-concept demonstrations of global wireless power transmission. The facility was not completed because of insufficient funding.

Earth is a naturally conducting body and forms one conductor of the system. A second path is established through the upper troposphere and lower stratosphere starting at an elevation of approximately 4.5 miles (7.2 km).

A global system for "the transmission of electrical energy without wires" called the World Wireless System, dependent upon the high electrical conductivity of plasma and the high electrical conductivity of the earth, was proposed as early as 1904.

#### Terrestrial single-conductor surface wave transmission line

The same transmitter used for the atmospheric conduction method is used for the terrestrial single-conductor earth resonance method.

The fundamental earth resonance frequency is claimed to be approximately 11.78 Hz. With the earth resonance method some harmonic of this fundamental frequency is used. "I would say that the frequency should be smaller then twenty thousand per second, through shorter waves might be practicable" and on the low end, "a frequency of nine hundred and twenty-five per second" is used, "when it is indispensable to operate motors of the ordinary kind."

Observations have been made that may be inconsistent with a basic tenet of physics related to the scalar derivatives of the electromagnetic potentials that are presently considered to be *nonphysical.*

## *Timeline of wireless power*

- **1820**: André-Marie Ampère develops Ampere's law showing that electric current produces a magnetic field.
- **1831**: Michael Faraday develops Faraday's law of induction describing the electromagnetic force induced in a conductor by a time-varying magnetic flux.
- **1836**: Nicholas Callan invents the electrical transformer.
- **1864**: James Clerk Maxwell synthesizes the previous observations, experiments and equations of electricity, magnetism and optics into a consistent theory and mathematically models the behavior of electromagnetic radiation.
- **1888**: Heinrich Rudolf Hertz confirms the existence of electromagnetic radiation. Hertz's "*apparatus for generating electromagnetic waves*" was a VHF or UHF "radio wave" spark gap transmitter.

- **1891**: Tesla improves Hertz-wave wireless transmitter RF power supply or exciter in his patent No. 454,622, "System of Electric Lighting."
- **1893**: Tesla demonstrates the wireless illumination of phosphorescent lamps of his design at the World's Columbian Exposition in Chicago.
- **1893**: Tesla publicly demonstrates wireless power before a meeting of the National Electric Light Association in St. Louis.
- **1894**: Tesla lights incandescent lamps wirelessly at the 35 South Fifth Avenue laboratory in New York City by means of "electro-dynamic induction" or resonant inductive coupling.
- **1894**: Hutin & LeBlanc, espouse long held view that inductive energy transfer should be possible, they received U.S. Patent # 527,857 describing a system for power transmission at 3 kHz.
- **1894**: Jagdish Chandra Bose ignites gunpowder and rings a bell at a distance using electromagnetic waves, showing that communications signals can be sent without using wires.
- **1896**: Tesla demonstrates wireless transmission over a distance of about 48 kilometres (30 mi).
- **1897**: Tesla files his first patent application dealing specifically with wireless transmission.
- **1899**: Tesla continues his wireless power transmission research in Colorado Springs and writes, "the inferiority of the induction method would appear immense as compared with the *disturbed charge of ground and air method*."
- **1902**: Nikola Tesla vs. Reginald Fessenden - U.S. Patent Interference No. 21,701, System of Signaling (wireless); wireless power transmission, time and frequency domain spread spectrum telecommunications, electronic logic gates in general.
- **1904**: At the St. Louis World's Fair, a prize is offered for a successful attempt to drive a 0.1 horsepower (75 W) airship motor by energy transmitted through space at a distance of at least 100 feet (30 m).
- **1916**: Tesla states, "In my [*disturbed charge of ground and air*] system, you should free yourself of the idea that there is [electromagnetic] radiation, that energy is radiated. It is not radiated; it is conserved."
- **1917**: Tesla's Wardenclyffe tower is demolished. . . .

- **1926**: Shintaro Uda and Hidetsugu Yagi publish their first paper on Uda's *"tuned high-gain directional array"* better known as the Yagi antenna.

- **1961**: William C. Brown publishes an article exploring possibilities of microwave power transmission.
- **1964**: Brown demonstrates on CBS News with Walter Cronkite a model helicopter that receives all of the power needed for flight from a microwave beam. Between 1969 and 1975, Brown is technical director of a JPL Raytheon program that beams 30 kW over a distance of 1 mile at 84% efficiency.
- **1968**: Peter Glaser proposes wirelessly transmitting solar energy captured in space using "Powerbeaming" technology. This is usually recognized as the first description of a solar power satellite.

- **1971**: Prof. Don Otto develops a small trolley powered by induction at The University of Auckland, in New Zealand.
- **1973**: The world's first passive RFID system is demonstrated at Los-Alamos National Lab.
- **1975**: Goldstone Deep Space Communications Complex does experiments in the tens of kilowatts.
- **1988**: A power electronics group led by Prof. John Boys at The University of Auckland in New Zealand, develops an inverter using novel engineering materials and power electronics and conclude that power transmission by means of electrodynamic induction should be achievable. A first prototype for a contact-less power supply is built. Auckland Uniservices, the commercial company of The University of Auckland, patents the technology.
- **1989**: Daifuku, a Japanese company, engages Auckland Uniservices Ltd. to develop technology for car assembly plants and materials handling providing challenging technical requirements including multiplicity of vehicles.
- **1990**: Prof. John Boys team develops novel technology enabling multiple vehicles to run on the same inductive power loop and provide independent control of each vehicle. Auckland UniServices Patents the technology.
- **1996**: Auckland Uniservices develops an Electric Bus power system using electrodynamic induction to charge (30-60 kW) opportunistically commencing implementation in New Zealand. Prof John Boys Team commission 1st commercial IPT Bus in the world at Whakarewarewa, in New Zealand.
- **1998**: RFID tags are powered by electrodynamic induction over a few feet.
- **1999**: Dr. Herbert L. Becker powers a lamp and a hand held fan from a distance of 30 feet.
- **1999**: Prof. Shu Yuen (Ron) Hui and Mr. S.C. Tang of the City University of Hong Kong file a patent on "Coreless Printed-Circuit-Board (PCB) transformers and operating techniques", which form the basis for future planar charging surface with "vertical flux" leaving the planar surface. The circuit uses resonant circuits for wireless power transfer. EP(GB)0935263B
- **2000**: Prof. Shu Yuen (Ron) Hui invent a planar wireless charging pad using the "vertical flux" approach and resonant power transfer for charging portable consumer electronic products. A patent is filed on "Apparatus and method of an inductive battery charger," PCT Patent PCT/AU03/00 721, 2000.
- **2000**: Based on the coreless PCB transformer developed by Prof. Ron Hui, Prof. B. Choi and his team at Kyungpook National University publish a paper on "A new contactless battery charger for portable telecommunication/computing electronics," in Proc. ICCE'00 Int. Conf. Consumer Electron., 2000, pp. 58–59. The coreless PCB transformer is used to wirelessly charge a mobile phone.
- **2001** Prof. Shu Yuen (Ron) Hui and Dr. S.C. Tang file a patent on "Planar Printed-Circuit-Board Transformers with Effective Electromagnetic Interference (EMI) Shielding". The EM shield consists of a thin layer of ferrite and a thin layer of copper sheet. It enables the underneath of the future wireless charging pads to be shielded with a thin EM shield structure with thickness of typically 0.7mm or less. Patent: US6,501,364.

- **2001**: Prof. Ron Hui's team demonstrate that the coreless PCB transformer can transmit power close to 100W in ‘A low-profile low-power converter with coreless PCB isolation transformer, IEEE Transactions on Power Electronics, Volume: 16 Issue: 3 , May 2001. A team of Philips Research Center Aachen, led by Dr. Eberhard Waffenschmidt, use it to power an 100W lighting device in their paper "Size advantage of coreless transformers in the MHz range" in the European Power Electronics Conference in Graz.
- **2001**: Splashpower formed in the UK. Uses coupled resonant coils in a flat "pad" style to transfer tens of watts into a variety of consumer devices, including lamp, phone, PDA, iPod etc.
- **2002**: Prof. Shu Yuen (Ron) Hui extends the planar wireless charging pad concept using the vertical flux approach to incorporate free-positioning feature for multiple loads. This is achieved by using a multilayer planar winding array structure. Patent were granted as "Planar Inductive Battery Charger", GB2389720 and GB 2389767.
- **2004**: Electrodynamic induction used by 90 percent of the US$1 billion clean room industry for materials handling equipment in semiconductor, LCD and plasma screen manufacture.
- **2005**: Prof. Shu Yuen (Ron) Hui and Dr. W.C. Ho of City University of Hong Kong publish their work in the IEEE Transactions on a planar wireless charging platform with free-positioning feature. The planar wireless charging pad is able to charge several loads simultaneously on a flat surface.
- **2005**: Prof Boys' team at The University of Auckland, refines 3-phase IPT Highway and pick-up systems allowing transmission of power to moving vehicles in the lab.
- **2007**: A localized charging technique is reported by Dr. Xun Liu and Prof. Ron Hui for the wireless charging pad with free-positioning feature. With the aid of the double-layer EM shields enclosing the transmitter and receiver coils, the localized charging selects the right transmitter coil so as to minimize flux leakage and human exposure to radiation.
- **2007**: Using electrodynamic induction a physics research group, led by Prof. Marin Soljacic, at MIT, wirelessly power a 60W light bulb with 40% efficiency at a 2 metres (6.6 ft) distance with two 60 cm-diameter coils.
- **2008**: Bombardier offers a new wireless power transmission product PRIMOVE, a system for use on trams and light-rail vehicles.
- **2008**: Industrial designer Thanh Tran, at Brunel University make a wireless lamp incorporating a high efficiency 3W LED.
- **2008**: Intel reproduces Tesla's original 1894 implementation of electrodynamic induction and Prof. John Boys group's 1988 follow-up experiments by wirelessly powering a nearby light bulb with 75% efficiency.
- **2008**: Greg Leyh and Mike Kennan of the Nevada Lightning Laboratory publish a paper on Tesla's *disturbed charge of ground and air method* of wireless power transmission with circuit simulations and test results showing an efficiency greater than can be obtained using the electrodynamic induction method.

- **2009**: A Consortium of interested companies called the Wireless Power Consortium announce they are nearing completion for a new industry standard for low-power inductive charging
- **2009**: Palm (now a division HP) launches the Palm Pre smartphone with the Palm Touchstone wireless charger.
- **2009**: An Ex approved Torch and Charger aimed at the offshore market is introduced. This product is developed by Wireless Power & Communication, a Norway based company.
- **2009**: A simple analytical electrical model of electrodynamic induction power transmission is proposed and applied to a wireless power transfer system for implantable devices.
- **2009**: Lasermotive uses diode laser to win $900k NASA prize in power beaming, breaking several world records in power and distance, by transmitting over a kilowatt more than several hundred meters.
- **2009**: Sony shows a wireless electrodynamic-induction powered TV set, 60 W over 50 cm
- **2010**: Haier Group debuts “the world's first” completely wireless LCD television at CES 2010 based on Prof. Marin Soljacic's follow-up research on Tesla's electrodynamic induction wireless energy transmission method and the Wireless Home Digital Interface (WHDI).
- **2010**: System On Chip (SoC) group in University of British Columbia develops an optimization tool for the design of highly efficient wireless power transmission systems using multiple coils. The design is optimized for implantable applications and power transfer efficiency of 82% is achieved.

## Chapter 8

# Power Transmission

**Power transmission** is the movement of energy from its place of generation to a location where it is applied to performing useful work.

Power is defined formally as units of energy per unit time. In SI units:

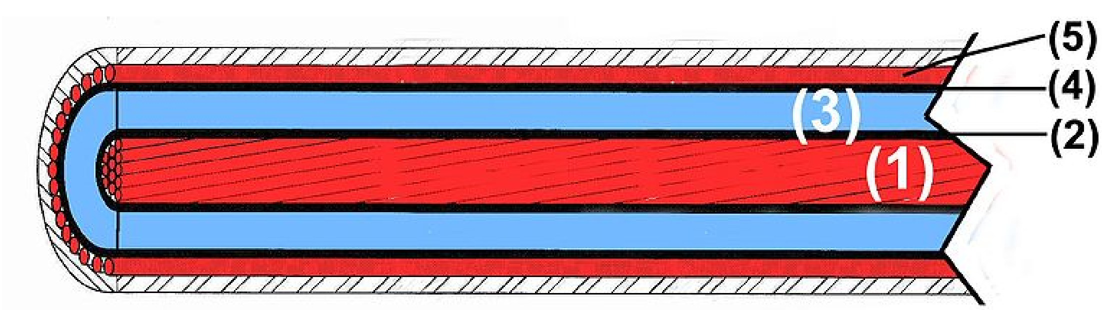
$$\text{watt} = \frac{\text{joule}}{\text{second}} = \frac{\text{newton} \times \text{meter}}{\text{second}}$$

Since the development of technology, transmission and storage systems have been of immense interest to technologists and technology users.

### *Electrical power*

Electric power transmission with overhead line.

With the widespread establishment of power grids, power transmission is usually associated most with electric power transmission. Alternating current is normally preferred as its voltage may be easily stepped up by a transformer in order to minimize resistive loss in the conductors used to transmit power over great distances; another set of transformers is required to step it back down to safer or more usable voltage levels at destination.




Electric power transmission with underground cable. Here (1) is the conductor for heavy currents and (3) the insulation for high voltages.

Power transmission is usually performed with overhead lines as this is the most economical way to do so. Underground transmission by high voltage cables is chosen in crowded urban areas and in HVDC submarine connections.

## Wireless transmission

Power might also be transmitted by changing electromagnetic fields or by radio waves; microwave energy may be carried efficiently over short distances by a waveguide.

## *Mechanical power*

Mechanical power transmission

Electrical power transmission has replaced mechanical power transmission in all but the very shortest distances. From the 16th century through the industrial revolution to the end of the 19th century mechanical power transmission was the norm. The oldest long-distance power transmission technology involved systems of push-rods (*stängenkunst* or *feldstängen*) connecting waterwheels to distant mine-drainage and brine-well pumps. A surviving example from 1780 exists at Bad Kösen that transmits power approximately 200 meters from a waterwheel to a salt well, and from there, an additional 150 meters to a brine evaporator. This technology survived into the 21st century in a handful of oilfields in the US, transmitting power from a central pumping engine to the numerous pump-jacks in the oil field.

Factories were fitted with overhead line shafts providing rotary power. Short line-shaft systems were described by Agricola, connecting a waterwheel to numerous ore-processing machines. While the machines described by Agricola used geared connections from the shafts to the machinery, by the 19th century, drivebelts would become the norm for linking individual machines to the line shafts. One mid 19th century factory had 1,948 feet of line shafting with 541 pulleys.

Mechanical power may be transmitted directly using a solid structure such as a driveshaft; transmission gears can adjust the amount of torque or force vs. speed in much the same way an electrical transformer adjusts voltage vs current.

Hydraulic systems use liquid under pressure to transmit power; canals and hydroelectric power generation facilities harness natural water power to lift ships or generate electricity. Pumping water or pushing mass uphill with (windmill pumps) is one possible means of energy storage. London had a hydraulic network powered by five pumping stations operated by the London Hydraulic Power Company, with a total effect of 5 MW.

Pneumatic systems use gasses under pressure to transmit power; compressed air is commonly used to operate pneumatic tools in factories and repair garages. A pneumatic wrench (for instance) is used to remove and install automotive tyres far more quickly than could be done with standard manual hand tools.

A pneumatic system was proposed by proponents of Edison's direct current as the basis of the power grid. Compressed air generated at Niagara Falls would drive far away generators of DC power. The War of Currents ended with alternating current (AC) as the only means of long distance power transmission.

### *Chemicals and fuels*

Power (and energy) may be transmitted by physically transporting chemical or nuclear fuels. Possible artificial fuels include radioactive isotopes, wood alcohol, grain alcohol, methane, synthetic gas, hydrogen gas ($H_2$), cryogenic gas, and liquefied natural gas (LNG).

## Chapter 9

# Load Control and Load Management

## Load control

One approach many electrical utilities have taken to ensure the electrical load is less than what can be generated is to exercise some form of **load control**. In this case, certain applications are identified as “deferrable”, to run later in the day, after the peak. These applications will vary by region, but common loads include residential electric hot-water heaters, air conditioners, pool pumps, crop-irrigation pumps, etc. In a distribution network outfitted with load control, these devices are outfitted with communicating controllers that can run a program that limits the duty cycle of the equipment under control. The utility only exercises the equipment when necessary. The consumer is usually rewarded for participating in the optional load control program by paying a reduced rate for energy. Proper Load management by the utility allows them to practice Load shedding on a less drastic scale to avoid Rolling blackouts and penalties by the Public Utility Commission.

### *Comparisons to Demand Response*

When the decision is made to curtail load, it is done so on the basis of system *reliability*. The utility (in a sense) “owns the switch” and sheds load only when the stability or reliability of the electrical distribution system is threatened. The utility (being in the business of generating, transporting, and delivering electricity) will not disrupt their business process without due cause. Load Control, when done properly, is non-invasive, and imposes no hardship on the consumer.

Demand response on the other hand places the “on-off switch” in the hands of the consumer using devices such as a Smart grid controlled load control switch. While many residential consumers pay a flat rate for electricity year-round, the utility’s costs are anything but flat. In a free market, the wholesale price of energy varies widely throughout the day, every day. Demand Response programs such as those enabled by smart grids attempt to incentivise the consumer to limit usage based upon *cost* concerns. As cost rises during the day in the supply of electricity as the system reaches peak capacity and more expensive "peaking" power generation is used, a free market economy should allow the price to rise. A corresponding drop in demand for the commodity should meet a fall in price. While this works for predictable shortages, many crises develop within seconds due to unforeseen equipment failures. They must be resolved in the same timeframe in order to avoid a Power blackout. Many utilities who are interested in demand response have also expressed an interest in load control capability so that they might be able to operate the “on-off switch” before price updates could be published to the consumers.

## *Implementations of Load Control systems*

Early implementations occurred in WWII in various parts of the world using a system that communicates over the powerline (known as the "Ripple Control" system). The application of load control technology continues to grow today with the sale of both Radio frequency and Powerline communication based systems. Certain types of AMI systems can also serve as load control systems.

The largest residential load control system in the world is found in the United States, in Florida at FPL. It utilizes 800,000 Load Control Transponders (LCT’s) and controls 1,000 MW of electrical power (2,000 MW in an emergency). FPL has been able to avoid the construction of numerous new power plants due to their demand side management programs.  Smaller utilities which buy power instead of generating their own, find that they can also benefit by installing a load control system. The penalties they must pay to the energy provider for peak usage can be significantly reduced. Many report that a load control system can pay for itself in a single season.

## *Plant load factor*

A plant load factor is a measure of average capacity utilization. It is a measure of the output of a power plant compared to the maximum output it could produce.

The two commonest definitions are:

- the ratio of average load to capacity
- the ratio of average load to peak load in a period.

Assuming the first definition, a higher load factor is better:

- A power plant may be less efficient at low load factors.
- A high load factor means fixed costs are spread over more kWh of output.
- A high load factor means greater total output.

Therefore a higher load factor usually means more output and a lower cost per unit, which means an electricity generator can sell more electricity at a higher spark spread.

If the PLF is affected by non-availability of fuel, maintenance shut-down, unplanned break down and no offtake (as consumption pattern fluctuates lower in nights), the generation has to be adjusted. A power (electricity) storage is not feasible. A generation of power is controlled to match the offtake. For any duration, a power plant generates below its full capacity. To that extent it is a capacity loss.

### *Ripple control for many years in New Zealand*

Ripple control can be used to manage electric water heaters, allowing energy tariffs to be switched from daytime to evening, or hot water power supply to be turned off during daytime. Most electricity lines companies set 7:00am–11:00pm for a more costly daytime tariff, and 11:00pm–7:00am for a discounted evening tariff, which favors dairy farmers that complete milking soon after 7:00am. However, some electricity lines companies set 6:00am as the start of the more expensive daytime tariff, which is somewhat less favorable to dairy farmers - the option being to complete morning milking before 6:00am.

Local lines companies benefit from spreading energy demand throughout the evening as well as the daytime. This reduces the utilization of the electricity network and can be used to avoid investment in electricity transmission and distribution lines. However, ripple control is often not utilized by the lines company to control water heating, unless periods of peak demand or power shortages occur.

# Load management

**Load management** is the process of balancing the supply of electricity on the network with the electrical load by adjusting or controlling the load rather than the power station output. This can be achieved by direct intervention of the utility in real time, by the use of frequency sensitive relays triggering circuit breakers, or by time clocks, or by using special tariffs to influence consumer behavior.

Electrical energy is a form of Energy that cannot be stored in bulk. It must be generated, shipped to the point where it is needed, and immediately consumed. Consequently, for the generation and distribution of electrical power, load management is a subject that is continually on the minds of the electrical network operators (also known as Transmission system operators). Sometimes the load on a system can approach the maximum generating capacity or the rate at which the load is increasing can surpass the rate at which generating output can be increased, even though there is ultimately enough capacity. When this happens, the network operators must either find additional supplies of energy or find ways to curtail the load. If they are unsuccessful within the time allowed, the system will become unstable and blackouts can occur.

The Load Management may involve sophisticated load analysis in which models are built to describe the physical properties of the distribution network (i.e. topology, capacity, and other characteristics of the lines), as well as the load behavior. The analysis may include scenarios that account for weather forecasts, the predicted impact of proposed load-shed commands, estimated time-to-repair for off-line equipment, and other factors.

Monitoring of the load and the effect a Load control program or Demand response price event might have, is typically done in real-time by human operators, using a SCADA system. If the actual outcome differs from the predicted outcome, the human can intervene to make corrections, applying more or less load shed as necessary but automatic systems are commonplace.

The accuracy of the load forecast requires ongoing diligence in order to refine the demographics, monitor growth patterns, and maintain knowledge of the amount of dis patchable load.

Load Management might be achieved in the utility using any combination of tools and programs including: construction and operation of new power plants (especially peak generation units), participation in a power pool, demand side management programs (such as operation of a load control system and customer programs to improve energy conservation), as well as demand response programs. New technologies are always under development—both by private industry and public entities.

## *Brief history*

In 1972, Theodore George “Ted” Paraskevakos, while working with Boeing in Huntsville, Alabama, United States developed a sensor monitoring system which used digital transmission for security, fire and medical alarm systems as well as meter reading capabilities for all utilities. This technology was a spin off of his patented automatic telephone line identification system, now known as Caller ID. In, 1974, Mr. Paraskevakos was awarded a U.S. Patent for this technology.

At the request of the Alabama Power Company, Mr. Paraskevakos developed a load management system along with automatic meter reading technology. In doing so, he utilized the ability of the system to monitor the speed of the watt power meter disc and, consequently, power consumption, creating a "Smart Meter." This information, along with the time of day, gave the power Company the ability to instruct the individual meters to manage water heater and air conditioning consumption in order to prevent peaks in usage during the high consumption portions of the day. For this approach, Mr. Paraskevakos was awarded multiple Patents.

## *Examples of schemes*

Many countries including United States, United Kingdom and France, the power grids routinely use privately held, often emergency diesel generators in load management schemes

It was recently announced that domestic fridges are being sold into the UK fitted with dynamic load response systems working of system frequency.

## New Zealand

New Zealand has for many years had a system of load control based on rippled control allowing the utility to switch off or on domestic and commercial water heaters, at will.

## France

France has an EJP tariff, which allows it to disconnect certain loads and to encourage consumers to disconnect certain loads.. This tariff is no longer available for new clients (as of July 2009). The *Tempo* tariff also includes different types of days with different prices, but has been discontinued for new clients as well (as of July 2009). Reduced prices during nighttime are available for customers for a higher monthly fee..

## United Kingdom

In the UK, night storage heaters are used to increase the load by about 5 GW to accommodate the nuclear programme. There is also a programme that allows industrial loads to be disconnected using circuit breakers triggered automatically by frequency sensitive relays fitted on site. This operates in conjunction with Standing Reserve, a programme using diesel generators.

These can also be remotely switched using BBC Radio 4 Longwave Radio teleswitch.

## Germany

Existing storage heater in Germany are loaded with a lower tariff electricity, mainly during night and afternoon hours. The switch and the two-tariff electricity meter as well are remote controlled by using of ripple contol through the main powerline or by the European radio teleswitching system based on longwave radio signals.

## Chapter 10

# High Voltage Cable

A **high voltage cable** - also called **HV cable** - is used for electric power transmission at high voltage. High voltage cables of differing types have a variety of applications in instruments, ignition systems, AC and DC power transmission. In all applications, the insulation of the cable must not deteriorate due to the high voltage stress, ozone produced by electric discharges in air, or tracking. The cable system must prevent contact of the high-voltage conductor with other objects or persons, and must contain and control leakage current. Cable joints and terminals must be designed to control the high-voltage stress to prevent breakdown of the insulation. Often a high-voltage cable will have a metallic shield layer over the insulation, connected to earth ground and designed to equalize the dielectric stress on the insulation layer, and to prevent shock.

Segments of high-voltage cables

High voltage cables may be any length, with relatively short cables used in apparatus, longer cables run within buildings or as buried cables in an industrial plant or for power distribution, and the longest cables are often run as submarine cables under the ocean for power transmission.

## *Construction*

A cross-section through a 400 kV cable, showing the stranded segmented copper conductor in the center, semiconducting and insulating layers, copper shield conductors, aluminum sheath and plastic outer jacket.

Like other power cables, high voltage cables have the structural elements of one or more conductors, insulation, and a protective jacket. High voltage cables differ from lower-voltage cables in that they have additional internal layers in the insulation jacket to control the electric field around the conductor.

For circuits operating at or above 2,000 volts between conductors, a conductive shield may surround each insulated conductor. This equalizes electrical stress on the cable insulation. This technique was patented by Martin Hochstadter in 1916; the shield is sometimes called a Hochstadter shield. The individual conductor shields of a cable are connected to earth ground at the ends of the shield, and at splices. Stress relief cones are applied at the shield ends.

Cables for power distribution of 10kV or higher may be insulated with oil and paper, and are run in a rigid steel pipe, semi-rigid aluminum or lead sheath. For higher voltages the oil may be kept under pressure to prevent formation of voids that would allow partial discharges within the cable insulation.

Sebastian Ziani de Ferranti was the first to demonstrate in 1887 that carefully dried and prepared paper could form satisfactory cable insulation at 11,000 volts. Previously paper-insulated cable had only been applied for low-voltage telegraph and telephone circuits. An extruded lead sheath over the paper cable was required to ensure that the paper remained absolutely dry.

Vulcanized rubber was patented by Charles Goodyear in 1844, but it was not applied to cable insulation until the 1880s, when it was used for lighting circuits. Rubber-insulated cable was used for 11,000 volt circuits in 1897 installed for the Niagara Falls power project.

Mass-impregnated paper-insulated medium voltage cables were commercially practical by 1895. During World War II several varieties of synthetic rubber and polyethylene insulation were applied to cables. Modern high voltage cables use polymers or polyethylene, including (XLPE) for insulation.

### *AC power cable*

High voltage is defined as any voltage over 1000 volts. Cables for 3000 and 6000 volts exist, but the majority of cables are used from 10 kV and upward. Those of 10 to 33 kV are usually called *medium voltage* cables, those over 50 kV *high voltage* cables.

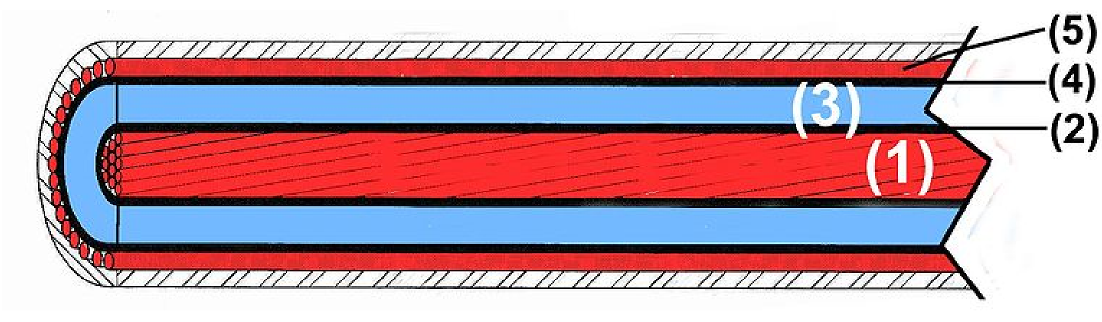



Figure 1, cross section of a high voltage cable, (1) conductor, (3) insulation.

Modern HV cables have a simple design consisting of few parts. A conductor of copper or aluminum wires transports the current, see (1) in figure 1. Conductor sections up to 2000 $mm^2$ may transport currents up to 2000 amperes. The individual strands are often preshaped to provide a smoother overall circumference. The insulation (3) may consists of cross-linked polyethylene, also called XLPE. It is reasonably flexible and tolerates operating temperatures up to 120 °C. EPDM is also an insulation.

At the inner (2) and outer (4) sides of this insulation, semi-conducting layers are fused to the insulation. The function of these layers is to prevent air-filled cavities between the metal conductors and the dielectric so that little electric discharges can arise and endanger the insulation material.
The outer conductor or sheath (5) serves as an earthed layer and will conduct leakage currents if needed.

Most high voltage cables for power transmission that are currently sold on the market are insulated by a sheath of cross-linked polyethylene (XLPE). Some cables may have a lead or aluminium jacket in conjunction with XLPE insulation to allow for fiber optics. Before 1960, underground power cables were insulated with oil and paper and ran in a rigid steel pipe, or a semi-rigid aluminium or lead jacket or sheath. The oil was kept under pressure to prevent formation of voids that would allow partial discharges within the cable insulation. There are still many of these oil-and-paper insulated cables in use worldwide. Between 1960 and 1990, polymers became more widely used at distribution voltages, mostly EPDM (ethylene propylene diene M-class); however, their relative unreliability, particularly early XLPE, resulted in a slow uptake at transmission voltages. While cables of 330 kV are commonly constructed using XLPE, this has occurred only in recent decades.

## Quality

During the development of the HV insulation, which has taken about half a century, two characteristics proved to be paramount. First, the introduction of the semiconducting layers. These layers must be absolutely smooth, without even protrusions as small as some microns. Further the fusion between the insulation and these layers must be absolute; any fission, air-pocket or other defect - of the same micro-dimensions as above - is detrimental for the breakdown characteristics of the cable.

Secondly, the insulation must be free of inclusions, cavities or other defects of the same sort of size. Any defect of these types shortens the voltage life of the cable which is supposed to be in the order of 30 years or more.

Cooperation between cable-makers and manufacturers of materials has resulted in grades of XLPE with tight specifications about the number and size of foreign particles per pound or per kilogram. Packing the raw material and unloading it within a cleanroom environment in the cable-making machines is required. The development of extruders for plastics extrusion and cross-linking has resulted in cable-making installations for making defect-free and pure insulations.

### *HVDC cable*

A high voltage cable for HVDC transmission has the same construction as the AC cable shown in figure 1. The physics and the test-requirements are different. In this case the smoothness of the semiconducting layers (2) and (4) is of utmost importance. Cleanliness of the insulation remains imperative.

Many HVDC cables are used for DC submarine connections, because at distances over 30 km AC can no longer be used. The longest submarine cable today is the NorNed cable between Norway and Holland that is almost 600 km long and transports 700 megawatts, a capacity equal to two large power stations.
Most of these long deep-sea cables are made in an older construction, using oil-impregnated paper as an insulator.

### *Cable terminals*

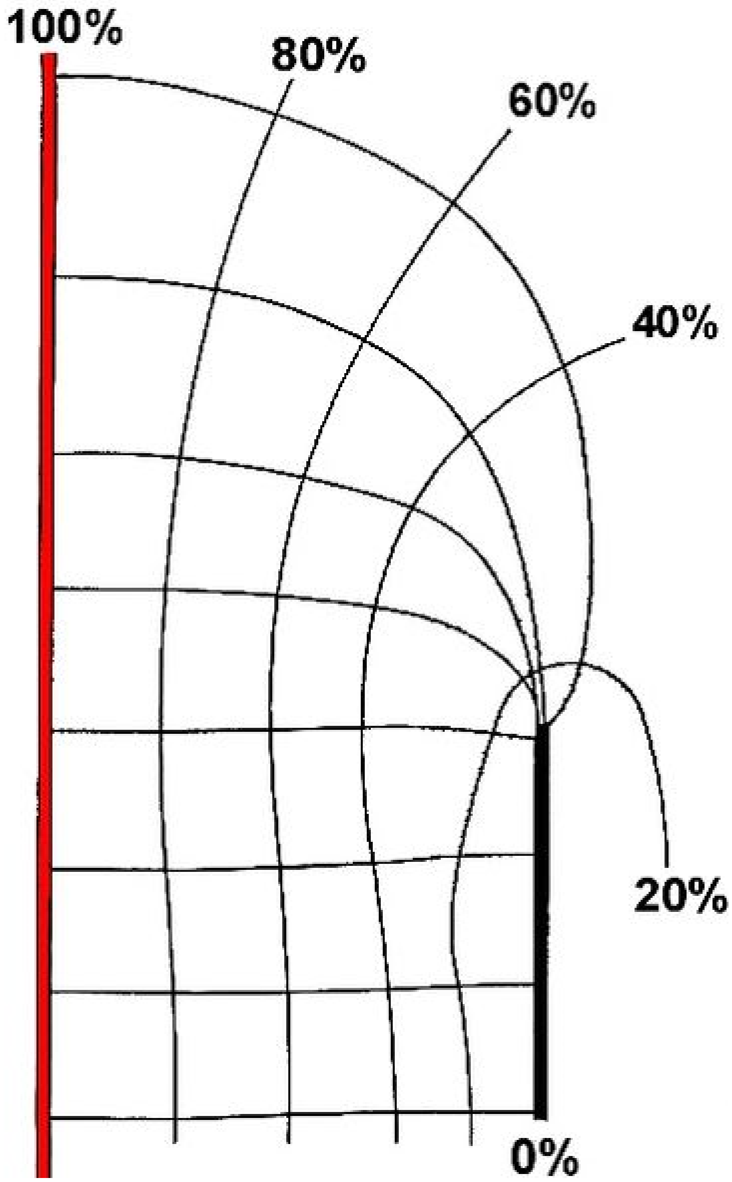



Figure 2, the earth shield of a cable (0%) is cut off, the equipotential lines (from 20% to 80%) concentrate at the edge of the earth electrode, causing danger of breakdown.

Terminals of high voltage cables must manage the electric fields at the ends. Without such a construction the electric field will concentrate at the end of the earth-conductor as shown in figure 2.

Equipotential lines are shown here which can be compared with the contour lines on a map of a mountainous region: the nearer these lines are to each other, the steeper the slope and the greater the danger, in this case the danger of an electric breakdown. The equipotential lines can also be compared with the isobars on a weather map: the denser the lines, the more wind and the greater the danger of damage.

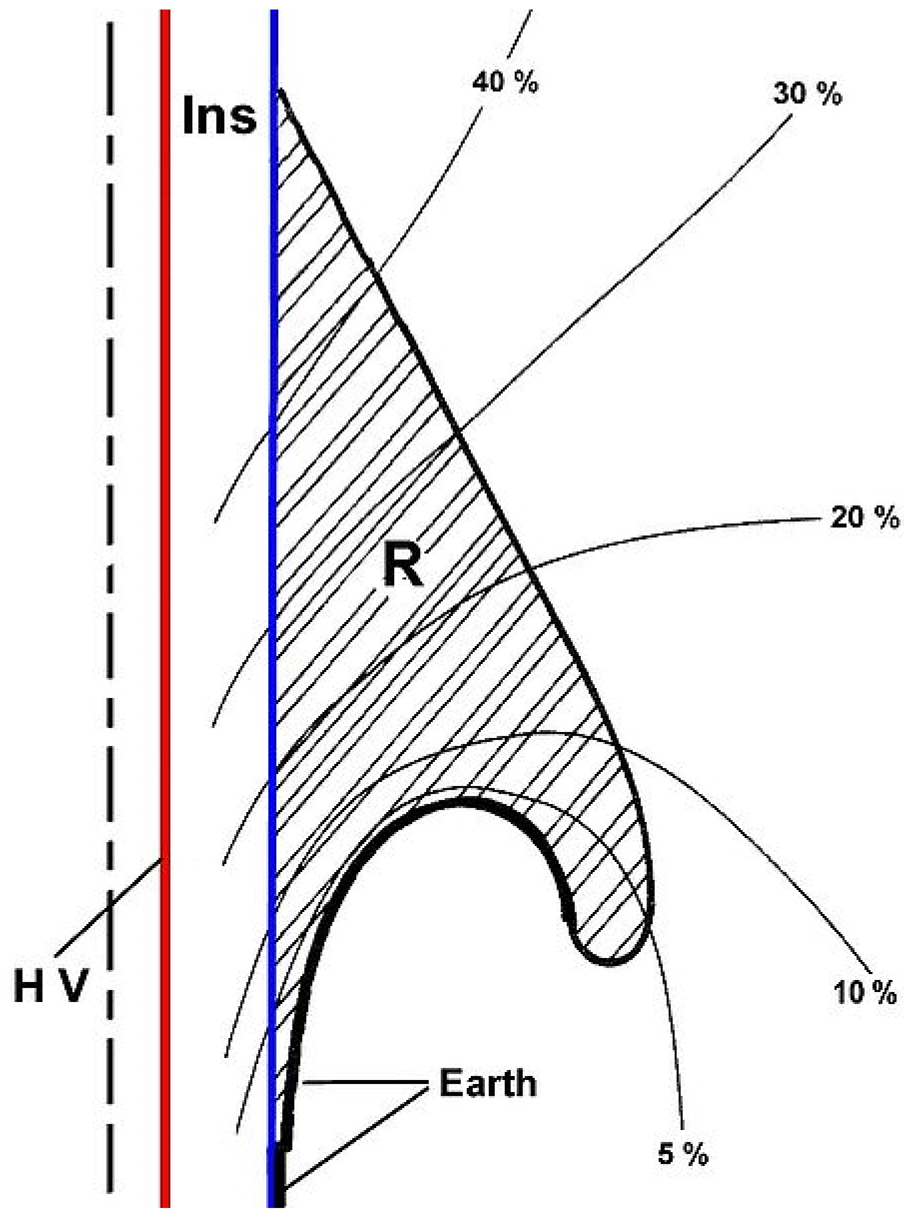



Figure 3, a rubber or elastomer body **R** is pushed over the insulation (blue) of the cable. The equipotential lines between **HV** (high voltage) and **earth** are evenly spread out by the shape of the earth electrode. Field concentrations are prevented in this way.

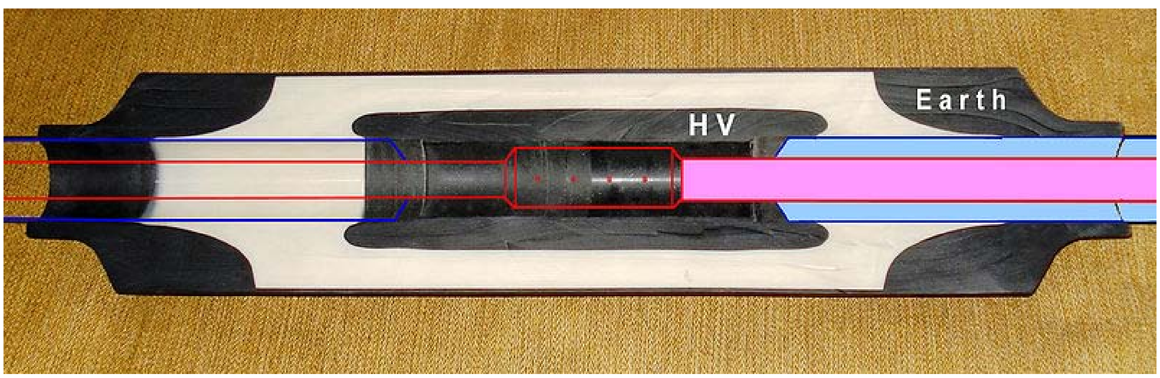
In order to control the equipotential lines (that is to control the electric field) a device is used that is called a **stress-cone**, see figure 3. The crux of stress relief is to flare the shield end along a logarithmic curve. Before 1960, the stress cones were hand made using tape—after the cable was installed. These were protected by potheads, so named because a potting compound/ dielectric was poured around the tape inside a metal/ porcelain body insulators. About 1960, preformed terminations were developed. Shuch consists of a rubber or elastomer body that is stretched over the cable end. On this rubber-like body **R** an **earth**electrode is applied that spreads the equipotential lines. These lines pass the surface of the body after they have sufficiently been spread out to guarantee a low electric field.

The crux of this device, invented by NKF in Delft in 1964, is the fact that the bore of the elastic body R is narrower than the diameter of the cable. In this way the (blue) interface between cable and stress-cone is brought under mechanical pressure so that no cavities or air-pockets can be formed between cable and cone. Electric breakdown in this region is prevented in this way.

This construction can further be surrounded by a porcelain or silicone insulator for outdoor use, or by contraptions to enter the cable into a power transformer under oil, or switchgear under gas-pressure.

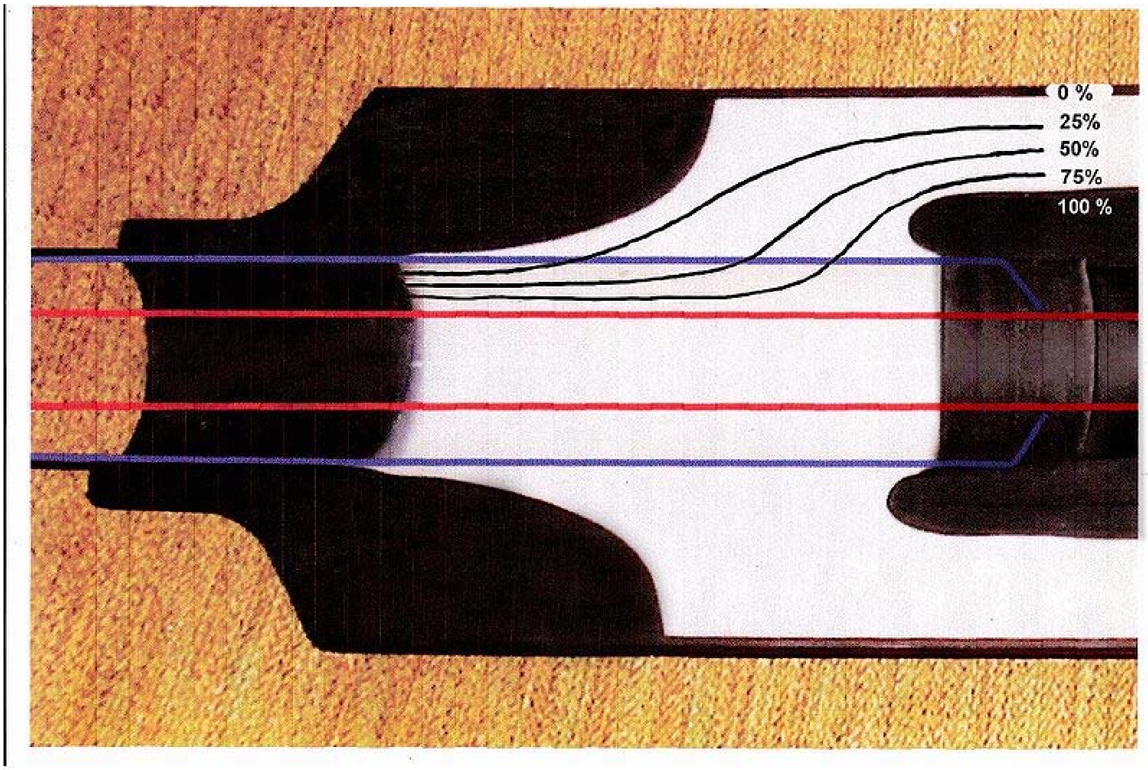
## *Cable joints*

Connecting two high-voltage cables with one another poses two main problems. First, the outer conducting layers in both cables shall be terminated without causing a field concentration, similar as with the making of a cable terminal. Secondly, a field free space shall be created where the cut-down cable insulation and the connector of the two conductors safely can be accommodated. These problems have been solved by NKF in Delft in 1965 by introducing a device called **bi-manchet**.




Photograph of a section of a high-voltage joint, **bi-manchet**, with a high voltage cable mounted at the right hand side of the device.

Figure 4 shows a photograph of the cross-section of such a device. At one side of this photograph the contours of a high voltage cable are drawn. Here **red** represents the conductor of that cable and **blue** the insulation of the cable. The black parts in this picture are semi-conducting rubber parts. The outer one is at earth potential and spreads the electric field in a similar way as in a cable terminal. The inner one is at high-voltage and shields the connector of the conductors from the electric field.
The field itself is diverted as shown in figure 5, where the equipotential lines are smoothly directed from the inside of the cable to the outer part of the bi-manchet (and vice versa at the other side of the device).




Field distribution in a **bi-manchet** or HV joint.

The crux of the matter is here, like in the cable terminal, that the inner bore of this bi-manchet is chosen smaller than the diameter over the cable-insulation. In this way a permanent pressure is created between the bi-manchet and the cable surface and cavities or electrical weak points are avoided.

Installing a terminal or bi-manchet is skilled work. Removing the outer semiconducting layer at the end of the cables, placing the field-controlling bodies, connecting the conductors, etc., require skill, cleanness and precision.

## *X-ray cable*

X-ray cables are used in lengths of some meters to connect the HV source with an X-ray tube or any other HV device in scientific equipment. They transmit small currents, in the order of milliamperes at DC voltages of 30 to 200 kV, or sometimes higher. The cables are flexible, with rubber or other elastomer insulation, stranded conductors, and an outer sheath of braided copper-wire. The construction has the same elements as other HV power cables.