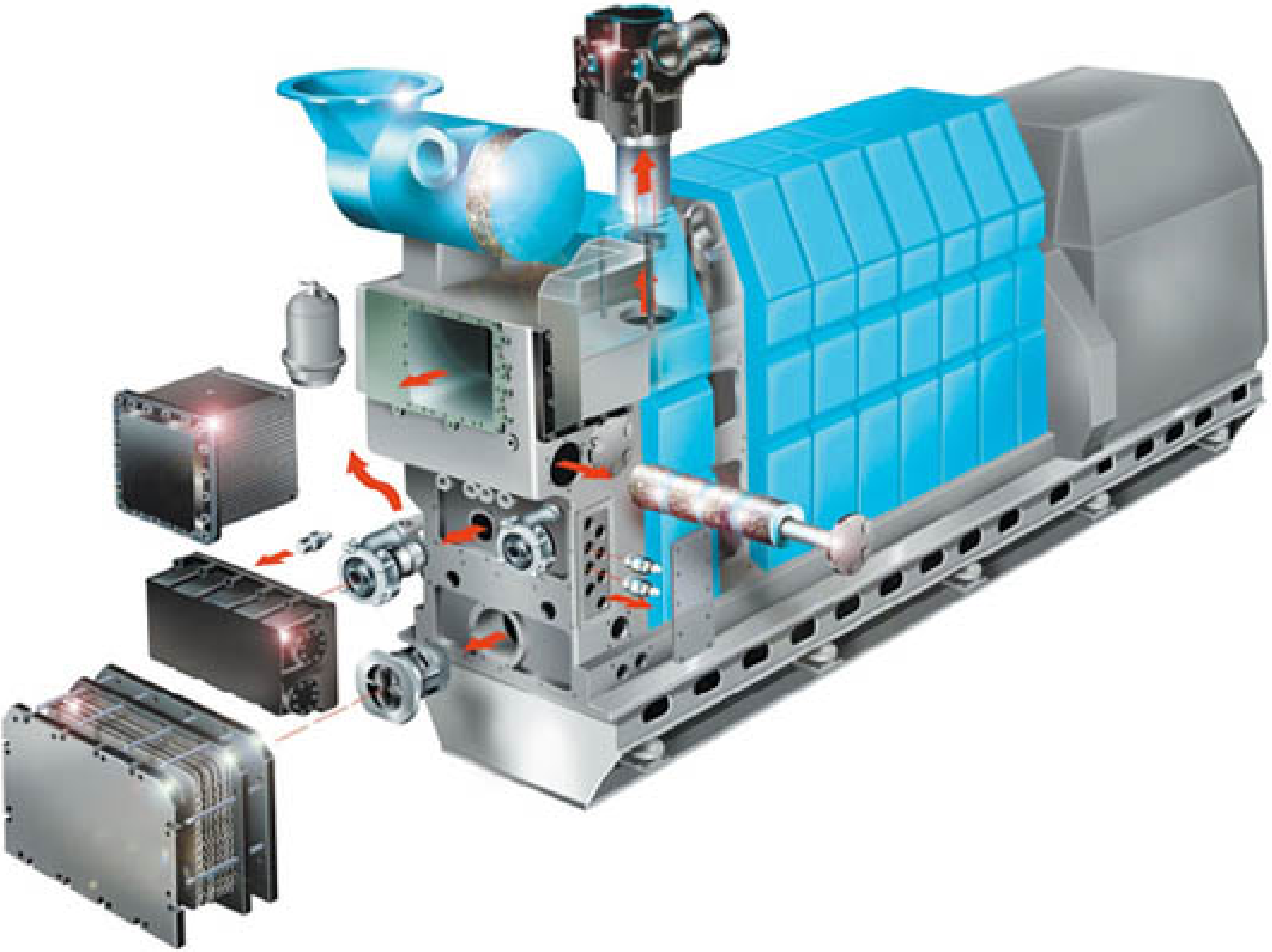
Elements and Components of Electrical Power Engineering



Fatima Merriman

First Edition, 2012

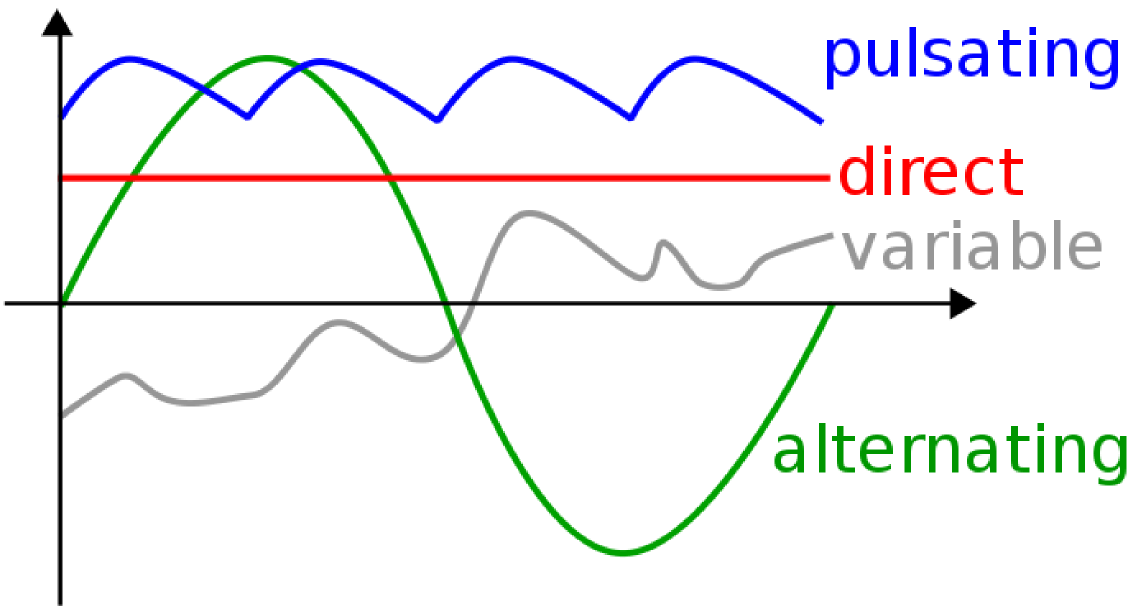
ISBN 978-81-323-3544-3

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

Table of Contents

Chapter- 1

Alternating Current

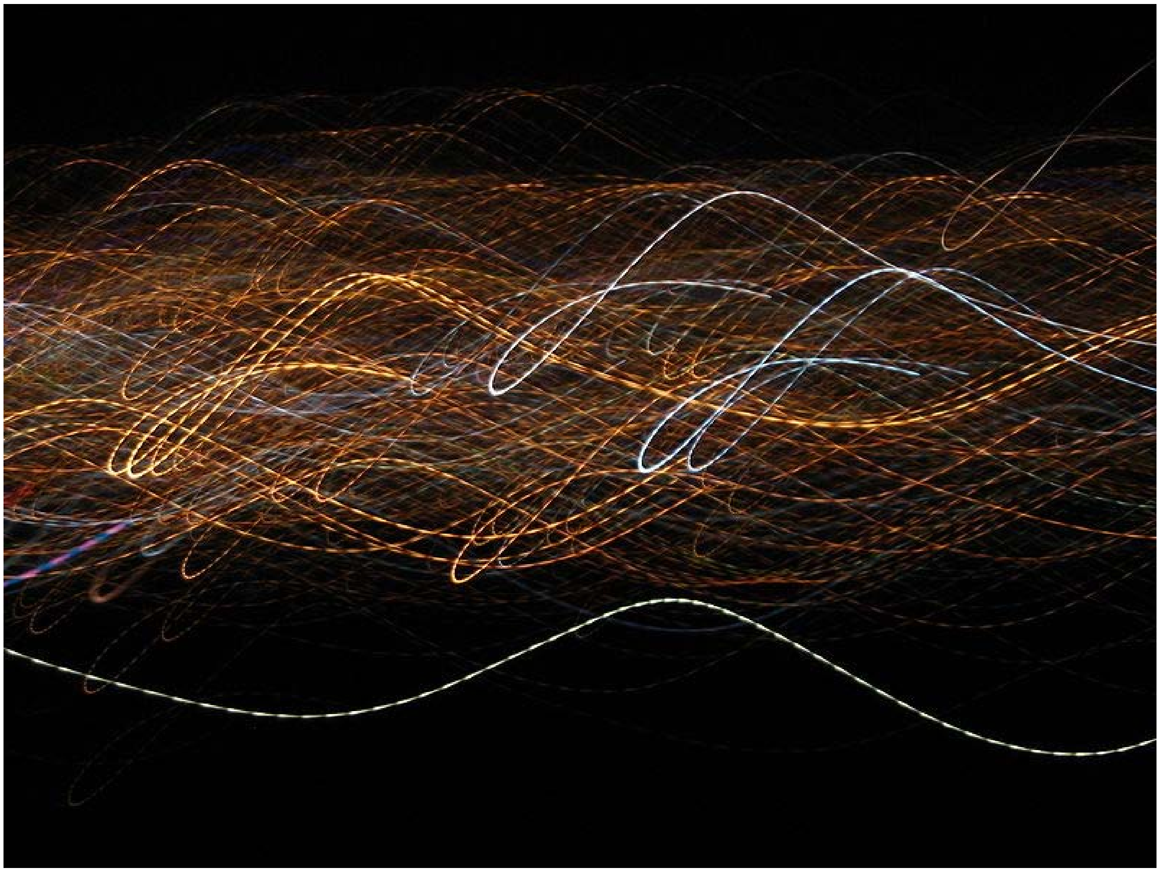


Alternating Current (green curve). The horizontal axis measures time; the vertical, current or voltage.

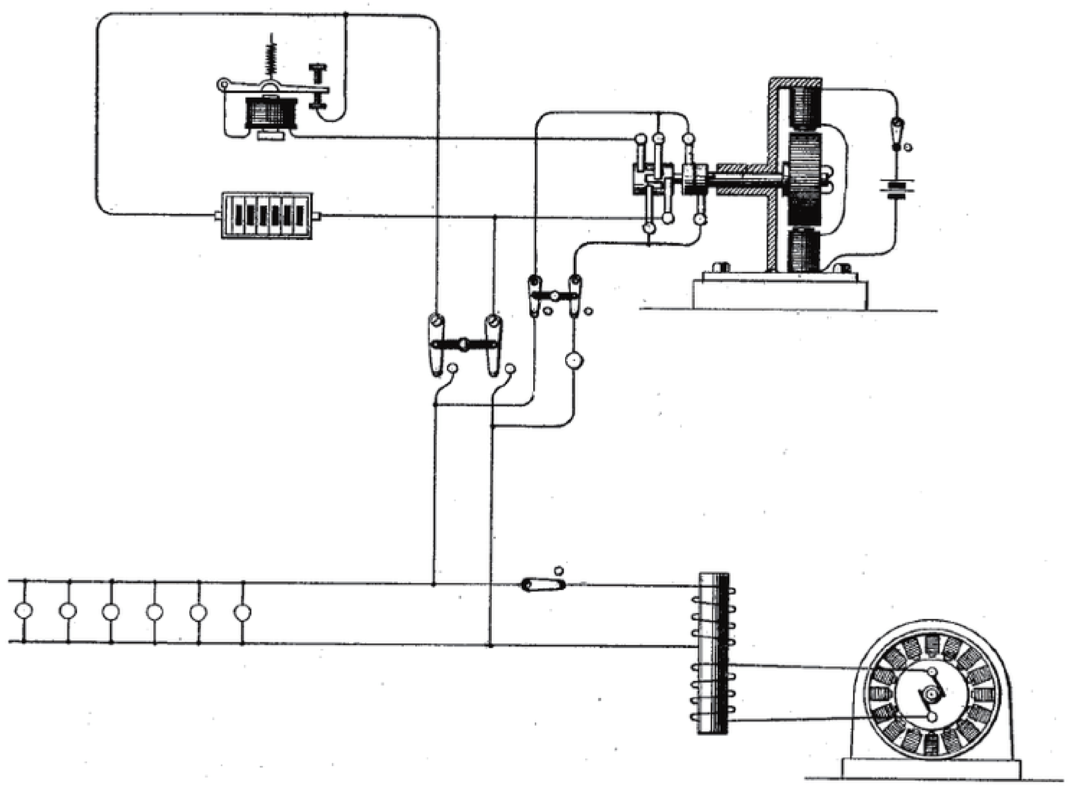
In **alternating current** (**AC,** also **ac**) the movement of electric charge periodically reverses direction. In direct current (DC), the flow of electric charge is only in one direction.

AC is the form in which electric power is delivered to businesses and residences. The usual waveform of an AC power circuit is a sine wave. In certain applications, different waveforms are used, such as triangular or square waves. Audio and radio signals carried on electrical wires are also examples of alternating current. In these applications, an important goal is often the recovery of information encoded (or modulated) onto the AC signal.

History



City lights viewed in a motion blurred exposure. The AC blinking causes the lines to be dotted rather than continuous.



Westinghouse Early AC System 1887
(US patent 373035)

The earliest recorded practical application of alternating current is by Guillaume Duchenne, inventor and developer of electrotherapy. In 1855, he announced that AC was superior to direct current for electrotherapeutic triggering of muscle contractions.

A power transformer developed by Lucien Gaulard and John Dixon Gibbs was demonstrated in London in 1881, and attracted the interest of Westinghouse. They also exhibited the invention in Turin in 1884, where it was adopted for an electric lighting system. Many of their designs were adapted to the particular laws governing electrical distribution in the UK.

In 1882, 1884, and 1885 Gaulard and Gibbs applied for patents on their transformer; however, these were overturned due to prior arts of Nikola Tesla and actions initiated by Sebastian Ziani de Ferranti.

Ferranti went into this business in 1882 when he set up a shop in London designing various electrical devices. Ferranti believed in the success of alternating current power distribution early on, and was one of the few experts in this system in the UK. In 1887 the London Electric Supply Corporation (LESCo) hired Ferranti for the design of their power station at Deptford. He designed the building, the generating plant and the distribution system. On its completion in 1891 it was the first truly modern power station, supplying high-voltage AC power that was then "stepped down" for consumer use on each street. This basic system remains in use today around the world. Many homes all over the world still have electric meters with the Ferranti AC patent stamped on them.

William Stanley, Jr. designed one of the first practical devices to transfer AC power efficiently between isolated circuits. Using pairs of coils wound on a common iron core, his design, called an induction coil, was an early transformer. The AC power system used today developed rapidly after 1886, and includes key concepts by Nikola Tesla, who subsequently sold his patent to George Westinghouse. Lucien Gaulard, John Dixon Gibbs, Carl Wilhelm Siemens and others contributed subsequently to this field. AC systems overcame the limitations of the direct current system used by Thomas Edison to distribute electricity efficiently over long distances even though Edison attempted to discredit alternating current as too dangerous during the War of Currents.

The first commercial power plant in the United States using three-phase alternating current was at the Mill Creek No. 1 Hydroelectric Plant near Redlands, California, in 1893 designed by Almirian Decker. Decker's design incorporated 10,000-volt three-phase transmission and established the standards for the complete system of generation, transmission and motors used today.

The Ames Hydroelectric Generating Plant (spring of 1891) and the original Niagara Falls Adams Power Plant (August 25, 1895) were among the first AC-powered hydroelectric plants.

The Jaruga Hydroelectric Power Plant in Croatia was set in operation on 28 August 1895. The two generators (42 Hz, 550 kW each) and the transformers were produced and installed by the Hungarian company Ganz. The transmission line from the power plant to the City of Šibenik was 11.5 kilometers (7.1 mi) long on wooden towers, and the municipal distribution grid 3000 V/110 V included six transforming stations.

Alternating current circuit theory developed rapidly in the latter part of the 19th and early 20th century. Notable contributors to the theoretical basis of alternating current calculations include Charles Steinmetz, James Clerk Maxwell, Oliver Heaviside, and many others. Calculations in unbalanced three-phase systems were simplified by the symmetrical components methods discussed by Charles Legeyt Fortescue in 1918. .

Transmission, distribution, and domestic power supply

Alternating Current voltage may be increased or decreased with a transformer. Use of a higher voltage leads to significantly more efficient transmission of power. The power losses in a conductor are a product of the square of the current and the resistance of the conductor, described by the formula

$$P_{\mathrm{L}} = I^2 R\,.$$

This means that when transmitting a fixed power on a given wire, if the current is doubled, the power loss will be four times greater.

The power transmitted is equal to the product of the current and the voltage (assuming no phase difference); that is,

$$P_{\mathrm{T}} = IV \, .$$

Thus, the same amount of power can be transmitted with a lower current by increasing the voltage. It is therefore advantageous when transmitting large amounts of power to distribute the power with high voltages (often hundreds of kilovolts).

High voltage transmission lines deliver power from electric generation plants over long distances using alternating current. These lines are located in eastern Utah.

However, high voltages also have disadvantages, the main one being the increased insulation required, and generally increased difficulty in their safe handling. In a power plant, power is generated at a convenient voltage for the design of a generator, and then stepped up to a high voltage for transmission. Near the loads, the transmission voltage is stepped down to the voltages used by equipment. Consumer voltages vary depending on the country and size of load, but generally motors and lighting are built to use up to a few hundred volts between phases.

The utilization voltage delivered to equipment such as lighting and motor loads is standardized, with an allowable range of voltage over which equipment is expected to operate. Standard power utilization voltages and percentage tolerance vary in the different mains power systems found in the world.

Modern high-voltage, direct-current electric power transmission systems contrast with the more common alternating-current systems as a means for the efficient bulk transmission of electrical power over long distances. HVDC systems, however, tend to be more expensive and less efficient over shorter distances than transformers. Transmission with high voltage direct current was not feasible when Edison, Westinghouse and Tesla were designing their power systems, since there was then no way to economically convert AC power to DC and back again at the necessary voltages.

Three-phase electrical generation is very common. The simplest case is three separate coils in the generator stator that are physically offset by an angle of 120° to each other. Three current waveforms are produced that are equal in magnitude and 120° out of phase to each other. If coils are added opposite to these (60° spacing), they generate the same phases with reverse polarity and so can be simply wired together.

In practice, higher "pole orders" are commonly used. For example, a 12-pole machine would have 36 coils (10° spacing). The advantage is that lower speeds can be used. For example, a 2-pole machine running at 3600 rpm and a 12-pole machine running at 600 rpm produce the same frequency. This is much more practical for larger machines.

If the load on a three-phase system is balanced equally among the phases, no current flows through the neutral point. Even in the worst-case unbalanced (linear) load, the neutral current will not exceed the highest of the phase currents. Non-linear loads (e.g. computers) may require an oversized neutral bus and neutral conductor in the upstream distribution panel to handle harmonics. Harmonics can cause neutral conductor current levels to exceed that of one or all phase conductors.

For three-phase at utilization voltages a four-wire system is often used. When stepping down three-phase, a transformer with a Delta (3-wire) primary and a Star (4-wire, center-earthed) secondary is often used so there is no need for a neutral on the supply side.

For smaller customers (just how small varies by country and age of the installation) only a single phase and the neutral or two phases and the neutral are taken to the property. For larger installations all three phases and the neutral are taken to the main distribution panel. From the three-phase main panel, both single and three-phase circuits may lead off.

Three-wire single-phase systems, with a single center-tapped transformer giving two live conductors, is a common distribution scheme for residential and small commercial buildings in North America. This arrangement is sometimes incorrectly referred to as "two phase". A similar method is used for a different reason on construction sites in the UK. Small power tools and lighting are supposed to be supplied by a local center-tapped transformer with a voltage of 55 V between each power conductor and earth. This significantly reduces the risk of electric shock in the event that one of the live conductors becomes exposed through an equipment fault whilst still allowing a reasonable voltage of 110 V between the two conductors for running the tools.

A third wire, called the bond (or earth) wire, is often connected between non-current-carrying metal enclosures and earth ground. This conductor provides protection from electric shock due to accidental contact of circuit conductors with the metal chassis of portable appliances and tools. Bonding all non-current-carrying metal parts into one complete system ensures there is always a low electrical impedance path to ground sufficient to carry any fault current for as long as it takes for the system to clear the fault. This low impedance path allows the maximum amount of fault current, causing the overcurrent protection device (breakers, fuses) to trip or burn out as quickly as possible, bringing the electrical system to a safe state. All bond wires are bonded to ground at the main service panel, as is the Neutral/Identified conductor if present.

AC power supply frequencies

The frequency of the electrical system varies by country; most electric power is generated at either 50 or 60 Hz. Some countries have a mixture of 50 Hz and 60 Hz supplies, notably Japan.

A low frequency eases the design of low-speed electric motors, particularly for hoisting, crushing and rolling applications, and commutator-type traction motors for applications such as railways, but also causes a noticeable flicker in incandescent lighting and an objectionable flicker in fluorescent lamps. 16.7 Hz power (in former times nominal 16 2/3 cycles per second, practically invariably) is still used in some European rail systems, such as in Austria, Germany, Norway, Sweden and Switzerland. The use of lower frequencies also provided the advantage of lower impedance losses, which are proportional to frequency. The original Niagara Falls generators were built to produce 25 Hz power, as a compromise between low frequency for traction and heavy induction motors, while still allowing incandescent lighting to operate (although with noticeable flicker); most of the 25 Hz residential and commercial customers for Niagara Falls power were converted to 60 Hz by the late 1950s, although some 25 Hz industrial customers still existed as of the start of the 21st century.

Off-shore, military, textile industry, marine, computer mainframe, aircraft, and spacecraft applications sometimes use 400 Hz, for benefits of reduced weight of apparatus or higher motor speeds.

Effects at high frequencies

A direct current flows constantly and uniformly throughout the cross-section of a uniform wire. An alternating current of any frequency is forced away from the wire's center, toward its outer surface. This is because the acceleration of an electric charge in an alternating current produces waves of electromagnetic radiation that cancel the propagation of electricity toward the center of materials with high conductivity. This phenomenon is called skin effect.

At very high frequencies the current no longer flows *in* the wire, but effectively flows *on* the surface of the wire, within a thickness of a few skin depths. The skin depth is the thickness at which the current density is reduced by 63%. Even at relatively low frequencies used for high power transmission (50–60 Hz), non-uniform distribution of current still occurs in sufficiently thick conductors. For example, the skin depth of a copper conductor is approximately 8.57 mm at 60 Hz, so high current conductors are usually hollow to reduce their mass and cost.

Since the current tends to flow in the periphery of conductors, the effective cross-section of the conductor is reduced. This increases the effective AC resistance of the conductor, since resistance is inversely proportional to the cross-sectional area in which the current actually flows. The AC resistance often is many times higher than the DC resistance, causing a much higher energy loss due to ohmic heating (also called I^2R loss).

Techniques for reducing AC resistance

For low to medium frequencies, conductors can be divided into stranded wires, each insulated from one other, and the relative positions of individual strands specially arranged within the conductor bundle. Wire constructed using this technique is called Litz wire. This measure helps to partially mitigate skin effect by forcing more equal current throughout the total cross section of the stranded conductors. Litz wire is used for making high-Q inductors, reducing losses in flexible conductors carrying very high currents at lower frequencies, and in the windings of devices carrying higher radio frequency current (up to hundreds of kilohertz), such as switch-mode power supplies and radio frequency transformers.

Techniques for reducing radiation loss

As written above, an alternating current is made of electric charge under periodic acceleration, which causes radiation of electromagnetic waves. Energy that is radiated is lost. Depending on the frequency, different techniques are used to minimize the loss due to radiation.

Twisted pairs

At frequencies up to about 1 GHz, pairs of wires are twisted together in a cable, forming a twisted pair. This reduces losses from electromagnetic radiation and inductive coupling. A twisted pair must be used with a balanced signalling system, so that the two wires carry equal but opposite currents. Each wire in a twisted pair radiates a signal, but it is effectively cancelled by radiation from the other wire, resulting in almost no radiation loss.

Coaxial cables

Coaxial cables are commonly used at audio frequencies and above for convenience. A coaxial cable has a conductive wire inside a conductive tube, separated by a dielectric layer. The current flowing on the inner conductor is equal and opposite to the current flowing on the inner surface of the tube. The electromagnetic field is thus completely contained within the tube, and (ideally) no energy is lost to radiation or coupling outside the tube. Coaxial cables have acceptably small losses for frequencies up to about 5 GHz. For microwave frequencies greater than 5 GHz, the losses (due mainly to the electrical resistance of the central conductor) become too large, making waveguides a more efficient medium for transmitting energy. Coaxial cables with an air rather than solid dielectric are preferred as they transmit power with lower losses.

Waveguides

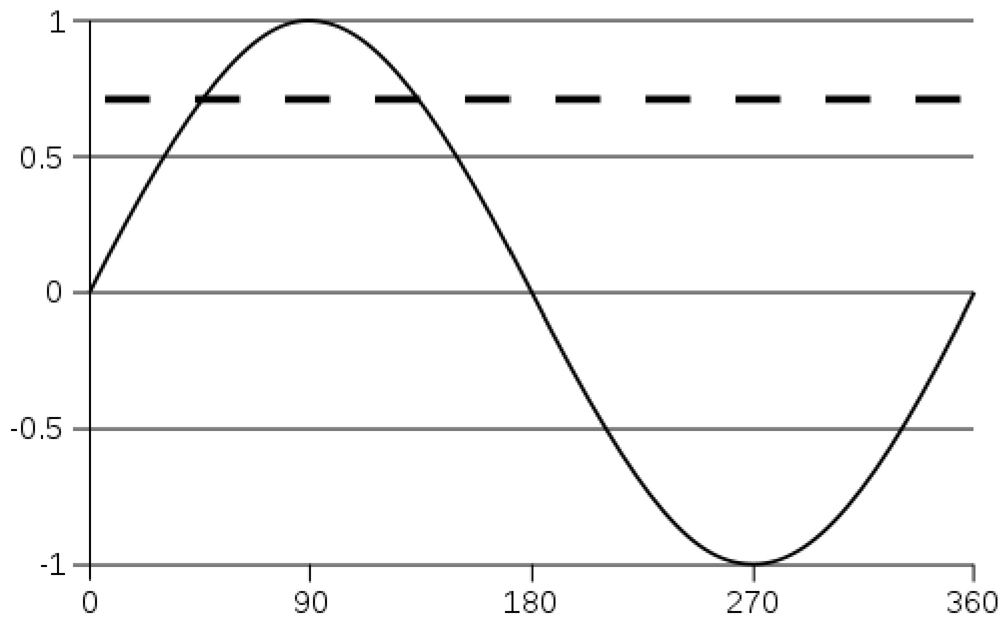
Waveguides are similar to coax cables, as both consist of tubes, with the biggest difference being that the waveguide has no inner conductor. Waveguides can have any arbitrary cross section, but rectangular cross sections are the most common. Because waveguides do not have an inner conductor to carry a return current, waveguides cannot deliver energy by means of an electric current, but rather by means of a *guided* electromagnetic field. Although surface currents do flow on the inner walls of the waveguides, those surface currents do not carry power. Power is carried by the guided electromagnetic fields. The surface currents are set up by the guided electromagnetic fields and have the effect of keeping the fields inside the waveguide and preventing leakage of the fields to the space outside the waveguide.

Waveguides have dimensions comparable to the wavelength of the alternating current to be transmitted, so they are only feasible at microwave frequencies. In addition to this mechanical feasibility, electrical resistance of the non-ideal metals forming the walls of the waveguide cause dissipation of power (surface currents flowing on lossy conductors dissipate power). At higher frequencies, the power lost to this dissipation becomes unacceptably large.

Fiber optics

At frequencies greater than 200 GHz, waveguide dimensions become impractically small, and the ohmic losses in the waveguide walls become large. Instead, fiber optics, which are a form of dielectric waveguides, can be used. For such frequencies, the concepts of voltages and currents are no longer used.

Mathematics of AC voltages



A sine wave, over one cycle (360°). The dashed line represents the root mean square (RMS) value at about 0.707

Alternating currents are accompanied (or caused) by alternating voltages. An AC voltage *v* can be described mathematically as a function of time by the following equation:

$$v(t) = V_{\mathrm{peak}} \cdot \sin(\omega t),$$

where

- V_{peak} is the peak voltage (unit: volt),
- ω is the angular frequency (unit: radians per second)
    - The angular frequency is related to the physical frequency, f (unit = hertz), which represents the number of cycles per second , by the equation $\omega = 2\pi f$.
- t is the time (unit: second).

The peak-to-peak value of an AC voltage is defined as the difference between its positive peak and its negative peak. Since the maximum value of sin(*x*) is +1 and the minimum value is −1, an AC voltage swings between $+V_{\mathrm{peak}}$ and $-V_{\mathrm{peak}}$. The peak-to-peak voltage, usually written as V_{pp} or $V_{\mathrm{P-P}}$, is therefore $V_{\mathrm{peak}} - (-V_{\mathrm{peak}}) = 2V_{\mathrm{peak}}$.

Power and root mean square

The relationship between voltage and the power delivered is

$$p(t) = \frac{v^2(t)}{R}$$ where R represents a load resistance.

Rather than using instantaneous power, $p(t)$, it is more practical to use a time averaged power (where the averaging is performed over any integer number of cycles). Therefore, AC voltage is often expressed as a root mean square (RMS) value, written as V_{rms}, because

$$P_{\text{time averaged}} = \frac{V^2{}_{\text{rms}}}{R}.$$

For a sinusoidal voltage:

$$V_{\text{rms}} = \frac{V_{\text{peak}}}{\sqrt{2}}.$$

The factor $\sqrt{2}$ is called the crest factor, which varies for different waveforms.

- For a triangle wave form centered about zero

$$V_{\text{rms}} = \frac{V_{\text{peak}}}{\sqrt{3}}.$$

- For a square wave form centered about zero

$$V_{\text{rms}} = V_{\text{peak}}.$$

Example

To illustrate these concepts, consider a 230 V AC mains supply used in many countries around the world. It is so called because its root mean square value is 230 V. This means that the time-averaged power delivered is equivalent to the power delivered by a DC voltage of 230 V. To determine the peak voltage (amplitude), we can rearrange the above equation to:

$$V_{\text{peak}} = \sqrt{2}\ V_{\text{rms}}.$$

For our 230 V AC, the peak voltage V_{peak} is therefore $230V \times \sqrt{2}$, which is about 325 V. The peak-to-peak value V_{P-P} of the 230 V AC is double that, at about 650 V.

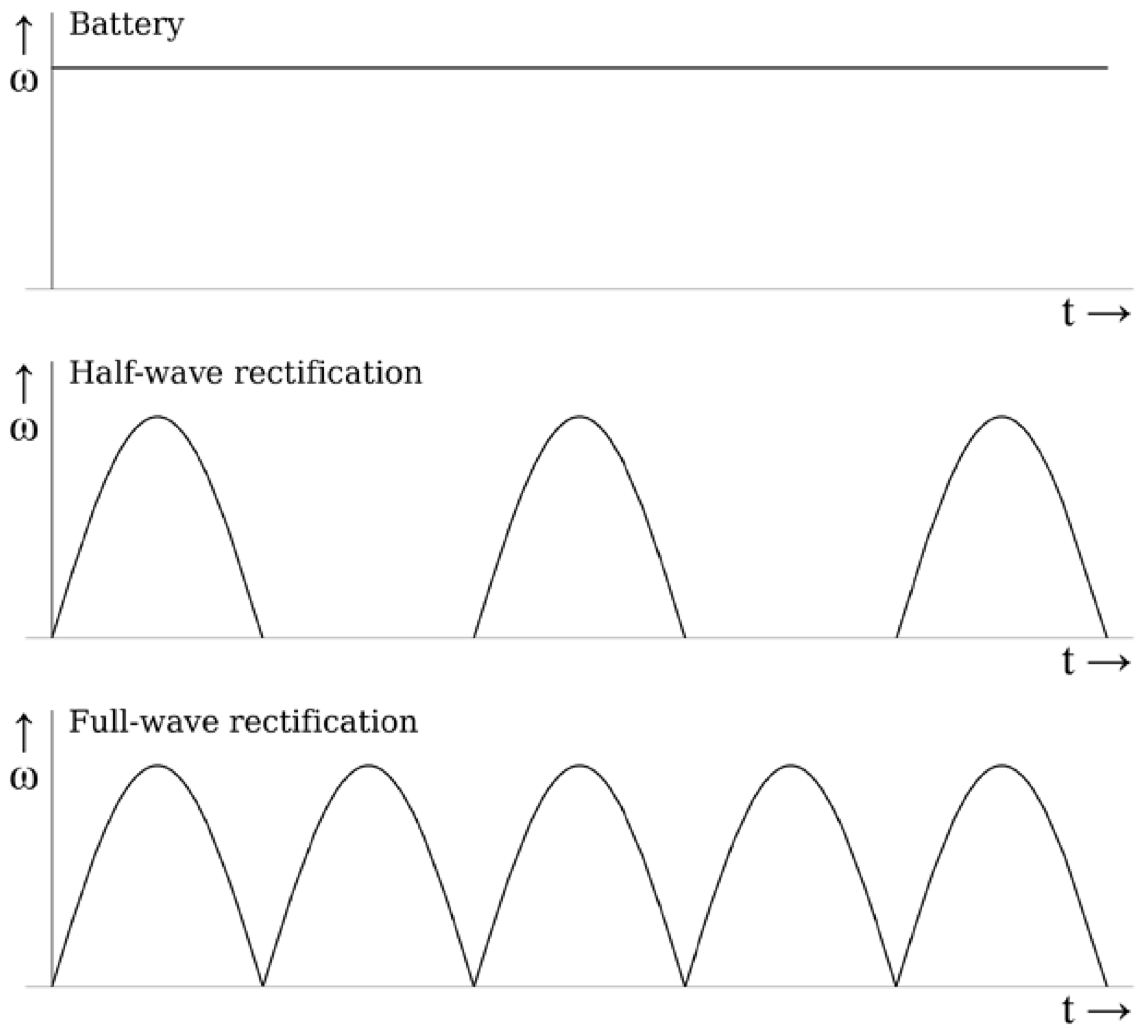
Note that some countries use a frequency of 50 Hz, while others use a frequency of 60 Hz. The calculation to convert from RMS voltage to peak voltage is independent of the frequency.

Chapter- 2

Direct Current & Ward Leonard Control

Direct current

Direct current (**DC**) is the unidirectional flow of electric charge. Direct current is produced by such sources as batteries, thermocouples, solar cells, and commutator-type electric machines of the dynamo type. Direct current may flow in a conductor such as a wire, but can also be through semiconductors, insulators, or even through a vacuum as in electron or ion beams. The electric charge flows in a constant direction, distinguishing it from alternating current (AC). A term formerly used for *direct current* was **galvanic current**.



Types of direct current.

Direct current may be obtained from an alternating current supply by use of a current-switching arrangement called a rectifier, which contains electronic elements (usually) or electromechanical elements (historically) that allow current to flow only in one direction. Direct current may be made into alternating current with an inverter or a motor-generator set.

The first commercial electric power transmission (developed by Thomas Edison in the late nineteenth century) used direct current. Because of significant historical advantages of alternating current over direct current in transforming and transmission, electric power distribution was nearly all alternating current until a few years ago. In the mid 1950s, HVDC transmission was developed, which is now replacing the older high voltage alternating current systems. For applications requiring direct current, such as third rail power systems, alternating current is distributed to a substation, which utilizes a rectifier to convert the power to direct current.

Direct current is used to charge batteries, and in nearly all electronic systems as the power supply. Very large quantities of direct-current power are used in production of aluminum and other electrochemical processes. Direct current is used for some railway propulsion, especially in urban areas. High-voltage direct current is used to transmit large amounts of power from remote generation sites or to interconnect alternating current power grids.

Various definitions

Within electrical engineering, the term *DC* is used to refer to power systems that use only one polarity of voltage or current, and to refer to the constant, zero-frequency, or slowly varying local mean value of a voltage or current. For example, the voltage across a DC voltage source is constant as is the current through a DC current source. The DC solution of an electric circuit is the solution where all voltages and currents are constant. It can be shown that any stationary voltage or current waveform can be decomposed into a sum of a DC component and a zero-mean time-varying component; the DC component is defined to be the expected value, or the average value of the voltage or current over all time.

Although DC stands for "direct current", DC often refers to "constant polarity". Under this definition, DC voltages can vary in time, as seen in the raw output of a rectifier or the fluctuating voice signal on a telephone line.

Some forms of DC (such as that produced by a voltage regulator) have almost no variations in voltage, but may still have variations in output power and current.

Applications

Direct-current installations usually have different types of sockets, switches, and fixtures, mostly due to the low voltages used, from those suitable for alternating current. It is usually important with a direct-current appliance not to reverse polarity unless the device has a diode bridge to correct for this (most battery-powered devices do not).

This symbol is found on many electronic devices that either require or produce direct current.

DC is commonly found in many low-voltage applications, especially where these are powered by batteries, which can produce only DC, or solar power systems, since solar cells can produce only DC. Most automotive applications use DC, although the alternator is an AC device which uses a rectifier to produce DC. Most electronic circuits require a

DC power supply. Applications using fuel cells (mixing hydrogen and oxygen together with a catalyst to produce electricity and water as byproducts) also produce only DC.

Many telephones connect to a twisted pair of wires, and internally separate the AC component of the voltage between the two wires (the audio signal) from the DC component of the voltage between the two wires (used to power the phone).

Telephone exchange communication equipment, such as DSLAM, uses standard -48V DC power supply. The negative polarity is achieved by grounding the positive terminal of power supply system and the battery bank. This is done to prevent electrolysis depositions.

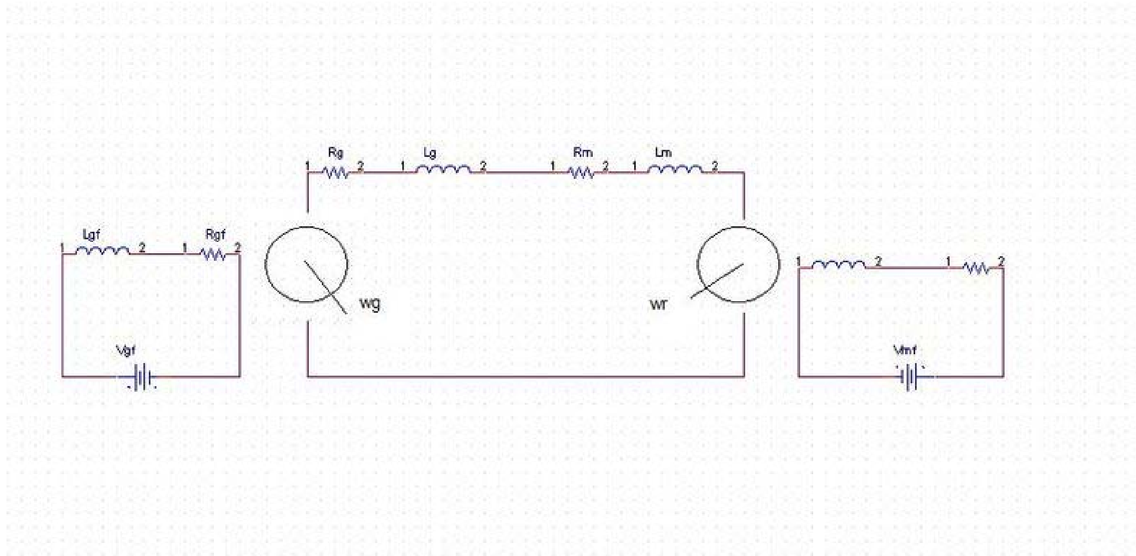
Ward Leonard control

Ward Leonard Control, also known as the Ward Leonard Drive System, was a widely used DC motor speed control system introduced by Harry Ward Leonard in 1891. In early 1900s, the control system of Ward Leonard was adopted by the U.S. Navy and also used in passenger lift of large mines. It also provided a solution to a moving sidewalk at the Paris Exposition of 1900, where many others had failed to operate properly. An outstanding contribution to the war effort was with the use of Ward-Leonard Control systems in antiaircraft radars. Connected to “calculators/directors” the automatic tracking motion in two dimensions had to be extremely smooth and precise. MIT (Rad lab) selected Ward-Leonard to equip the famous radar SCR-584, ca. 1942. *Until the 1980s, when the Ward Leonard control system started to be replaced by other systems, primarily thyristor controllers, it was widely used for elevators because it offered smooth speed control and consistent torque. Many Ward Leonard control systems and variations on them remain in use.

Basic concept

A Ward Leonard drive is a high-power amplifier in the multi-kilowatt range, built from rotating electrical machinery. A Ward Leonard drive unit consists of a motor and generator with shafts coupled together. The motor, which turns at a constant speed, may be AC or DC powered. The generator is a DC generator, with field windings and armature windings. The input to the amplifier is applied to the field windings, and the output comes from the armature windings. The amplifier output is usually connected to a second motor, which moves the load, such as an elevator. With this arrangement, small changes in current applied to the input, and thus the generator field, result in large changes in the output, allowing smooth speed control. Armature voltage control only controls the motor speed from zero to motor base speed. If higher motor speeds are needed the motor field current can be lowered,however by doing this the available torque at the motor armature will be reduced.

A more technical description



A Ward Leonard Control system with generator and motor connected directly.

The speed of motor is controlled by varying the voltage fed from the generator, V_{gf}, which varies the output voltage of the generator. The varied output voltage will change the voltage of the motor, since they are connected directly through the armature. Consequently changing the V_{gf} will control the speed of the motor. The picture of the right shows the Ward Leonard control system, with the V_{gf} feeding the generator and V_{mf} feeding the motor.

Mathematical approach

Among many ways of defining the characteristic of a system, obtaining a transfer characteristic is one of the most commonly used methods. Below are the steps to obtain the transfer function, eq 4.

Before going into the equations, first conventions should be set up, which will follow the convention data used. The first subscripts 'g' and 'm' each represents generator and motor. The superscripts 'f', 'r',and 'a', correspond to field, rotor, and armature.

W_i = plant state vector K = gain t = time constant J = polar moment of inertia D = angular viscous friction G = rotational inductance constant s = Laplace operator

eq 1: The generator field equation

$$V_g^f = R_g^f I_g^f + L_g^f I_g^f$$

eq 2: The equation of electrical equilibrium in the armature circuit

$$-G_g^{fa} I_g^f W_g^r + (R_g^a + R_m^a)\ I^a + (L_g^a + L_m^a)\ I^a + G_m^{fa} I_m^f W_m^r = 0$$

eq 3: Motor torque equation

$$-T_L = J_m W_m^r + D_m W_m^r$$

With total impedance, $L_g^a + L_m^a$, neglected, the transfer function can be obtained by solving eq 3 $T_L = 0$.

eq 4: Transfer function

$$\frac{W_m^r(S)}{V_g^f(S)} = \frac{K_B K_v / D_m}{(t_g^f s + 1)\left[t_m s + \dfrac{K_m}{D_m}\right]}$$

with the constants defined as below.

$$K_B = \frac{G_m^f a V_m^f}{R_m^f (R_g^a + R_m^a)}$$
$$K_v = \frac{G_g^f a W_g^r}{R_g^f}$$
$$t_m = \frac{J_m}{D_m}$$
$$t_g^f = \frac{L_g^f}{R_g^f}$$
$$K_m = D_m + K_B^2 (R_g^a + R_m^a)$$

Chapter- 3

Single-Phase Electric Power & Two-Phase Electric Power

Single-phase electric power

In electrical engineering, **single-phase electric power** refers to the distribution of alternating current electric power using a system in which all the voltages of the supply vary in unison. Single-phase distribution is used when loads are mostly lighting and heating, with few large electric motors. A single-phase supply connected to an alternating current electric motor does not produce a revolving magnetic field; single-phase motors need additional circuits for starting, and such motors are uncommon above 10 or 20 kW in rating.

In contrast, in a three-phase system, the currents in each conductor reach their peak instantaneous values sequentially, not simultaneously; in each cycle of the power frequency, first one, then the second, then the third current reaches its maximum value. The waveforms of the three supply conductors are offset from one another in time (delayed in phase) by one-third of their period.

Standard frequencies of single-phase power systems are either 50 or 60 Hz. Special single-phase traction power networks may operate at 16.67 Hz or other frequencies to power electric railways.

Splitting out

Single phase polemount stepdown transformer (Canadian).

No arrangement of transformers can convert a single-phase load into a balanced load on a polyphase system. A single-phase load may be powered from a three-phase distribution system either by connection between a phase and neutral or by connecting the load between two phases. The load device must be designed for the voltage in each case. The neutral point in a three phase system exists at the mathematical center of an equilateral triangle formed by the three phase points, and the phase-to-phase voltage is accordingly $\sqrt{3}$times the phase-to-neutral voltage. For example, in places using a 415 volt 3 phase system, the phase-to-neutral voltage is 240 volts, allowing single-phase lighting to be connected phase-to-neutral and three-phase motors to be connected to all three phases.

In North America, a typical three-phase system will have 208 volts between the phases and 120 volts between phase and neutral. If heating equipment designed for the 240-volt three-wire single phase system is connected to two phases of a 208 volt supply, it will only produce 75% of its rated heating effect. Single-phase motors may have taps to allow their use on either 208 V or 240 V supplies.

On higher voltage systems (kilovolts) where a single phase transformer is in use to supply a low voltage system the method of splitting varies. In North American utility distribution practice, the primary of the step-down transformer is wired across a single high voltage feed wire and neutral, at least for smaller supplies. Rural distribution may be a single phase at a medium voltage; in some areas single wire earth return distribution is used when customers are very far apart. In Britain the step-down primary is wired phase-phase.

Applications

Single-phase power distribution is widely used especially in rural areas, where the cost of a three-phase distribution network is high and motor loads are small and uncommon.

High power systems, say, hundreds of kVA or larger, are nearly always three phase. The largest supply normally available as single phase varies according to the standards of the electrical utility. In the UK a single-phase household supply may be rated 100 A or even 125 A, meaning that there is little need for 3 phase in a domestic or small commercial environment. Much of the rest of Europe has traditionally had much smaller limits on the size of single phase supplies resulting in even houses being supplied with 3 phase (in urban areas with three-phase supply networks).

In North America, individual residences and small commercial buildings with services up to about 100 kV·A (417 amperes at 240 volts) will usually have three-wire single-phase distribution, often with only one customer per distribution transformer. In exceptional cases larger single-phase three-wire services can be provided, usually only in remote areas where poly-phase distribution is not available. In rural areas farmers who wish to use three-phase motors may install a phase converter if only a single-phase supply is available. Larger consumers such as large buildings, shopping centers, factories, office blocks, and multiple-unit apartment blocks will have three-phase service. In densely populated areas of cities, network power distribution is used with many customers and many supply transformers connected to provide hundreds or thousands of kV·A, a load concentrated over a few hundred square meters.

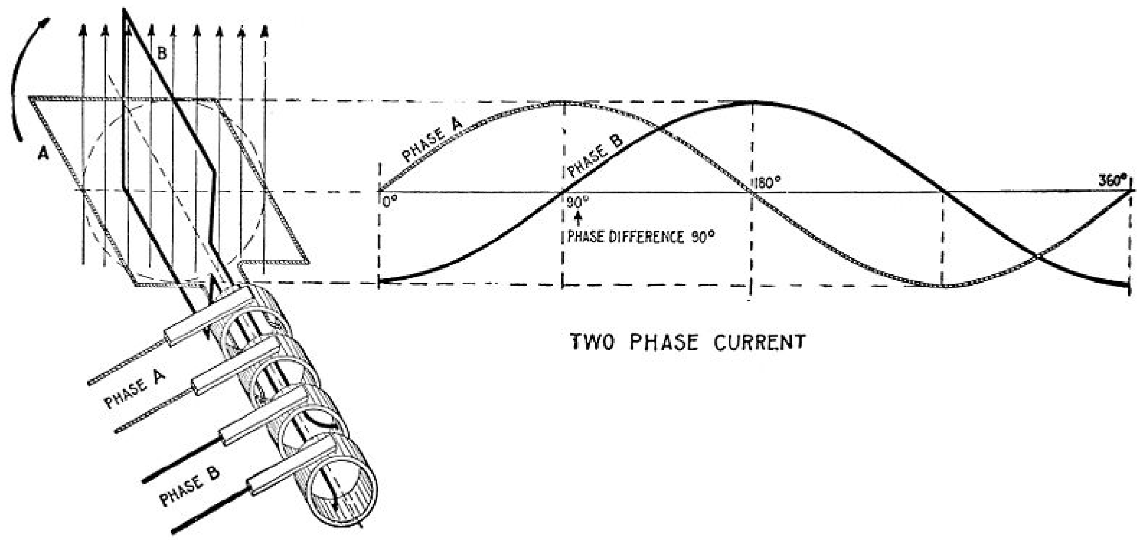
Three-wire single-phase systems are rarely used in the UK where large loads are needed off only two high voltage phases.

Single-phase power may be used for electric railways; the largest single-phase generator in the world, at Neckarwestheim Nuclear Power Plant, supplies a railway system on a dedicated traction power network.

Grounding

Typically a third conductor, called **ground** (or "safety ground") (U.S.) or **protective earth** (Europe, IEC), is used as a protection against electric shock, and ordinarily only carries significant current when there is a circuit fault. Several different earthing systems are in use.

Two-phase electric power



A simplified diagram of a two-phase alternator

Two-phase electrical power was an early 20th century polyphase alternating current electric power distribution system. Two circuits were used, with voltage phases differing by 90 degrees. Usually circuits used four wires, two for each phase. Less frequently, three wires were used, with a common wire with a larger-diameter conductor. Some early two-phase generators had two complete rotor and field assemblies, with windings physically offset by 90 electrical degrees to provide two-phase power. The generators at Niagara Falls installed in 1895 were the largest generators in the world at the time and were two-phase machines.

The advantage of two-phase electrical power was that it allowed for simple, self-starting electric motors. In the early days of electrical engineering, it was easier to analyze and design two-phase systems where the phases were completely separated. It was not until the invention of the method of symmetrical components in 1918 that polyphase power systems had a convenient mathematical tool for describing unbalanced load cases. The revolving magnetic field produced with a two-phase system allowed electric motors to provide torque from zero motor speed, which was not possible with a single-phase induction motor (without extra starting means). Induction motors designed for two-phase operation use the same winding configuration as capacitor start single-phase motors.

Three-phase electric power requires less conductor mass for the same voltage and overall amount of power, compared with a two-phase four-wire circuit of the same carrying capacity. It has all but replaced two-phase power for commercial distribution of electrical energy, but two-phase circuits are still found in certain control systems. Furthermore, power transfer in a three-phase system with balanced loads is nearly constant, whereas it pulsates at twice the line frequency in single-phase systems and four times the line frequency in two-phase systems. These power pulsations tend to cause increased mechanical noise in transformer and motor laminations due to magnestriction and torsional vibration in generator and motor drive shafts.

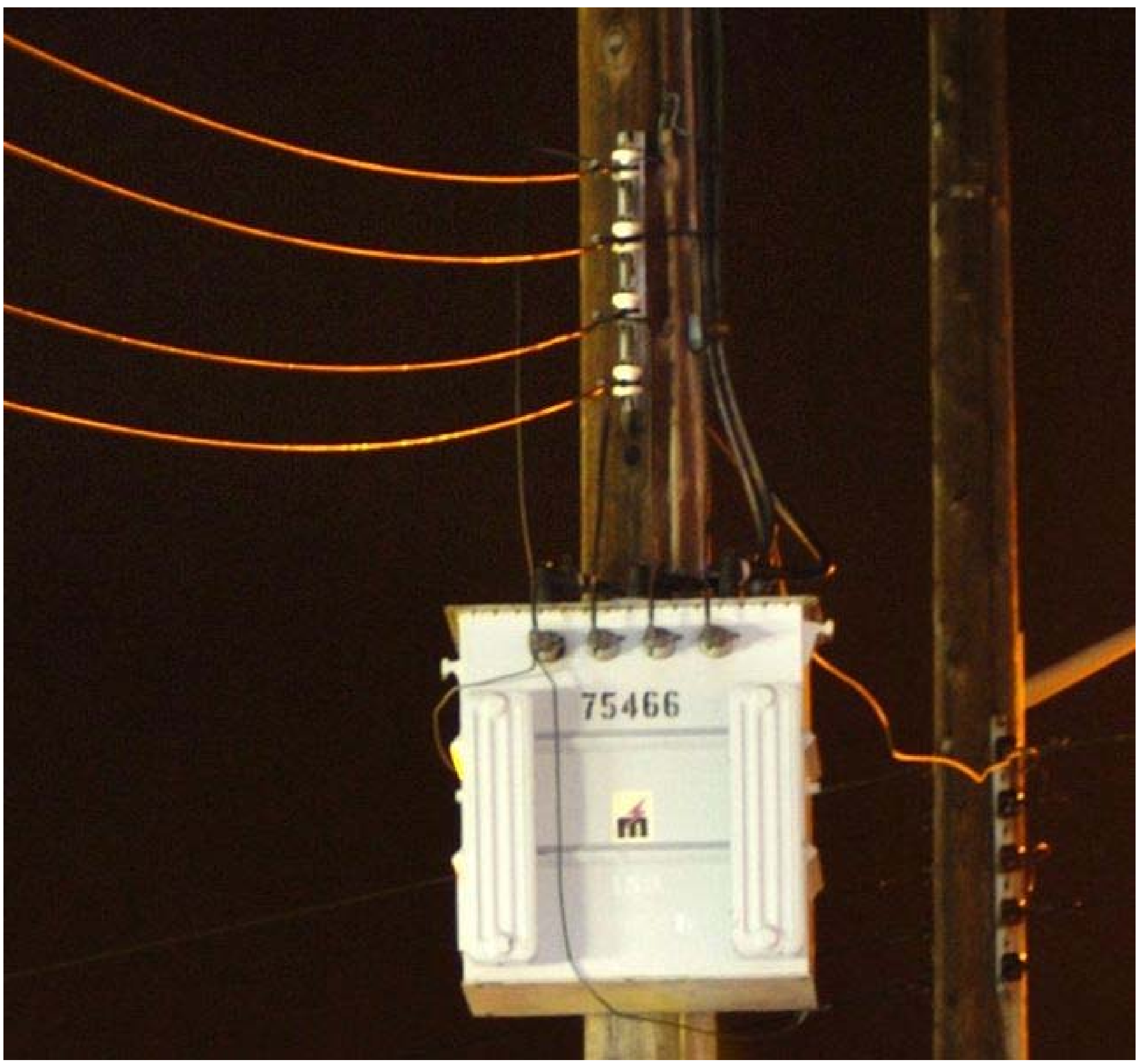
Two-phase circuits typically use two separate pairs of current-carrying conductors. Alternatively, three wires may be used, but the common conductor carries the vector sum of the phase currents, which requires a larger conductor. Three-phase can share conductors so that the three phases can be carried on three conductors of the same size. In electrical power distribution, a requirement of only three conductors, rather than four, represented a considerable distribution-wire cost savings due to the expense of conductors and installation.

Two-phase power can be derived from a three-phase source using two transformers in a Scott connection: One transformer primary is connected across two phases of the supply. The second transformer is connected to a center-tap of the first transformer, and is wound for 86.6% of the phase-to-phase voltage on the three-phase system. The secondaries of the transformers will have two phases 90 degrees apart in time, and a balanced two-phase load will be evenly balanced over the three supply phases.

Three-wire, 120/240 volt single phase power used in the United States and Canada is sometimes incorrectly called "two-phase". The proper term is *split phase* or *3-wire single-phase*. The two live outputs of a 3-wire single phase transformer secondary winding are properly called "legs".

Chapter- 4

Three-Phase Electric Power



Three-phase transformer with four wire output for 208Y/120 volt service: one wire for neutral, others for A, B and C phases.

Three-phase electric power transmission.

Three-phase electric power is a common method of alternating-current electric power generation, transmission, and distribution. It is a type of polyphase system and is the most common method used by grids worldwide to transfer power. It is also used to power large motors and other large loads. A three-phase system is generally more economical than others because it uses less conductor material to transmit electric power than equivalent single-phase or two-phase systems at the same voltage. The three-phase system was introduced and patented by Nikola Tesla in the years from 1887 to 1888.

In a three-phase system, three circuit conductors carry three alternating currents (of the same frequency) which reach their instantaneous peak values at different times. Taking one conductor as the reference, the other two currents are delayed in time by one-third and two-thirds of one cycle of the electric current. This delay between phases has the effect of giving constant power transfer over each cycle of the current and also makes it possible to produce a rotating magnetic field in an electric motor.

Three-phase systems may have a neutral wire. A neutral wire allows the three-phase system to use a higher voltage while still supporting lower-voltage single-phase appliances. In high-voltage distribution situations, it is common not to have a neutral wire as the loads can simply be connected between phases (phase-phase connection).

Three-phase has properties that make it very desirable in electric power systems:

- The phase currents tend to cancel out one another, summing to zero in the case of a linear balanced load. This makes it possible to eliminate or reduce the size of the

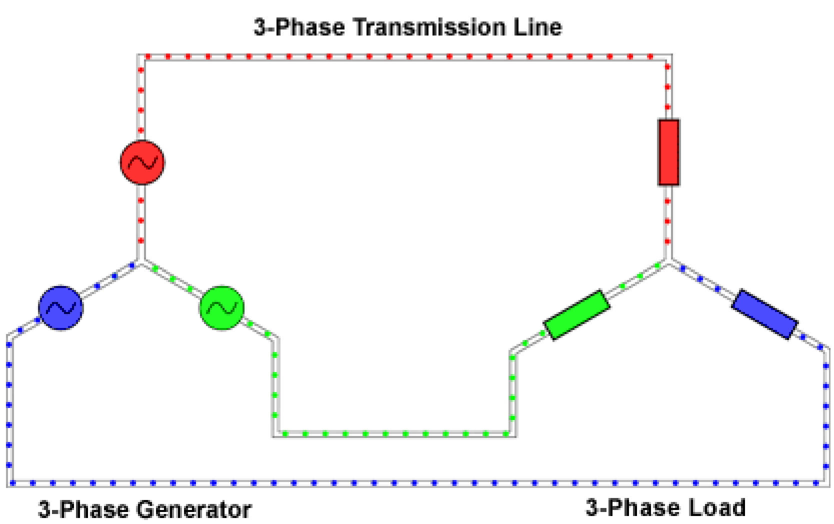
neutral conductor; all the phase conductors carry the same current and so can be the same size, for a balanced load.
- Power transfer into a linear balanced load is constant, which helps to reduce generator and motor vibrations.
- Three-phase systems can produce a magnetic field that rotates in a specified direction, which simplifies the design of electric motors.

Three is the lowest phase order to exhibit all of these properties.

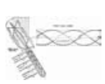
Most household loads are single-phase. In North America and some other countries, three-phase power generally does not enter homes. Even in areas where it does, it is typically split out at the main distribution board and the individual loads are fed from a single phase. Sometimes it is used to power electric stoves and electric clothes dryers.

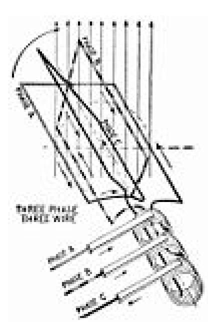
The three phases are typically indicated by colors which vary by country.

Generation and distribution



Three-phase current flow





Left: Elementary six-wire three-phase alternator, with each phase using a separate pair of transmission wires.
Right: Elementary three-wire three-phase alternator,

showing how the phases can share only three wires.

At the power station, an electrical generator converts mechanical power into a set of three alternating electric currents, one from each coil (a.k.a. "winding") of the generator. The windings are arranged such that the currents vary sinusoidally at the same frequency but with the peaks and troughs of their wave forms offset to provide three complementary currents with a phase separation of one-third cycle (120° or $2\pi/3$ radians). The generator frequency is typically 50 or 60 Hz, varying by country.

Large power generators provide an electric current at a potential which can be a few hundred volts or up to about 30 kV. At the power station, transformers step this voltage up to one suitable for transmission.

After numerous further conversions in the transmission and distribution network, the power is finally transformed to the standard utilization voltage for lighting and equipment. Single-phase loads are connected from one phase to neutral or between two phases. Three-phase loads such as larger motors must be connected to all three phases of the supply.

Three-wire versus four-wire

Three-phase circuits occur in two varieties. In one case, there are only three energized ("hot") wires; in the other case, there are three hot wires plus a neutral wire. Four-wire circuits offer flexibility, since a load may be connected "line-to-line" or "line-to-neutral"; three-wire circuits offer economy, since the neutral conductor is eliminated. Commonly, distribution voltage circuits are four-wire, while higher voltage transmission circuits are three-wire. Transmission lines often figure a ground wire, but this is solely for lightning protection and is not connected to deliver electrical power.

Single-phase loads

Single-phase loads may be connected to a three-phase system in two ways. Either a load may be connected across two of the live conductors, or a load can be connected from a live phase conductor to the neutral conductor. Single-phase loads should be distributed evenly between the phases of the three-phase system for efficient use of the supply transformer and supply conductors. If the line-to-neutral voltage is a standard load voltage, for example 230 volt on a 400 volt three-phase system, single-phase loads can connect to a phase and the neutral. Loads can be distributed over three phases to balance the load. Where the line-to-neutral voltage is not the standard voltage for example 347 volts produced by a 600 V system, single-phase loads are connected through a step-down transformer.

In a symmetrical three-phase system, the system neutral has the same magnitude of voltage to each of the three phase conductors. The voltage between line conductors (V_l) is $\sqrt{3}$ times the phase conductor to neutral voltage (V_p). That is: $V_l=\sqrt{3}V_p$.

In some multiple-unit residential buildings of North America, three-phase power is supplied to the building but individual units have only single-phase power formed from two of the three supply phases. Lighting and convenience receptacles are connected from either phase conductor to neutral, giving the usual 120 V required by typical North American appliances. In the split-phase system, high-power loads are connected between the opposite "hot" poles, giving a voltage of 240 V. In some cases, they may be connected between phases of a three-phase system, giving a voltage of 208 V. This practice is common enough that 208 V single-phase equipment is readily available in North America. Attempts to use the more common 120/240 V equipment intended for split-phase distribution may result in poor performance since 240 V heating and lighting equipment will only produce 75% of its rating when operated at 208 V. Motors rated at 240 V will draw higher curent at 208 V; some motors are dual-labelled for both voltages.

Where three-phase at low voltage is otherwise in use, it may still be split out into single-phase service cables through joints in the supply network or it may be delivered to a master distribution board (breaker panel) at the customer's premises. Connecting an electrical circuit from one phase to the neutral generally supplies the country's standard single phase voltage (120 V AC or 230 V AC) to the circuit.

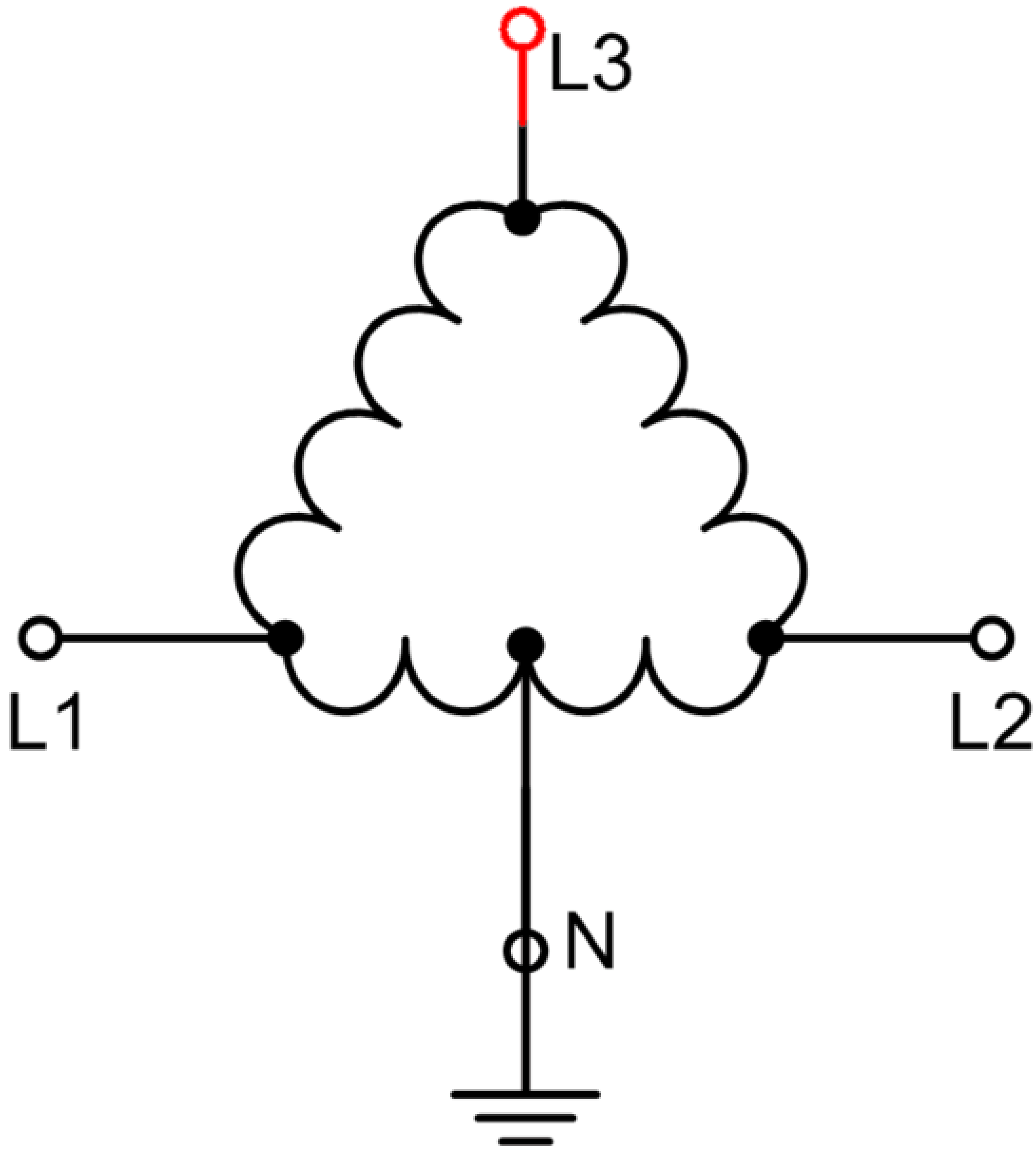
The currents returning from the customers' premises to the supply transformer all share the neutral wire. If the loads are evenly distributed on all three phases, the sum of the returning currents in the neutral wire is approximately zero. Any unbalanced phase loading on the secondary side of the transformer will use the transformer capacity inefficiently.

If the supply neutral of a three-phase system with line-to-neutral connected loads is broken, the voltage balance on the loads will no longer be maintained. The neutral point will tend to drift toward the most heavily loaded phase, causing undervoltage conditions on that phase only. Correspondingly, the lightly loaded phases may approach the line-to-line voltage, which exceeds the line-to-neutral voltage by a factor of $\sqrt{3}$, causing overheating and failure of many types of loads.

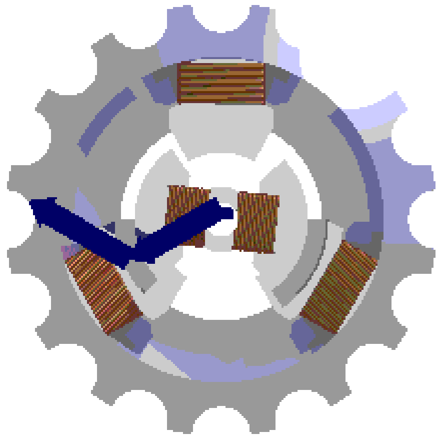
For example, if several houses are connected through a 240 V transformer, which is connected to one phase of the three phase system, each house might be affected by the imbalance on the three phase system. If the neutral connection is broken somewhere in the system, all equipment in a house might be damaged due to over-voltage. A similar phenomenon can exist if the house neutral (connected to the center tap of the 240 V pole transformer) is disconnected. This type of failure event can be difficult to troubleshoot if the drifting neutral effect is not understood. With inductive and/or capacitive loads, all phases can suffer damage as the reactive current moves across abnormal paths in the unbalanced system, especially if resonance conditions occur. For this reason, neutral connections are a critical part of a power distribution network and must be made as reliable as any of the phase connections.

Where a mixture of single-phase 120 volt lighting and three-phase, 240 volt motors are to be supplied, a system called high leg delta is used.

Three-phase loads



A transformer for a high-leg delta system; 240 V 3-phase motors would be connected to L1, L2 and L3. Single-phase lighting would be connected L1 or L2 to neutral (N). No loads would be connected from L3 (the high or wild leg) to neutral, since the voltage would be 208 V.



The rotating magnetic field of a three-phase motor.

The most important class of three-phase load is the electric motor. A three-phase induction motor has a simple design, inherently high starting torque and high efficiency. Such motors are applied in industry for pumps, fans, blowers, compressors, conveyor drives, electric vehicles and many other kinds of motor-driven equipment. A three-phase motor is more compact and less costly than a single-phase motor of the same voltage class and rating and single-phase AC motors above 10 HP (7.5 kW) are uncommon. Three-phase motors also vibrate less and hence last longer than single-phase motors of the same power used under the same conditions.

Resistance heating loads such as electric boilers or space heating may be connected to three-phase systems. Electric lighting may also be similarly connected. These types of loads do not require the revolving magnetic field characteristic of three-phase motors but take advantage of the higher voltage and power level usually associated with three-phase distribution. Legacy fluorescent lighting systems also benefit from reduced flicker if adjacent fixtures are powered from different phases.

Large rectifier systems may have three-phase inputs; the resulting DC is easier to filter (smooth) than the output of a single-phase rectifier. Such rectifiers may be used for battery charging, electrolysis processes such as aluminium production or for operation of DC motors.

An interesting example of a three-phase load is the electric arc furnace used in steelmaking and in refining of ores.

In much of Europe, stoves are designed for a three-phase feed. Usually the individual heating units are connected between phase and neutral to allow for connection to a single-phase supply. In many areas of Europe, single-phase power is the only source available.

Phase converters

Occasionally the advantages of three-phase motors make it worthwhile to convert single-phase power to three-phase. Small customers, such as residential or farm properties, may not have access to a three-phase supply or may not want to pay for the extra cost of a three-phase service but may still wish to use three-phase equipment. Such converters may also allow the frequency to be varied allowing speed control. Some railway locomotives are moving to multi-phase motors driven by such systems even though the incoming supply to a locomotive is nearly always either DC or single-phase AC.

Because single-phase power goes to zero at each moment that the voltage crosses zero but three-phase delivers power continuously, any such converter must have a way to store energy for the necessary fraction of a second.

One method for using three-phase equipment on a single-phase supply is with a rotary phase converter, essentially a three-phase motor with special starting arrangements and power factor correction that produces balanced three-phase voltages. When properly designed, these rotary converters can allow satisfactory operation of three-phase equipment such as machine tools on a single-phase supply. In such a device, the energy storage is performed by the mechanical inertia (flywheel effect) of the rotating components. An external flywheel is sometimes found on one or both ends of the shaft.

A second method that was popular in the 1940s and 1950s was the **transformer method**. At that time, capacitors were more expensive than transformers, so an autotransformer was used to apply more power through fewer capacitors. This method performs well and does have supporters, even today. The usage of the name *transformer method* separated it from another common method, the static converter, as both methods have no moving parts, which separates them from the rotary converters.

Another method often attempted is with a device referred to as a static phase converter. This method of running three-phase equipment is commonly attempted with motor loads though it only supplies ⅔ power and can cause the motor loads to run hot and in some cases overheat. This method does not work when sensitive circuitry is involved such as CNC devices or in induction and rectifier-type loads.

Some devices are made which create an imitation three-phase from three-wire single-phase supplies. This is done by creating a third "subphase" between the two live conductors, resulting in a phase separation of $180° - 90° = 90°$. Many three-phase devices can run on this configuration but at lower efficiency.

Variable-frequency drives (also known as solid-state inverters) are used to provide precise speed and torque control of three-phase motors. Some models can be powered by a single-phase supply. VFDs work by converting the supply voltage to DC and then converting the DC to a suitable three-phase source for the motor.

Digital phase converters are designed for fixed-frequency operation from a single-phase source. Similar to a variable-frequency drive, they use a microprocessor to control solid state power switching components to maintain balanced three-phase voltages.

Alternatives to three-phase

- Three-wire single-phase distribution is used when three-phase power is not available and allows double the normal utilization voltage to be supplied for high-power loads.

- Two-phase electric power, like three-phase, gives constant power transfer to a linear load. For loads that connect each phase to neutral, assuming the load is the same power draw, the two-wire system has a neutral current which is greater than neutral current in a three-phase system. Also motors are not entirely linear, which means that despite the theory, motors running on three-phase tend to run smoother than those on two-phase. The generators in the Adams Power Plant at Niagara Falls which were installed in 1895 were the largest generators in the world at the time and were two-phase machines. True two-phase power distribution is essentially obsolete. Special-purpose systems may use a two-phase system for control. Two-phase power may be obtained from a three-phase system using an arrangement of transformers called a Scott-T transformer.

- *Monocyclic power* was a name for an asymmetrical modified two-phase power system used by General Electric around 1897, championed by Charles Proteus Steinmetz and Elihu Thomson. This system was devised to avoid patent infringement. In this system, a generator was wound with a full-voltage single-phase winding intended for lighting loads and with a small (usually ¼ of the line voltage) winding which produced a voltage in quadrature with the main windings. The intention was to use this "power wire" additional winding to provide starting torque for induction motors, with the main winding providing power for lighting loads. After the expiration of the Westinghouse patents on symmetrical two-phase and three-phase power distribution systems, the monocyclic system fell out of use; it was difficult to analyze and did not last long enough for satisfactory energy metering to be developed.

- High phase-order systems for power transmission have been built and tested. Such transmission lines use six or 12 phases and employ design practices characteristic of extra-high voltage transmission lines. High phase-order transmission lines may allow transfer of more power through a given transmission line right-of-way without the expense of a high-voltage direct current (HVDC) converter at each end of the line.

Color codes

Conductors of a three phase system are usually identified by a color code, to allow for balanced loading and to assure the correct phase rotation for induction motors. Colors used may adhere to International Standard IEC 60446, older standards or to no standard at all and may vary even within a single installation. For example, in the U.S. and Canada, different color codes are used for grounded (earthed) and ungrounded systems.

	L1	L2	L3	Neutral	Ground/ protective earth
Australia and New Zealand (per AS/NZS 3000:2007 Figure 3.2)	Red[1]	White[1] (prev. yellow)	Dark blue[1]	Black[1]	Green/yellow striped (green on very old installations)
Canada (mandatory)	Red	Black	Blue	White	Green or bare copper
Canada (isolated three-phase installations)	Orange	Brown	Yellow	White	Green
European Union and all countries who use European CENELEC standards April 2004 (IEC 60446), Hong Kong from July 2007	Brown	Black	Grey	Blue	Green/yellow striped[2]
Older European (IEC 60446, varies by country[3])	Black or brown	Black or brown	Black or brown	Blue	Green/yellow striped[3]
UK until April 2006, Hong Kong until April 2009, South Africa, Malaysia, Singapore	Red	Yellow	Blue	Black	Green/yellow striped (green on installations approx. before 1970)
Republic of India and Pakistan	Red	Yellow	Blue	Black	Green
People's Republic of China (per GB 50303-2002 Section 15.2.2)	Yellow	Green	Red	Light blue	Green/yellow striped
Norway	Black	White/Grey	Brown	Blue	Yellow/green striped, older may be only yellow or bare copper
United States (common practice)[4]	Black	Red	Blue	White, or grey	Green, green/yellow

					striped or a bare copper wire
United States (alternative practice)[5]	Brown	Orange(delta) Violet(wye)	Yellow	Grey, or white	Green

^1 In Australia and New Zealand, active conductors can be any color except green/yellow, green, yellow, black or light blue. Yellow is no longer permitted in the 2007 revision of wiring code ASNZS 3000. European color codes are used for all IEC or flex cables such as extension leads, appliance leads etc. and are equally permitted for use in building wiring per AS/NZS 3000:2007.

Note that, in the U.S., a green/yellow striped wire may indicate an isolated ground. In most countries today, green/yellow striped wire may only be used for protective earth (safety ground) and may never be unconnected or used for any other purpose.

- **^2** The international standard green-yellow marking of protective-earth conductors was introduced to reduce the risk of confusion by color blind installers. About 7% to 10% of men cannot clearly distinguish between red and green, which is a particular concern in older schemes where red marks a live conductor and green marks protective earth or safety ground.
- **^3** In Europe, there still exist installations with older colors for protective earth but, since the early 1970s, all new installations use green/yellow according to IEC 60446.
- **^4** Paul Cook: Harmonised colours and alphanumeric marking. IEE Wiring Matters, Spring 2006.
- **^5** Since 1975, the U.S. National Electric Code has not specified coloring of phase conductors. It is common practice in many regions to identify 120/208Y conductors as black, red, and blue. Local regulations may amend the N.E.C. The U.S. National Electric Code has color requirements for grounded conductors, ground and grounded-delta 3-phase systems which result in one ungrounded leg having a higher voltage potential to ground than the other two ungrounded legs. Orange is only appropriate when the system has a grounded delta service, regardless of voltage.
- **^6** The U.S. National Electric Code does not specify coloring of phase conductors, other than orange for grounded delta. It is common practice in many regions to identify 277/480Y conductors as brown, orange and yellow (delta) or brown, violet and yellow (wye), with orange always being the center phase. Local practice may amend the N.E.C. The US N.E.C. rule 517.160 (5) states these colors are to be used for isolated power systems in health care facilities. Color of conductors does not identify voltage of a circuit, because there is no formal standard.

Chapter- 5

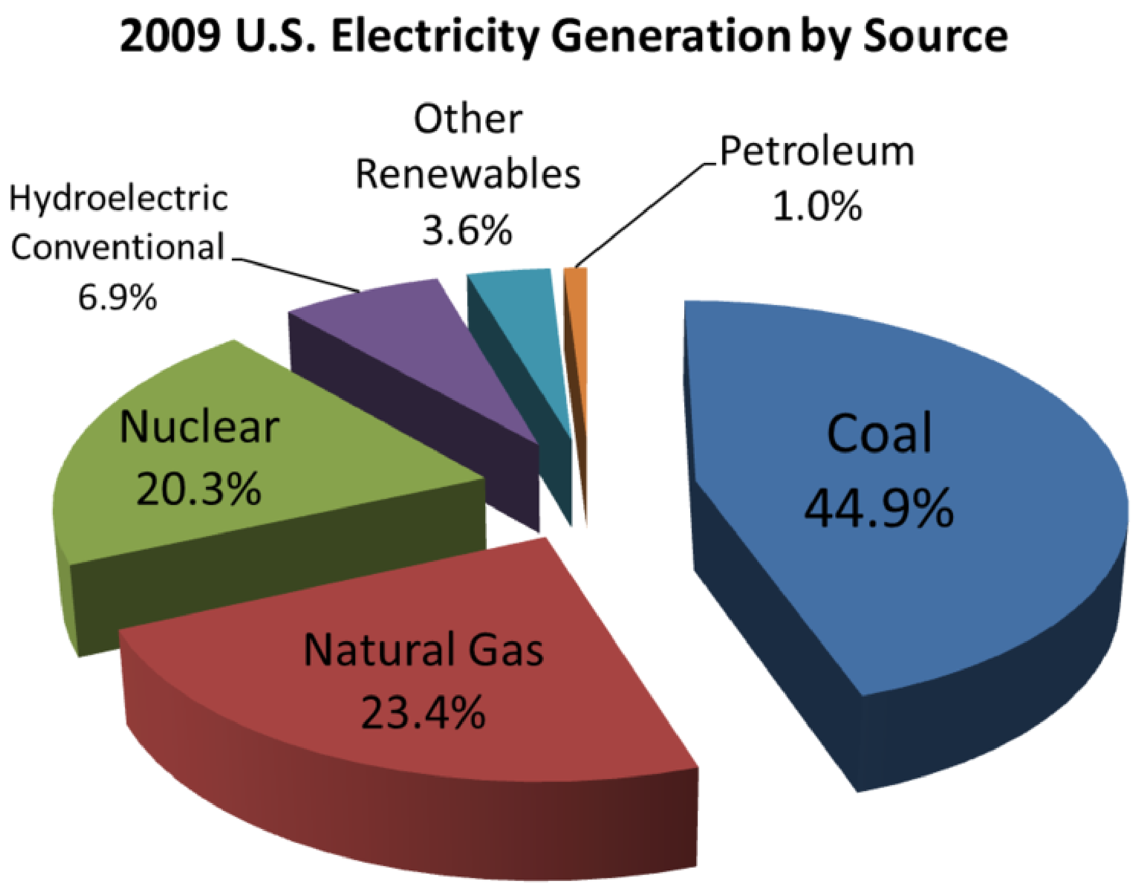
Electricity Generation

Electricity generation is the process of generating electricity from other forms of energy.

The fundamental principles of electricity generation were discovered during the 1820s and early 1830s by the British scientist Michael Faraday. His basic method is still used today: electricity is generated by the movement of a loop of wire, or disc of copper between the poles of a magnet.

For electric utilities, it is the first process in the delivery of electricity to consumers. The other processes, electricity transmission, distribution, and electrical power storage and recovery using pumped storage methods are normally carried out by the electrical power industry.

Electricity is most often generated at a power station by electromechanical generators, primarily driven by heat engines fueled by chemical combustion or nuclear fission but also by other means such as the kinetic energy of flowing water and wind. There are many other technologies that can be and are used to generate electricity such as solar photovoltaics and geothermal power.



Sources of electricity in the U.S. in 2009 fossil fuel generation (mainly coal) was the largest source.

Methods of generating electricity

Energy company PPL's headquarters in Allentown, Pennsylvania.

There are seven fundamental methods of directly transforming other forms of energy into electrical energy:

- Static electricity, from the physical separation and transport of charge (examples: triboelectric effect and lightning)
- Electromagnetic induction, where an electrical generator, dynamo or alternator transforms kinetic energy (energy of motion) into electricity

- Electrochemistry, the direct transformation of chemical energy into electricity, as in a battery, fuel cell or nerve impulse
- Photoelectric effect, the transformation of light into electrical energy, as in solar cells
- Thermoelectric effect, direct conversion of temperature differences to electricity, as in thermocouples, thermopiles, and Thermionic converters.

- Piezoelectric effect, from the mechanical strain of electrically anisotropic molecules or crystals
- Nuclear transformation, the creation and acceleration of charged particles (examples: betavoltaics or alpha particle emission)

Static electricity was the first form discovered and investigated, and the electrostatic generator is still used even in modern devices such as the Van de Graaff generator and MHD generators. Electrons are mechanically separated and transported to increase their electric potential.

Almost all commercial electrical generation is done using electromagnetic induction, in which mechanical energy forces an electrical generator to rotate. There are many different methods of developing the mechanical energy, including heat engines, hydro, wind and tidal power.

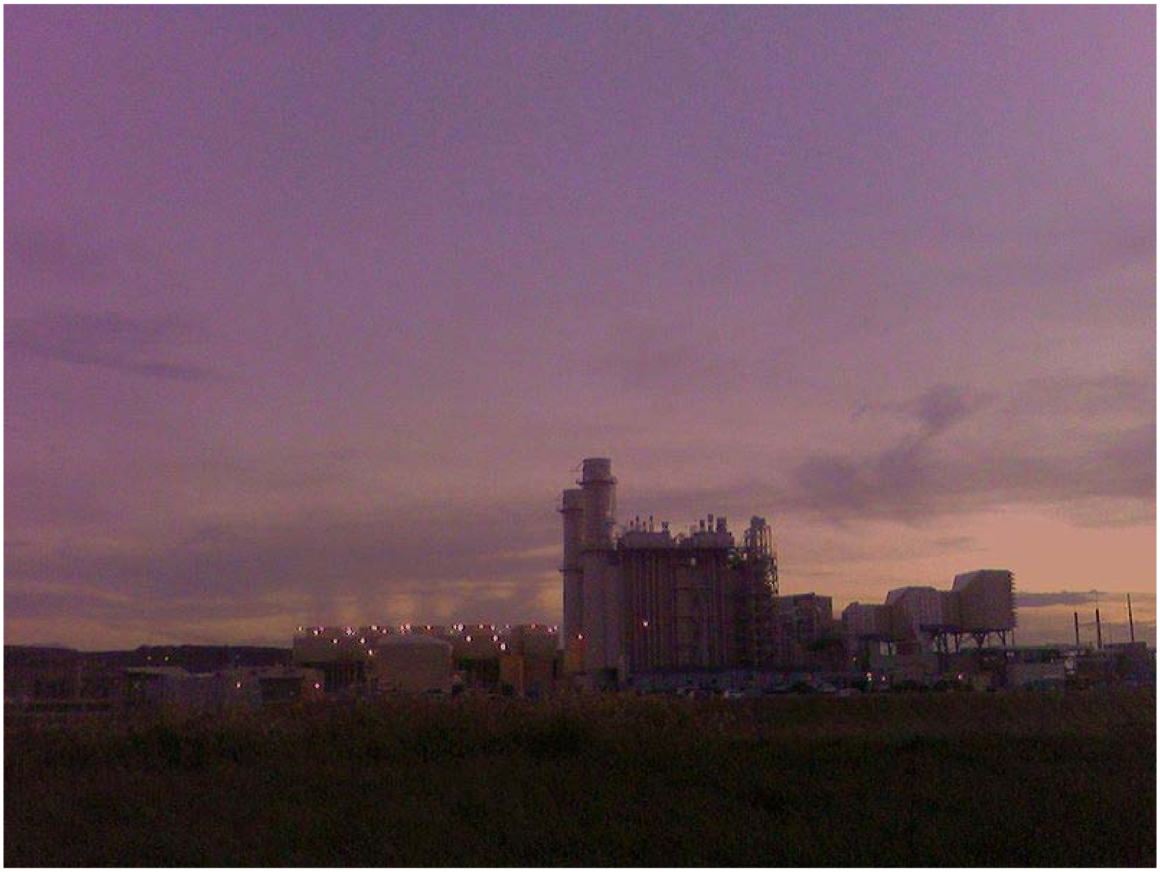
The direct conversion of nuclear energy to electricity by beta decay is used only on a small scale. In a full-size nuclear power plant, the heat of a nuclear reaction is used to run a heat engine. This drives a generator, which converts mechanical energy into electricity by magnetic induction.

Most electric generation is driven by heat engines. The combustion of fossil fuels supplies most of the heat to these engines, with a significant fraction from nuclear fission and some from renewable sources. The modern steam turbine invented by Sir Charles Parsons in 1884 - today generates about 80 percent of the electric power in the world using a variety of heat sources.

Turbines

Large dams such as Three Gorges Dam in China can provide large amounts of hydroelectric power; it will have a 22.5 GW capability.


Susquehanna Steam Electric Station, a nuclear power plant.



A combined cycle natural gas power plant near Orem, Utah.

All turbines are driven by a fluid acting as an intermediate energy carrier. Many of the heat engines just mentioned are turbines. Other types of turbines can be driven by wind or falling water.

Sources include:

- **Steam** - Water is boiled by:
    - Nuclear fission,
    - The burning of fossil fuels (coal, natural gas, or petroleum). In hot gas (gas turbine), turbines are driven directly by gases produced by the combustion of natural gas or oil. Combined cycle gas turbine plants are driven by both steam and natural gas. They generate power by burning natural gas in a gas turbine and use residual heat to generate additional electricity from steam. These plants offer efficiencies of up to 60%.
    - Renewables. The steam generated by:
        - Biomass
        - The sun as the heat source: solar parabolic troughs and solar power towers concentrate sunlight to heat a heat transfer fluid, which is then used to produce steam.

        - Geothermal power. Either steam under pressure emerges from the ground and drives a turbine or hot water evaporates a low boiling liquid to create vapour to drive a turbine.
        - Ocean thermal energy conversion (OTEC): uses the small difference between cooler deep and warmer surface ocean waters to run a heat engine usually a turbine.

- Other renewable sources:
    - **Water** (hydroelectric) - Turbine blades are acted upon by flowing water, produced by hydroelectric dams or tidal forces.
    - **Wind** - Most wind turbines generate electricity from naturally occurring wind. Solar updraft towers use wind that is artificially produced inside the chimney by heating it with sunlight, and are more properly seen as forms of solar thermal energy.

Reciprocating engines

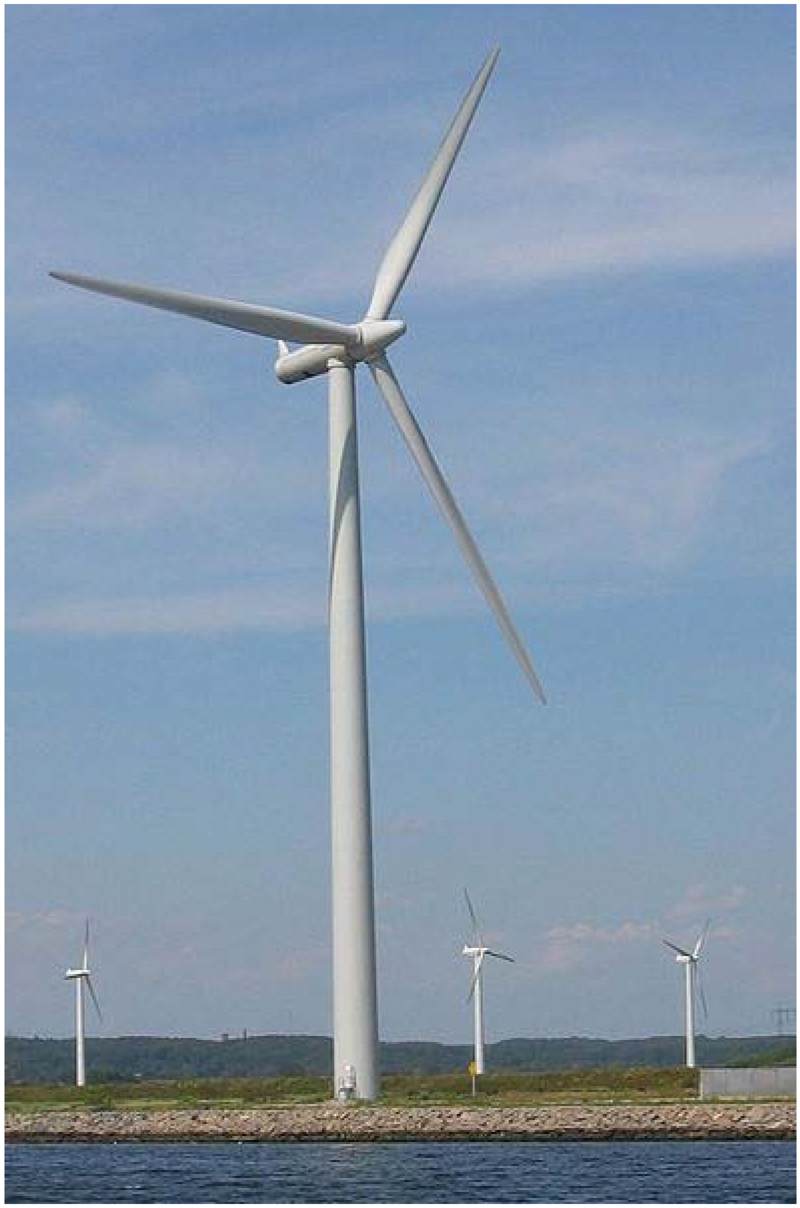
Small electricity generators are often powered by reciprocating engines burning diesel, biogas or natural gas. Diesel engines are often used for back up generation, usually at low voltages. However most large power grids also use diesel generators, originally provided as emergency back up for a specific facility such as a hospital, to feed power into the grid during certain circumstances. Biogas is often combusted where it is produced, such as a landfill or wastewater treatment plant, with a reciprocating engine or a microturbine, which is a small gas turbine.

A coal-fired power plant in Laughlin, Nevada U.S.A. Owners of this plant ceased operations after declining to invest in pollution control equipment to comply with pollution regulations.

Photovoltaic panels

Unlike the solar heat concentrators mentioned above, photovoltaic panels convert sunlight directly to electricity. Although sunlight is free and abundant, solar electricity is still usually more expensive to produce than large-scale mechanically generated power due to the cost of the panels. Low-efficiency silicon solar cells have been decreasing in cost and multijunction cells with close to 30% conversion efficiency are now commercially available. Over 40% efficiency has been demonstrated in experimental systems. Until recently, photovoltaics were most commonly used in remote sites where there is no access to a commercial power grid, or as a supplemental electricity source for individual homes and businesses. Recent advances in manufacturing efficiency and photovoltaic technology, combined with subsidies driven by environmental concerns, have dramatically accelerated the deployment of solar panels. Installed capacity is growing by 40% per year led by increases in Germany, Japan, California and New Jersey.

Other generation methods



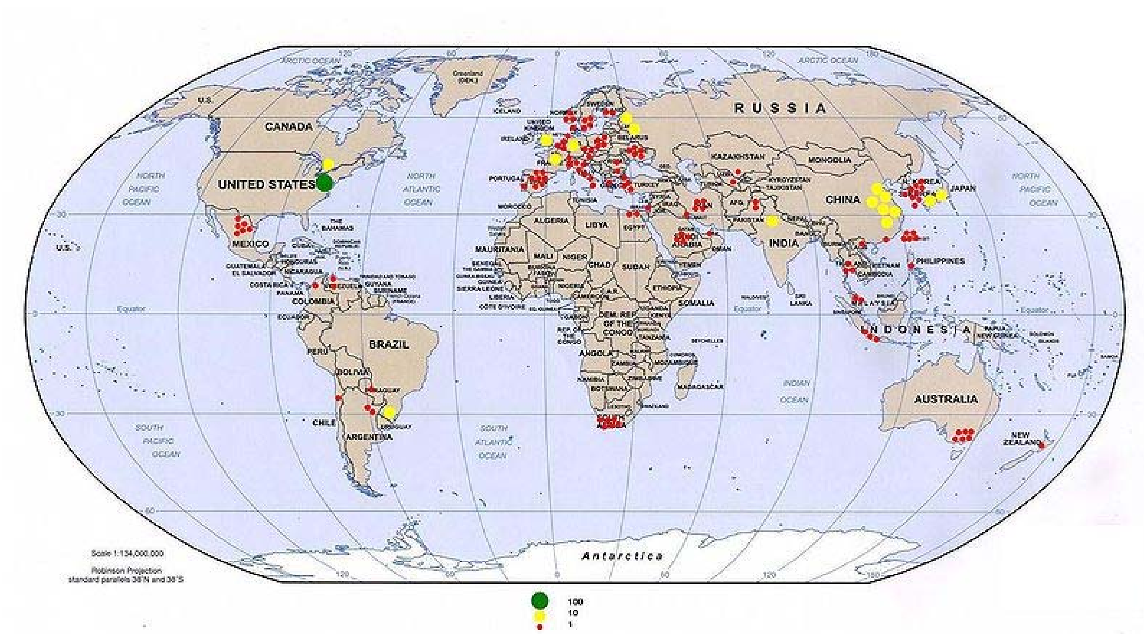
Wind-powered turbines usually provide electrical generation in conjunction with other methods of producing power.

Various other technologies have been studied and developed for power generation. Solid-state generation (without moving parts) is of particular interest in portable applications. This area is largely dominated by thermoelectric (TE) devices, though thermionic (TI) and thermophotovoltaic (TPV) systems have been developed as well. Typically, TE devices are used at lower temperatures than TI and TPV systems. Piezoelectric devices are used for power generation from mechanical strain, particularly in power harvesting. Betavoltaics are another type of solid-state power generator which produces electricity from radioactive decay. Fluid-based magnetohydrodynamic (MHD) power generation has been studied as a method for extracting electrical power from nuclear reactors and also from more conventional fuel combustion systems. Osmotic power finally is another possibility at places where salt and sweet water merges (e.g. deltas, ...)

Electrochemical electricity generation is also important in portable and mobile applications. Currently, most electrochemical power comes from closed electrochemical cells ("batteries"), which are arguably utilized more as storage systems than generation systems, but open electrochemical systems, known as fuel cells, have been undergoing a great deal of research and development in the last few years. Fuel cells can be used to extract power either from natural fuels or from synthesized fuels (mainly electrolytic hydrogen) and so can be viewed as either generation systems or storage systems depending on their use.

Cost of generating electricity

Production by country



Electricity output in 2005

The United States has long been the largest producer and consumer of electricity, with a global share in 2005 of at least 25%, followed by China, Japan, Russia, and India.

As of Jan-2010, total electricity generation for the 2 largest generators were as follows:

USA: 3992 billion KWh

China: 3715 billion KWh

Environmental Concerns

Most scientists agree that emissions of pollutants and greenhouse gases from fossil fuel-based electricity generation account for a significant portion of world greenhouse gas emissions; in the United States, electricity generation accounts for nearly 40 percent of emissions, the largest of any source. Transportation emissions are close behind, contributing about one-third of U.S. production of carbon dioxide.

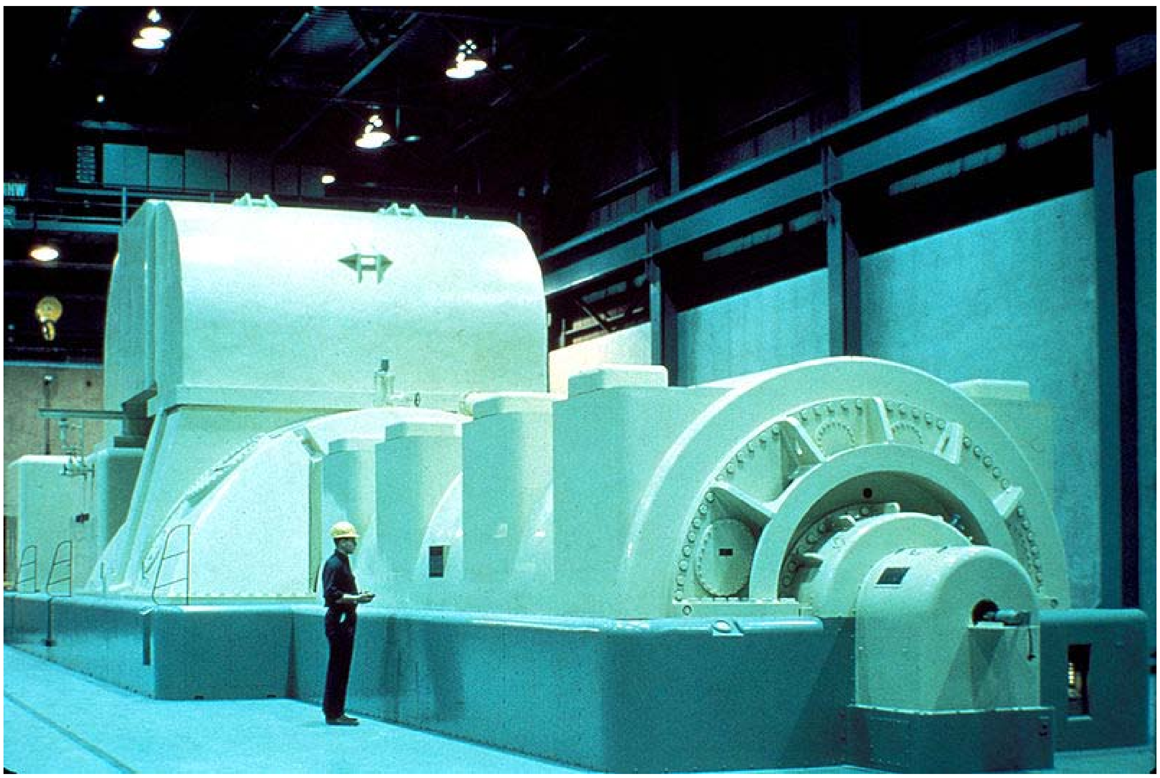
In the United States, fossil fuel combustion for electric power generation is responsible for 65% of all emissions of sulfur dioxide, the main component of acid rain. Electricity generation is the fourth highest combined source of NOx, carbon monoxide, and particulate matter in the US.

Water Consumption

Most large scale conventional electricity-only fossil fueled power stations consume considerable amounts of water for cooling purposes and boiler water make up - 1 L/kWh for once through (e.g. river cooling), and 1.7 L/kWh for cooling tower cooling. Water abstraction for cooling water accounts for about 40% of European total water abstraction, although most of this is returned to the original water body - river / lake albeit slightly warmer

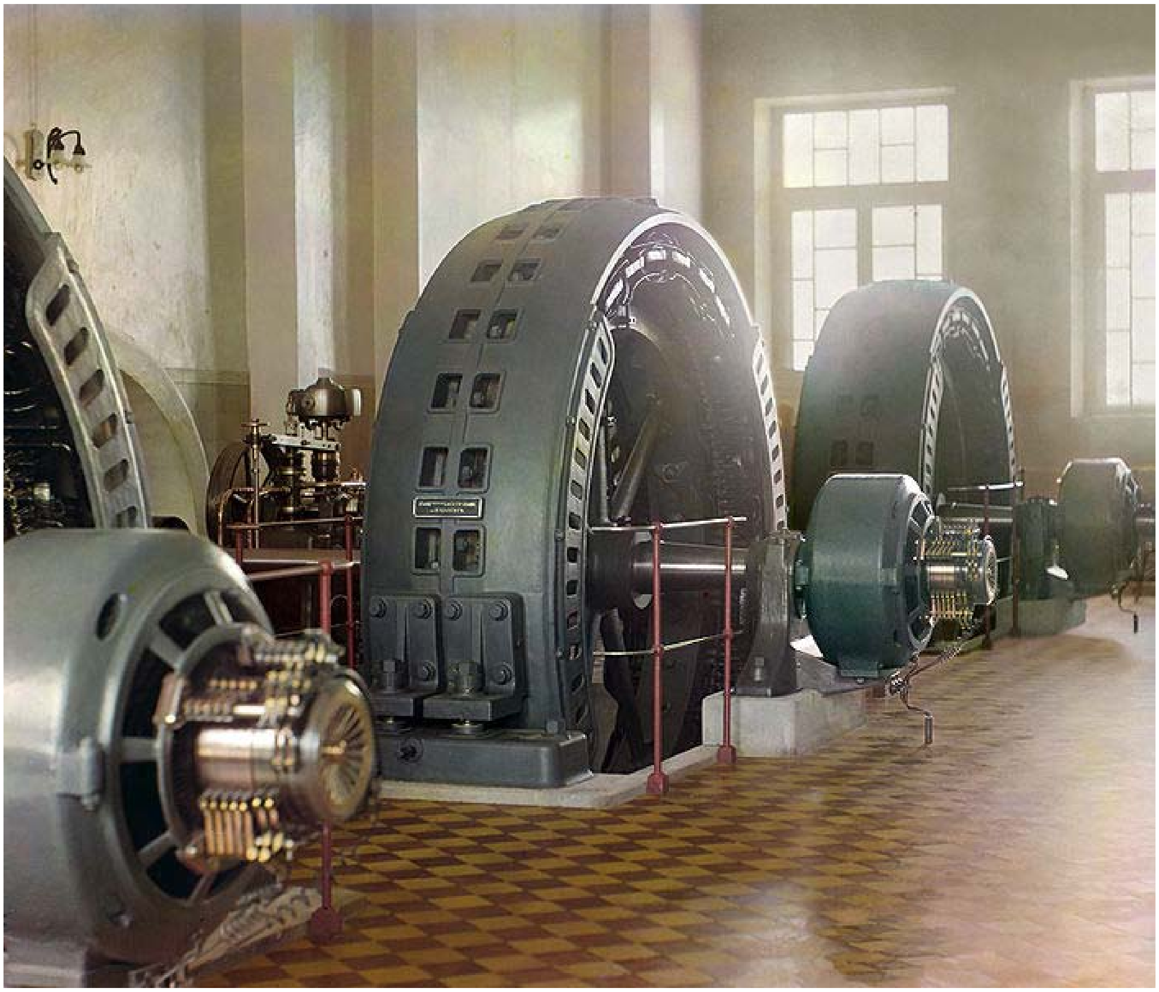
Chapter- 6

Electrical Generator



U.S. NRC image of a modern steam turbine generator

In electricity generation, an **electric generator** is a device that converts mechanical energy to electrical energy. The reverse conversion of electrical energy into mechanical energy is done by a motor; motors and generators have many similarities. A generator forces electrons in the windings to flow through the external electrical circuit. It is somewhat analogous to a water pump, which creates a flow of water but does not create the water inside. The source of mechanical energy may be a reciprocating or turbine steam engine, water falling through a turbine or waterwheel, an internal combustion engine, a wind turbine, a hand crank, compressed air or any other source of mechanical energy.


Early 20th century alternator made in Budapest, Hungary, in the power generating hall of a hydroelectric station

Generator in Zwevegem, West Flanders, Belgium

Historical developments

Before the connection between magnetism and electricity was discovered, electrostatic generators were invented that used electrostatic principles. These generated very high voltages and low currents. They operated by using moving electrically charged belts, plates and disks to carry charge to a high potential electrode. The charge was generated using either of two mechanisms:

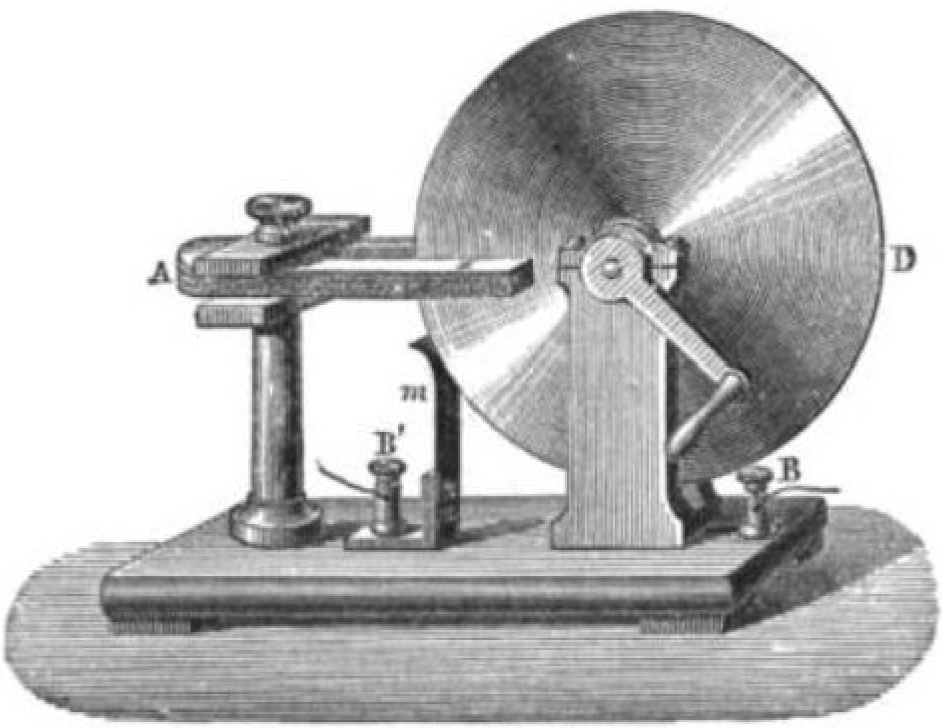
- Electrostatic induction
- The triboelectric effect, where the contact between two insulators leaves them charged.

Because of their inefficiency and the difficulty of insulating machines producing very high voltages, electrostatic generators had low power ratings and were never used for generation of commercially significant quantities of electric power. The Wimshurst machine and Van de Graaff generator are examples of these machines that have survived.

Jedlik's dynamo

In 1827, Hungarian Anyos Jedlik started experimenting with electromagnetic rotating devices which he called electromagnetic self-rotors. In the prototype of the single-pole electric starter (finished between 1852 and 1854) both the stationary and the revolving parts were electromagnetic. He formulated the concept of the dynamo at least 6 years before Siemens and Wheatstone but didn't patent it as he thought he wasn't the first to realize this. In essence the concept is that instead of permanent magnets, two electromagnets opposite to each other induce the magnetic field around the rotor. It was also the discovery of the principle of self-excitation.

Faraday's disk



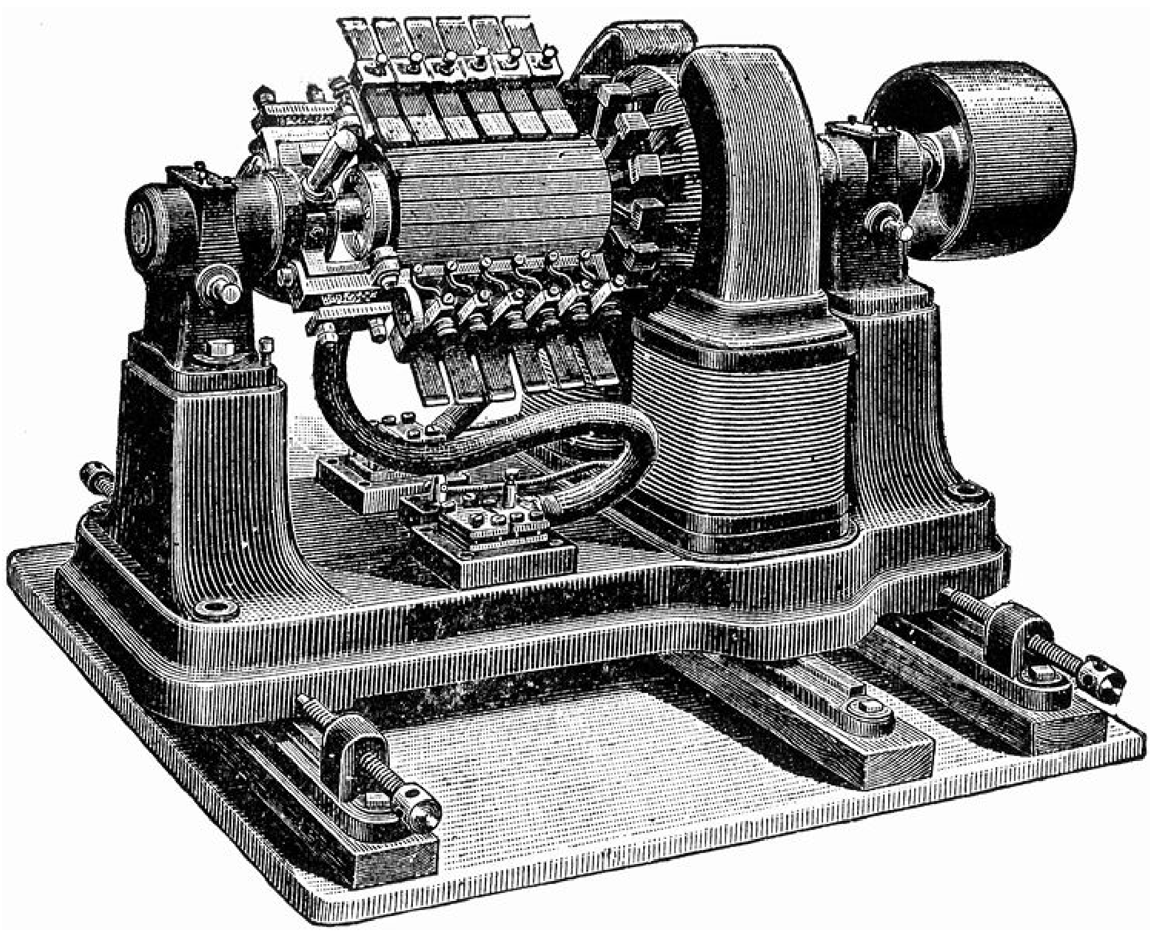
Faraday disk, the first electric generator. The horseshoe-shaped magnet *(A)* created a magnetic field through the disk *(D)*. When the disk was turned this induced an electric current radially outward from the center toward the rim. The current flowed out through the sliding spring contact *m*, through the external circuit, and back into the center of the disk through the axle.

In the years of 1831–1832, Michael Faraday discovered the operating principle of electromagnetic generators. The principle, later called Faraday's law, is that an electromotive force is generated in an electrical conductor that encircles a varying magnetic flux. He also built the first electromagnetic generator, called the Faraday disk, a type of homopolar generator, using a copper disc rotating between the poles of a horseshoe magnet. It produced a small DC voltage.

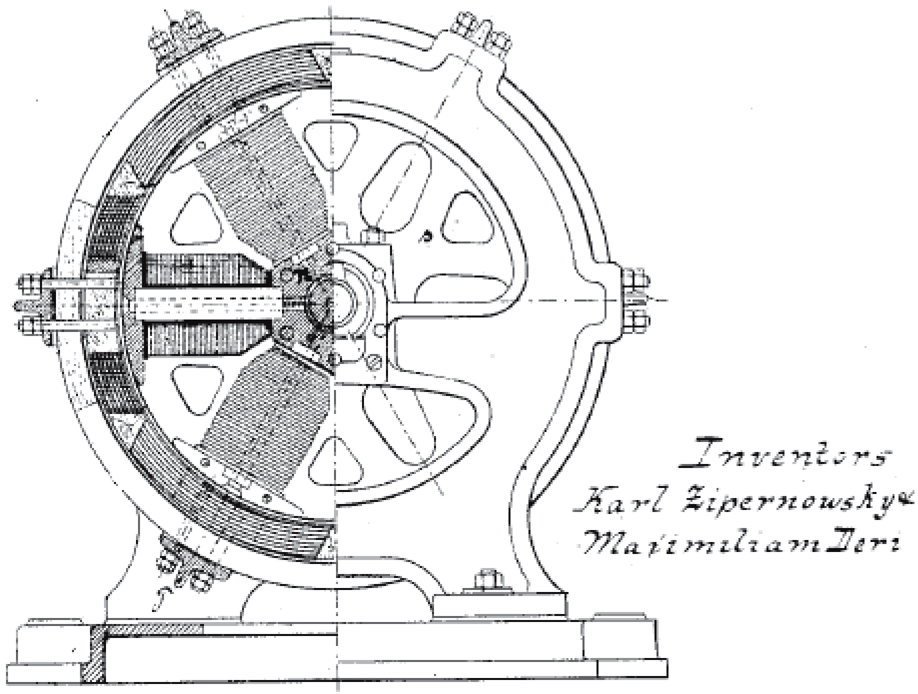
This design was inefficient due to self-cancelling counterflows of current in regions not under the influence of the magnetic field. While current was induced directly underneath the magnet, the current would circulate backwards in regions outside the influence of the magnetic field. This counterflow limits the power output to the pickup wires and induces waste heating of the copper disc. Later homopolar generators would solve this problem by using an array of magnets arranged around the disc perimeter to maintain a steady field effect in one current-flow direction.

Another disadvantage was that the output voltage was very low, due to the single current path through the magnetic flux. Experimenters found that using multiple turns of wire in a coil could produce higher more useful voltages. Since the output voltage is proportional to the number of turns, generators could be easily designed to produce any desired voltage by varying the number of turns. Wire windings became a basic feature of all subsequent generator designs.

Dynamo



Dynamos are no longer used for power generation due to the size and complexity of the commutator needed for high power applications. This large belt-driven high-current dynamo produced 310 amperes at 7 volts, or 2,170 watts, when spinning at 1400 RPM.



Dynamo Electric Machine [End View, Partly Section] (U.S. Patent 284,110)

The **dynamo** was the first electrical generator capable of delivering power for industry. The dynamo uses electromagnetic principles to convert mechanical rotation into a pulsing direct current (DC) through the use of a commutator. The first dynamo was built by Hippolyte Pixii in 1832.

Through a series of accidental discoveries, the dynamo became the source of many later inventions, including the DC electric motor, the AC alternator, the AC synchronous motor, and the rotary converter.

A dynamo machine consists of a stationary structure, which provides a constant magnetic field, and a set of rotating windings which turn within that field. On small machines the constant magnetic field may be provided by one or more permanent magnets; larger machines have the constant magnetic field provided by one or more electromagnets, which are usually called field coils.

Large power generation dynamos are now rarely seen due to the now nearly universal use of alternating current for power distribution and solid state electronic AC to DC power conversion. But before the principles of AC were discovered, very large direct-current dynamos were the only means of power generation and distribution. Now power generation dynamos are mostly a curiosity.

Other rotating electromagnetic generators

Without a commutator, a dynamo becomes an alternator, which is a synchronous singly-fed generator. When used to feed an electric power grid, an alternator must always operate at a constant speed that is precisely synchronized to the electrical frequency of the power grid. A DC generator can operate at any speed within mechanical limits but always outputs a direct current waveform.

Other types of generators, such as the asynchronous or induction singly-fed generator, the doubly-fed generator, or the brushless wound-rotor doubly-fed generator, do not incorporate permanent magnets or field windings (i.e., electromagnets) that establish a constant magnetic field, and as a result, are seeing success in variable speed constant frequency applications, such as wind turbines or other renewable energy technologies.

The full output performance of any generator can be optimized with electronic control but only the doubly-fed generators or the brushless wound-rotor doubly-fed generator incorporate electronic control with power ratings that are substantially less than the power output of the generator under control, which by itself offer cost, reliability and efficiency benefits.

MHD generator

A magnetohydrodynamic generator directly extracts electric power from moving hot gases through a magnetic field, without the use of rotating electromagnetic machinery. MHD generators were originally developed because the output of a plasma MHD generator is a flame, well able to heat the boilers of a steam power plant. The first practical design was the AVCO Mk. 25, developed in 1965. The U.S. government funded substantial development, culminating in a 25 MW demonstration plant in 1987. In the Soviet Union from 1972 until the late 1980s, the MHD plant U 25 was in regular commercial operation on the Moscow power system with a rating of 25 MW, the largest MHD plant rating in the world at that time. MHD generators operated as a topping cycle are currently (2007) less efficient than combined-cycle gas turbines.

Terminology

Rotor from generator at Hoover Dam, United States

The two main parts of a generator or motor can be described in either mechanical or electrical terms:

Mechanical:

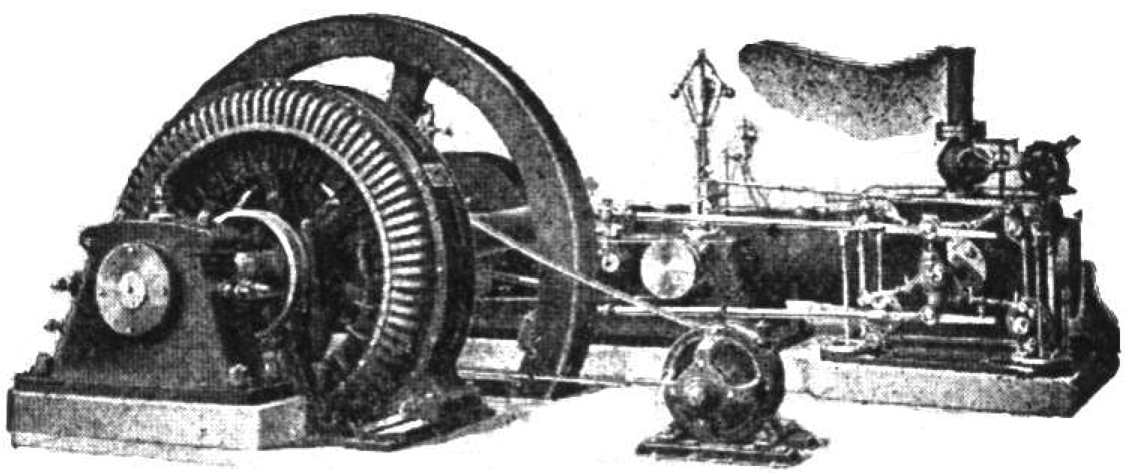
- Rotor: The rotating part of an electrical machine
- Stator: The stationary part of an electrical machine

Electrical:

- Armature: The power-producing component of an electrical machine. In a generator, alternator, or dynamo the armature windings generate the electric current. The armature can be on either the rotor or the stator.
- Field: The magnetic field component of an electrical machine. The magnetic field of the dynamo or alternator can be provided by either electromagnets or permanent magnets mounted on either the rotor or the stator.

Because power transferred into the field circuit is much less than in the armature circuit, AC generators nearly always have the field winding on the rotor and the stator as the armature winding. Only a small amount of field current must be transferred to the moving rotor, using slip rings. Direct current machines (dynamos) require a commutator on the rotating shaft to convert the alternating current produced by the armature to direct current, so the armature winding is on the rotor of the machine.

Excitation



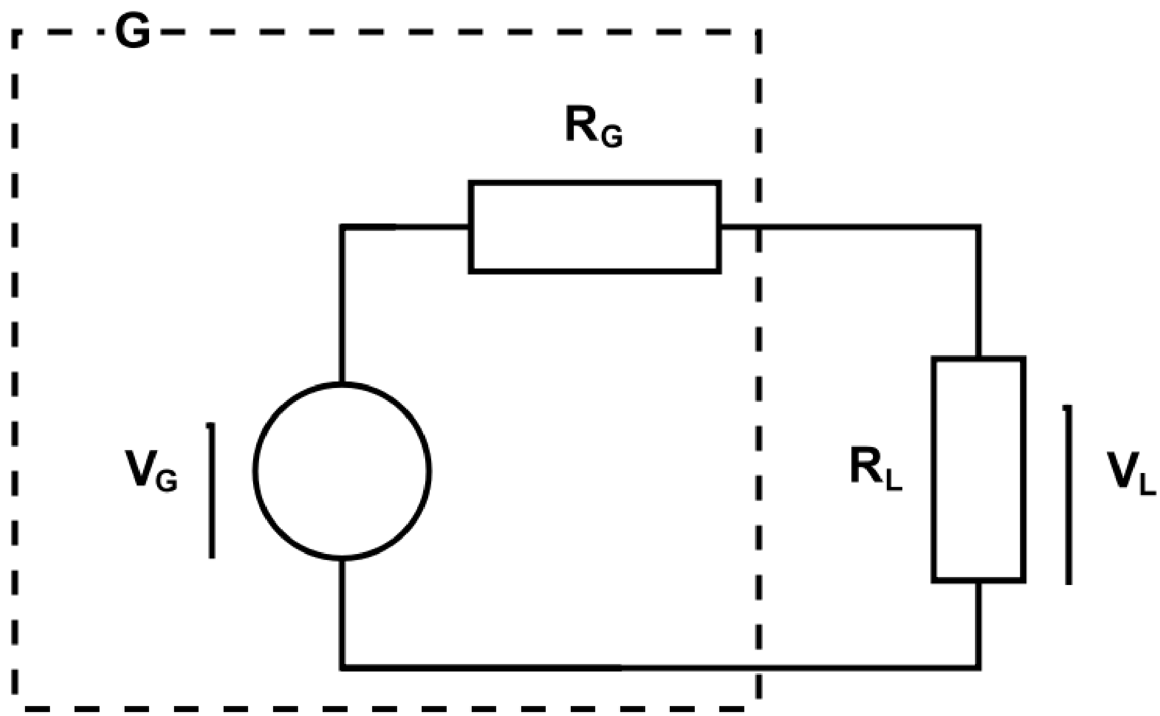
A small early 1900s 75 KVA direct-driven power station AC alternator, with a separate belt-driven exciter generator.

An electric generator or electric motor that uses field coils rather than permanent magnets requires a current to be present in the field coils for the device to be able to work. If the field coils are not powered, the rotor in a generator can spin without producing any usable electrical energy, while the rotor of a motor may not spin at all.

Smaller generators are sometimes *self-excited*, which means the field coils are powered by the current produced by the generator itself. The field coils are connected in series or parallel with the armature winding. When the generator first starts to turn, the small amount of remanent magnetism present in the iron core provides a magnetic field to get it started, generating a small current in the armature. This flows through the field coils, creating a larger magnetic field which generates a larger armature current. This "bootstrap" process continues until the magnetic field in the core levels off due to saturation and the generator reaches a steady state power output.

Very large power station generators often utilize a separate smaller generator to excite the field coils of the larger. In the event of a severe widespread power outage where islanding of power stations has occurred, the stations may need to perform a black start to excite the fields of their largest generators, in order to restore customer power service.

DC Equivalent circuit



Equivalent circuit of generator and load.
G = generator
V_G=generator open-circuit voltage
R_G=generator internal resistance
V_L=generator on-load voltage
R_L=load resistance

The equivalent circuit of a generator and load is shown in the diagram to the right. The generator's V_G and R_G parameters can be determined by measuring the winding resistance (corrected to operating temperature), and measuring the open-circuit and loaded voltage for a defined current load.

Vehicle-mounted generators

Early motor vehicles until about the 1960s tended to use DC generators with electromechanical regulators. These have now been replaced by alternators with built-in rectifier circuits, which are less costly and lighter for equivalent output. Automotive alternators power the electrical systems on the vehicle and recharge the battery after starting. Rated output will typically be in the range 50-100 A at 12 V, depending on the designed electrical load within the vehicle. Some cars now have electrically-powered steering assistance and air conditioning, which places a high load on the electrical system. Large commercial vehicles are more likely to use 24 V to give sufficient power at the starter motor to turn over a large diesel engine. Vehicle alternators do not use permanent magnets and are typically only 50-60% efficient over a wide speed range. Motorcycle alternators often use permanent magnet stators made with rare earth magnets, since they can be made smaller and lighter than other types.

Some of the smallest generators commonly found power bicycle lights. These tend to be 0.5 ampere, permanent-magnet alternators supplying 3-6 W at 6 V or 12 V. Being powered by the rider, efficiency is at a premium, so these may incorporate rare-earth magnets and are designed and manufactured with great precision. Nevertheless, the maximum efficiency is only around 80% for the best of these generators—60% is more typical—due in part to the rolling friction at the tyre–generator interface from poor alignment, the small size of the generator, bearing losses and cheap design. The use of permanent magnets means that efficiency falls even further at high speeds because the magnetic field strength cannot be controlled in any way. Hub generators remedy many of these flaws since they are internal to the bicycle hub and do not require an interface between the generator and tyre. Until recently, these generators have been expensive and hard to find. Major bicycle component manufacturers like Shimano and SRAM have only just entered this market. However, significant gains can be expected in future as cycling becomes more mainstream transportation and LED technology allows brighter lighting at the reduced current these generators are capable of providing.

Sailing yachts may use a water or wind powered generator to trickle-charge the batteries. A small propeller, wind turbine or impeller is connected to a low-power alternator and rectifier to supply currents of up to 12 A at typical cruising speeds.

Engine-generator

An *engine-generator* is the combination of an electrical generator and an engine (prime mover) mounted together to form a single piece of self-contained equipment. The engines used are usually piston engines, but gas turbines can also be used. Many different versions are available - ranging from very small portable petrol powered sets to large turbine installations.

Human powered electrical generators

A generator can also be driven by human muscle power (for instance, in field radio station equipment).

Human powered direct current generators are commercially available, and have been the project of some DIY enthusiasts. Typically operated by means of pedal power, a converted bicycle trainer, or a foot pump, such generators can be practically used to charge batteries, and in some cases are designed with an integral inverter. The average adult could generate about 125-200 watts on a pedal powered generator, but at a power of 200 W, a typical healthy human will reach complete exhaustion and fail to produce any more power after approximately 1.3 hours.

Linear electric generator

In the simplest form of linear electric generator, a sliding magnet moves back and forth through a solenoid - a spool of copper wire. An alternating current is induced in the loops of wire by Faraday's law of induction each time the magnet slides through. This type of generator is used in the Faraday flashlight. Larger linear electricity generators are used in wave power schemes.

Tachogenerator

Tachogenerators are frequently used to power tachometers to measure the speeds of electric motors, engines, and the equipment they power. Generators generate voltage roughly proportional to shaft speed. With precise construction and design, generators can be built to produce very precise voltages for certain ranges of shaft speeds

Chapter- 7

Transmission Tower

Suspension tower, near Aust, Gloucestershire, England, United Kingdom. The design of the tower is attributed to the Miliken Bros 1928 with design adjustments from Sir Reginald Blomfield.

A **transmission tower** (colloquially termed an **electricity pylon** in the United Kingdom and parts of Europe, an **ironman** in Australia, and a **hydro tower** in parts of Canada) is a tall structure, usually a steel lattice tower, used to support an overhead power line. They are used in high-voltage AC and DC systems, and come in a wide variety of shapes and sizes. Typical height ranges from 15 to 55 metres (49 to 180 ft), although heights in excess of 300 metres (980 ft) exist. In addition to steel, other materials may be used, including concrete and wood.

Four major functions of transmission towers are in use: suspension towers, terminal towers, tension towers, and transposition towers. Some transmission towers combine these basic functions. Transmission towers and their overhead power lines are often considered to be a form of visual pollution. Methods to reduce the visual impact include undergrounding.

Naming

"Transmission tower" is the name for the structure used in the industry in the United Kingdom, United States, and other English-speaking countries. The term "electricity pylon" comes from the basic shape of the structure of a lattice tower – an obelisk-like structure which tapers toward the top – and is mostly used in the United Kingdom and parts of Europe in everyday colloquial speech. This term is rarely, if ever, used in the United States, as the word "pylon" is commonly used for a multitude of other things, mostly for traffic cones. In Canada, the term "hydro tower" comes from the name of local hydroelectric power utility companies.

High voltage AC transmission towers

Three-phase alternating current transmission towers over water, near Darwin, Northern Territory, Australia

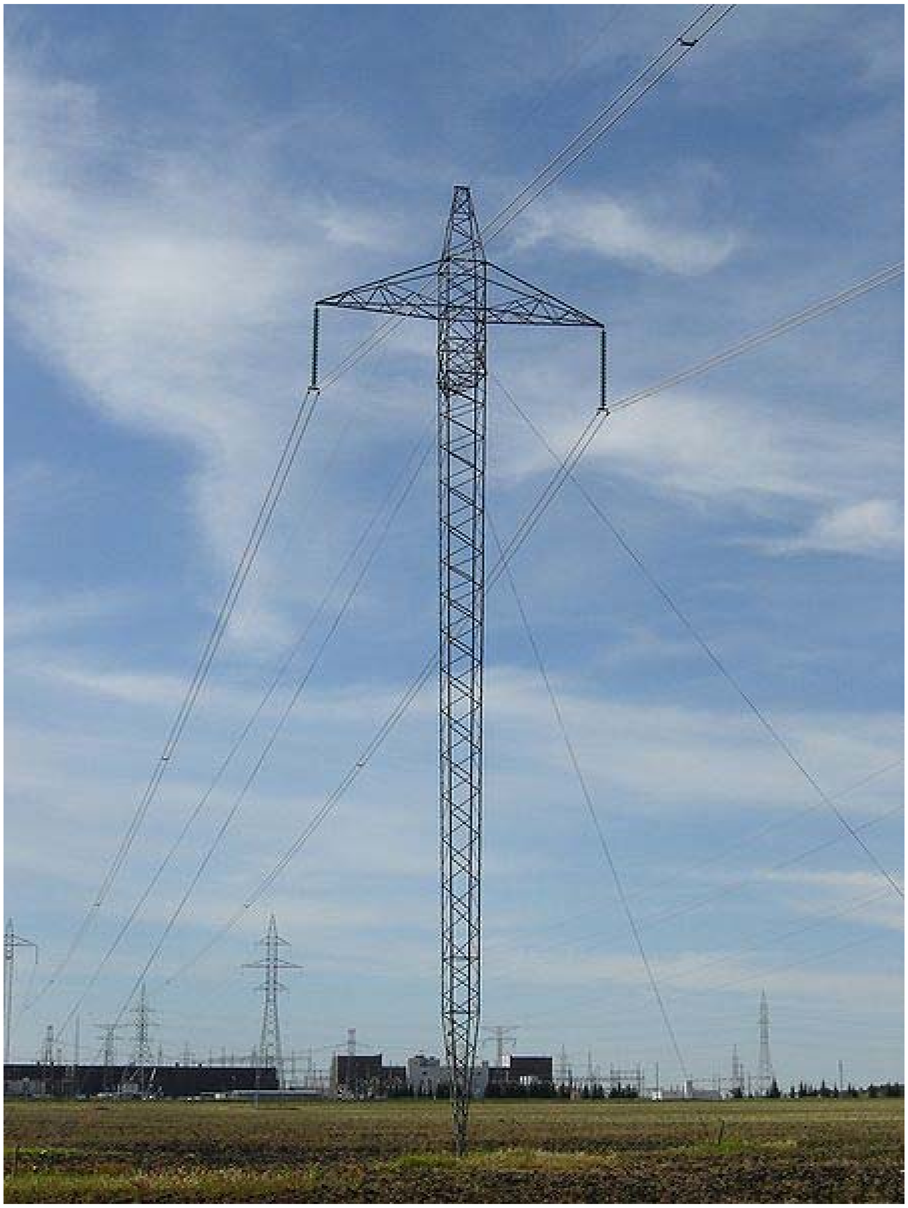
Three-phase electric power systems are used for high and extra-high voltage AC transmission lines (50 kV and above). The towers must be designed to carry three (or multiples of three) conductors. The towers are usually steel lattices or trusses (wooden structures are used in Canada, Germany, and Scandinavia in some cases) and the insulators are either glass or porcelain discs or composite insulators using silicone rubber or EPDM rubber material assembled in strings or long rods whose lengths are dependent on the line voltage and environmental conditions.

Typically, one or two ground wires are placed on top to intercept lightning and harmlessly divert it to ground.

In some countries, towers for high and extra-high voltage are usually designed to carry two or more electric circuits. For double circuit lines in Germany, the "Danube" towers or, more rarely, the "fir tree" towers are usually used. If a line is constructed using towers designed to carry several circuits, it is not necessary to install all the circuits at the time of construction.

Some high voltage circuits are often erected on the same tower as 110 kV lines. Paralleling circuits of 380 kV, 220 kV and 110 kV-lines on the same towers is common. Sometimes, especially with 110 kV circuits, a parallel circuit carries traction lines for railway electrification.

High voltage DC transmission towers



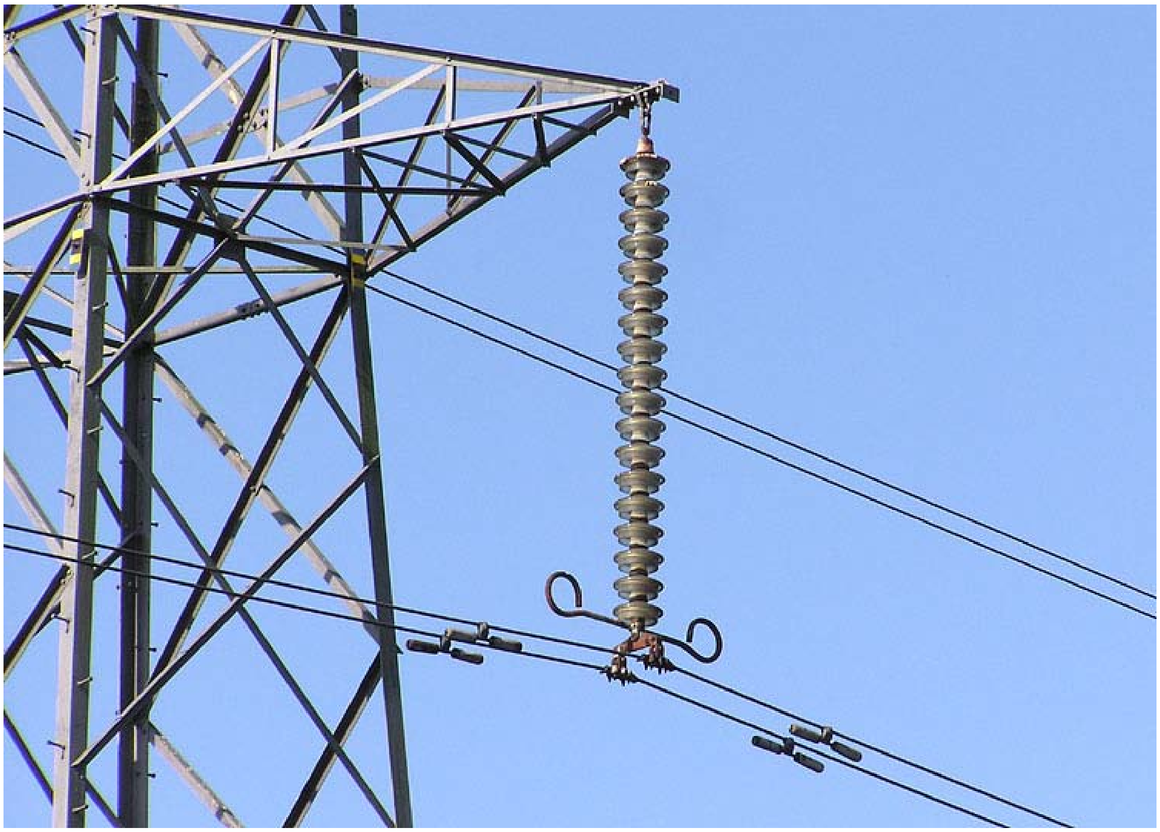
HVDC distance tower near the terminus of the Nelson River Bipole adjacent to Dorsey Converter Station near Rosser, Manitoba, Canada — August 2005

High-voltage direct current (HVDC) transmission lines are either monopolar or bipolar systems. With bipolar systems a conductor arrangement with one conductor on each side of the tower is used. For single-pole HVDC transmission with ground return, towers with only one conductor can be used. In many cases, however, the towers are designed for later conversion to a two-pole system. In these cases, conductors are installed on both sides of the tower for mechanical reasons. Until the second pole is needed, it is either grounded, or joined in parallel with the pole in use. In the latter case the line from the converter station to the earthing (grounding) electrode is built as underground cable.

Railway traction line towers

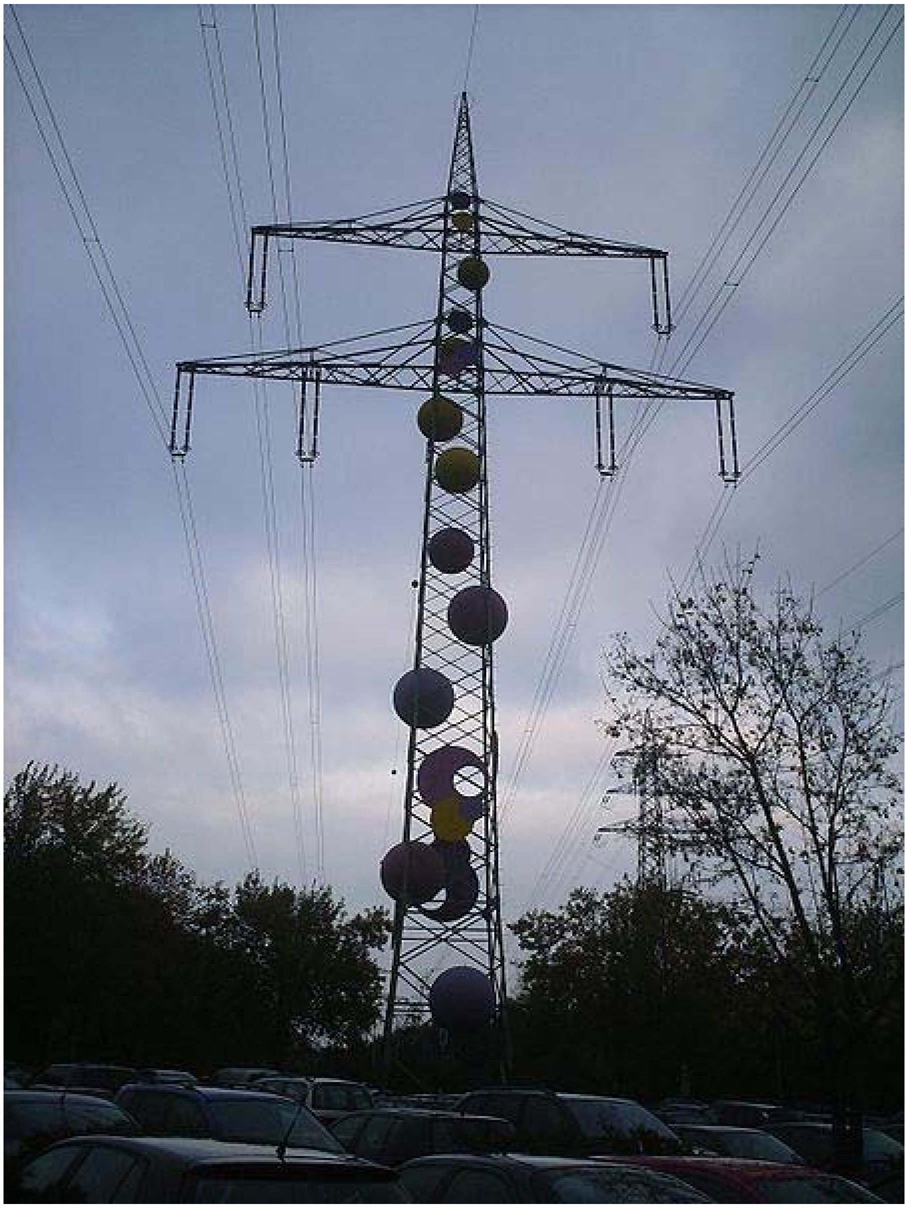
Tension tower with phase transposition of a powerline for single phase AC traction current (110 kV, 16.67 Hz) near Bartholomä, Germany

Towers used for single phase AC railway traction lines are similar in construction to those towers used for 110 kV-three phase lines. Steel tube or concrete poles are also often used for these lines. However, railway traction current systems are two-pole AC systems, so traction lines are designed for two conductors (or multiples of two, usually four, eight, or twelve). As a rule, the towers of railway traction lines carry two electric circuits, so they have four conductors. These are usually arranged on one level, whereby each circuit occupies one half of the crossarm. For four traction circuits the arrangement of the conductors is in two-levels and for six electric circuits the arrangement of the conductors is in three levels.



Detail of the insulators (the vertical string of discs) and conductor vibration dampers (the weights attached directly to the conductors) on a 275,000 volt suspension tower near Thornbury, South Gloucestershire, England, United Kingdom

A tubular pylon, or *muguet* (lily) pylon, of an Hydro-Québec TransÉnergie line in Gatineau, Quebec, Canada. The tubular monopolar towers are used in urban settings for high-voltage lines, from 110 to 315 kV, and are considered more aesthetically pleasing.



Pylon decorated with balls in Ruhr Park, Bochum, Germany

With limited space conditions, it is possible to arrange the conductors of one traction circuit in two levels. Running a traction power line parallel to a high voltage transmission line for three-phase AC on a separate crossarm of the same tower is possible. If traction lines are led parallel to 380 kV-lines, the insulation must be designed for 220 kV, because in the event of a fault, dangerous overvoltages to the three-phase alternating current line can occur. Traction lines are usually equipped with one earth conductor. In Austria, on some traction circuits, two earth conductors are used.

Assembly

Before transmission towers are even erected, prototype towers are tested at tower testing stations. There are a variety of ways they can then be assembled and erected:

- They can be assembled horizontally on the ground and erected by push-pull cable. This method is rarely used, however, because of the large assembly area needed.
- They can be assembled vertically (in their final upright position). Very tall towers, such as the Yangtze River Crossing, were assembled in this way.
- A jin-pole crane can be used to assemble lattice towers. This is also used for utility poles.
- Helicopters can serve as aerial cranes for their assembly in areas with limited accessibility. Towers can also be assembled elsewhere and flown to their place on the transmission right-of-way.

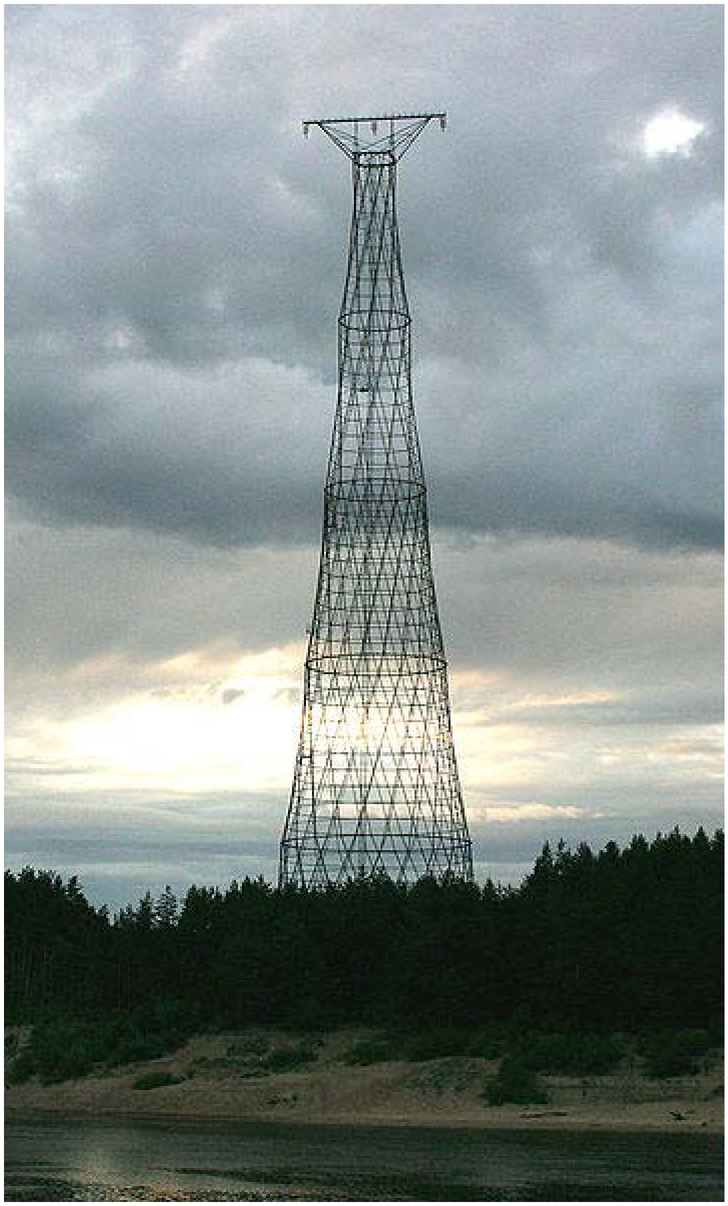
Sign markings

A typical tower identification tag

Electricity pylons often have an identification number or code placed on the pole in the form of a sign, an identification plate, painted numbers, or anything else the electric company chooses. These tags are usually marked with the names of the line (either the terminal points of the line or the internal designation of the power company) and the tower number. This makes identifying the location of a fault to the power company that owns the tower easier.

Transmission towers, much like other steel lattice towers including broadcasting or cellphone towers, are marked with signs which discourage public access due to the danger of the high voltage. Often this is accomplished with a sign warning of the high voltage; other times the entire access point to the transmission corridor is marked with a sign. Some countries require that lattice steel towers be equipped with a barbed wire barrier approximately 3 metres (9.8 ft) above ground in order to deter unauthorized climbing. Such barriers can often be found on towers close to roads or other areas with easy public access, even where there is not a legal requirement. In the United Kingdom, all such towers are fitted with barbed wire.

Special designs



Hyperboloid pylon in the suburb of Nizhniy Novgorod, Russia.

Sometimes (in particular on steel lattice towers for the highest voltage levels) transmitting plants are installed, and antennas mounted on the top above or below the overhead ground wire. Usually these installations are for mobile phone services or the operating radio of the power supply firm, but occasionally also for other radio services, like directional radio. Thus transmitting antennas for low-power FM radio and television transmitters were already installed on pylons. On the Elbe Crossing 1 tower, there is a radar facility belonging to the Hamburg water and navigation office.

One of the Pylons of Cádiz, Spain

For crossing broad valleys, a large distance between the conductors must be maintained to avoid short-circuits caused by conductor cables colliding during storms. To achieve this, sometimes a separate mast or tower is used for each conductor. For crossing wide rivers and straits with flat coastlines, very tall towers must be built due to the necessity of a large height clearance for navigation. Such towers and the conductors they carry must be equipped with flight safety lamps and reflectors.

Two well-known wide river crossings are the Elbe Crossing 1 and Elbe Crossing 2. The latter has the tallest overhead line masts in Europe, at 227 metres (745 ft) tall. In Spain, the overhead line crossing pylons in the Spanish bay of Cádiz have a particularly interesting construction. The main crossing towers are 158 metres (518 ft) tall with one crossarm atop a frustum framework construction. The longest overhead line spans are the crossing of the Norwegian Sognefjord (4,597 metres (15,082 ft) between two masts) and the Ameralik span in Greenland (5,376 metres (17,638 ft)). In Germany, the overhead line of the EnBW AG crossing of the Eyachtal has the longest span in the country at 1,444 metres (4,738 ft).

In order to drop overhead lines into steep, deep valleys, inclined towers are occasionally used. These are utilized at the Hoover Dam, located in the United States, to descend the cliff walls of the Black Canyon of the Colorado. In Switzerland, a NOK pylon inclined around 20 degrees to the vertical is located near Sargans, St. Gallens. Highly sloping masts are used on two 380 kV pylons in Switzerland, the top 32 meters of one of them being bent by 18 degrees to the vertical.

Power station chimneys are sometimes equipped with crossbars for fixing conductors of the outgoing lines. Because of possible problems with corrosion by the flue gases, such constructions are very rare.

A new type of pylon will be used in the Netherlands starting in 2010. The pylons were designed as a minimalist structure by Dutch architects Zwarts and Jansma. The use of physical laws for the design made a reduction of the magnetic field possible. Also, the visual impact on the surrounding landscape is reduced.

Tower functions

Steel lattice tension (dead-end) transmission towers near Rochester, New York, USA. Each tower carries two 3-phase 115kV circuits. In the background, for comparison, is a wood transmission pole carrying one 3-phase 115 kV circuit.

Tower structures can be classified by the way in which they support the line conductors. Suspension structures support the conductor vertically using suspension insulators. . Strain structures resist net tension in the conductors and teh conductors attach to the structure through strain insulators. Dead-end structures support the full weight of the conductor and also all the tension in it, and also use strain insulators.

Where the conductors are straight, a tangent towers is used. Angle towers are used where a line must change direction.

Structures are classified as tangent suspension, angle suspension, tangent strain, angle strain, tangent dead-end and angle dead-end.

Cross arms and conductor arrangement

Generally three conductors are required per AC 3-phase circuit, although single-phase adn DC circuits are also carried on towers. Conductors may be arranged in one plane, or by use of several cross-arms may be arranged in a roughly symmetrial, triangulated pattern to balance the impedances of all three phases. If more tahn one circuit is required to be acarried and the width of the line right-of-way does not permit multiple towers to be used, two or thre circuits can be carried on the same tower using several levels of cross-arms. Often multiple circuits are the same voltage, but mixed voltages can be found on some structures.

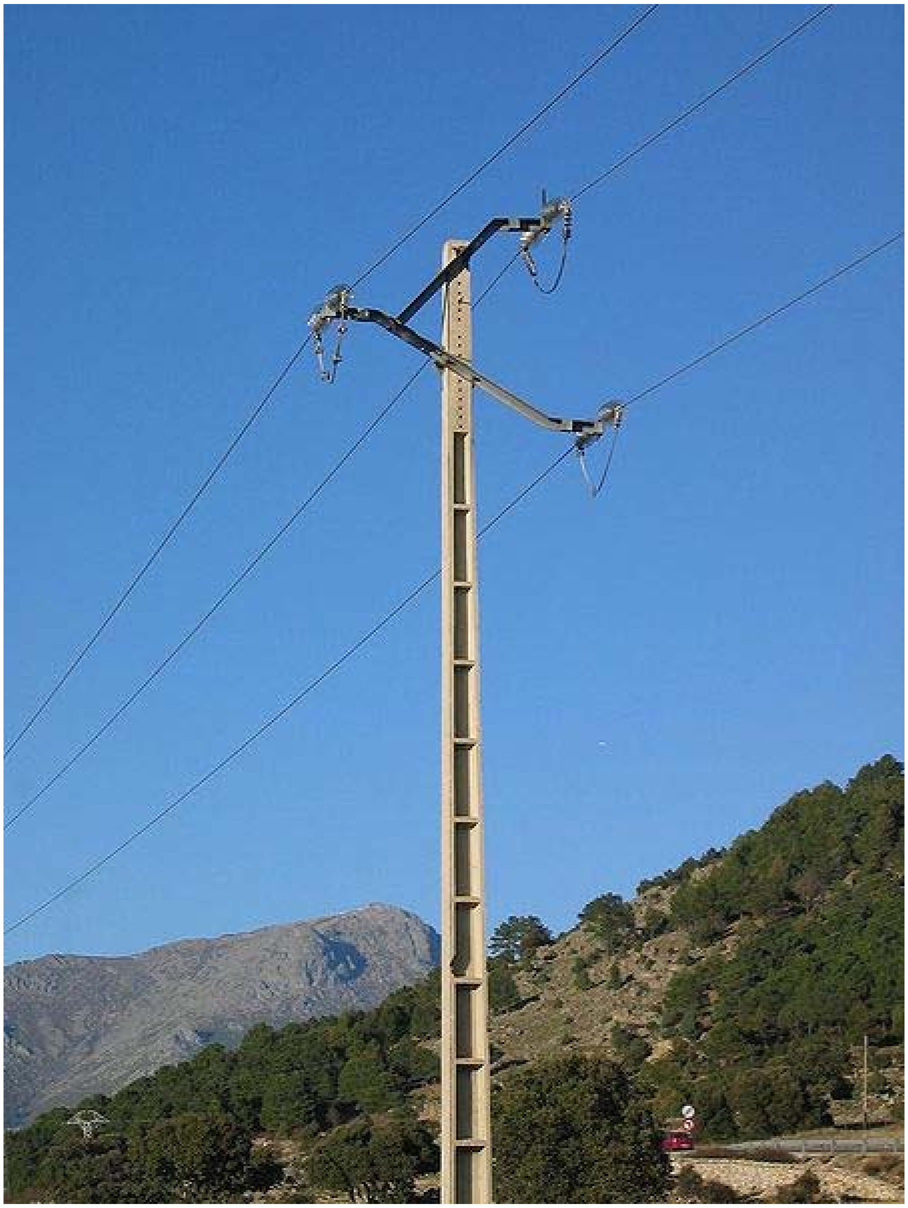
Tower designs

Wood

Because of the limited height of available trees the maximum height of wooden pylons is limited (approximately 30 metres). In Germany wood pylons are used as a rule only for lines with voltages up to approximately 30 kV.

In the United States wood poles are used to construct H-frame or K-frame stuctures for voltages up to 345 kV; these can be less costly than steel structures and take advantage of the surge voltage insulating properties of wood.

Concrete


A reinforced concrete pole in Spain

Because of its durability and ease of manufacturing and installation, many utilities in recent years prefer the use of concrete and steel tube pylons over wood and lattice steel pylons for new power lines and pylon replacements.

Concrete pylons are used in Germany normally only for lines with operating voltages below 30kV. In exceptional cases concrete pylons are used also for 110kV-lines, as well as for the public grid or for the railway traction current grid. In Switzerland, concrete pylons with heights of up to 59.5 metres (world's tallest pylon of prefabricated concrete at Littau) are used for 380kV-overhead lines. Concrete poles are also used in Canada.

Concrete pylons, which are not prefabricated, are also used for constructions taller than 60 metres. One example is a 66 metres tall pylon of a 380 kV powerline near Reutter

West Power Plant in Berlin. Such pylons look like industrial chimneys and some of these structures are also used as chimneys. In China some tall pylons of powerline crossings of wide rivers were built of concrete. The tallest of these pylons belong to the Yangtze Powerline crossing at Nanjing with a height of 257 metres.

Steel tube pylon near Madrid, Spain

Tubular steel monopole

Poles made of tubular steel generally are assembled at the factory and placed on the right-of-way afterward. Because of its durability and ease of manufacturing and installation, many utilities in recent years prefer the use of steel tube and concrete pylons over wood and lattice steel pylons for new power lines and pylon replacements.

In Germany steel tube pylons are also established predominantly for medium voltage lines, in addition, for high voltage transmission lines or two electric circuits for operating voltages by up to 110 kV. In France steel tube pylons are used frequently also for pylons by 380 kV lines in the USA also for 500 kV lines.

Lattice steel

A lattice steel tower is a steel framework construction. Lattice steel towers are used for powerlines of all voltages. Lattice steel towers are the most common type for high-voltage transmission lines.

A lattice tower is usually assembled at the location where it is to be erected. This makes very tall towers possible (up to 100 metres — in special cases even higher, as in the Elbe crossing 1 and Elbe crossing 2). Assembly of lattice steel twoerss can be done using a crane. Lattice steel towers are generallymade of angle-profiled steel beams (L- or T-beams). For very high towers, trusses are often used.

Aluminum

Where towers must be placed in inaccessible terrain by helicopters, the extra material cost of aluminum towers will be offset by lower instellation cost. Design of aluminum lattice towers is similar to that for steel, but must take into account alumunim's lower Young's modulus.

Chapter- 8

Transmission Line

A **transmission line** is a material medium or structure that forms a path for directing the transmission of energy from one place to another, such as electromagnetic waves or acoustic waves, as well as electric power transmission.

However in communications and electronic engineering, the term has a more specific meaning. In these fields, transmission lines are specialized cables and other media designed to carry alternating current and electromagnetic waves of radio frequency, that is, currents with a frequency high enough that its wave nature must be taken into account. Transmission lines are used for purposes such as connecting radio transmitters and receivers with their antennas, distributing cable television signals, and computer network connections.

Ordinary electrical cables suffice to carry low frequency AC, such as mains power, which reverses direction 50 to 60 times per second. However, they cannot be used to carry currents in the radio frequency range or higher, which reverse direction millions to billions of times per second, because the energy tends to radiate off the cable as radio waves, causing power losses. Radio frequency currents also tend to reflect from discontinuities in the cable such as connectors, and travel back down the cable toward the source. These reflections act as bottlenecks, preventing the power from reaching the destination. Transmission lines use specialized construction such as precise conductor dimensions and spacing, and impedance matching, to carry electromagnetic signals with minimal reflections and power losses. Types of transmission line include ladder line, coaxial cable, dielectric slabs, stripline, optical fiber, and waveguides. The higher the frequency, the shorter are the waves in a transmission medium. Transmission lines must be used when the frequency is high enough that the wavelength of the waves begins to approach the length of the cable used. To conduct energy at frequencies above the radio range, such as millimeter waves, infrared, and light, the waves become much smaller than the dimensions of the structures used to guide them, so transmission line techniques become inadequate and the methods of optics are used.

The theory of sound wave propagation is very similar mathematically to that of electromagnetic waves, so techniques from transmission line theory are also used to build structures to conduct acoustic waves; and these are also called transmission lines.

History

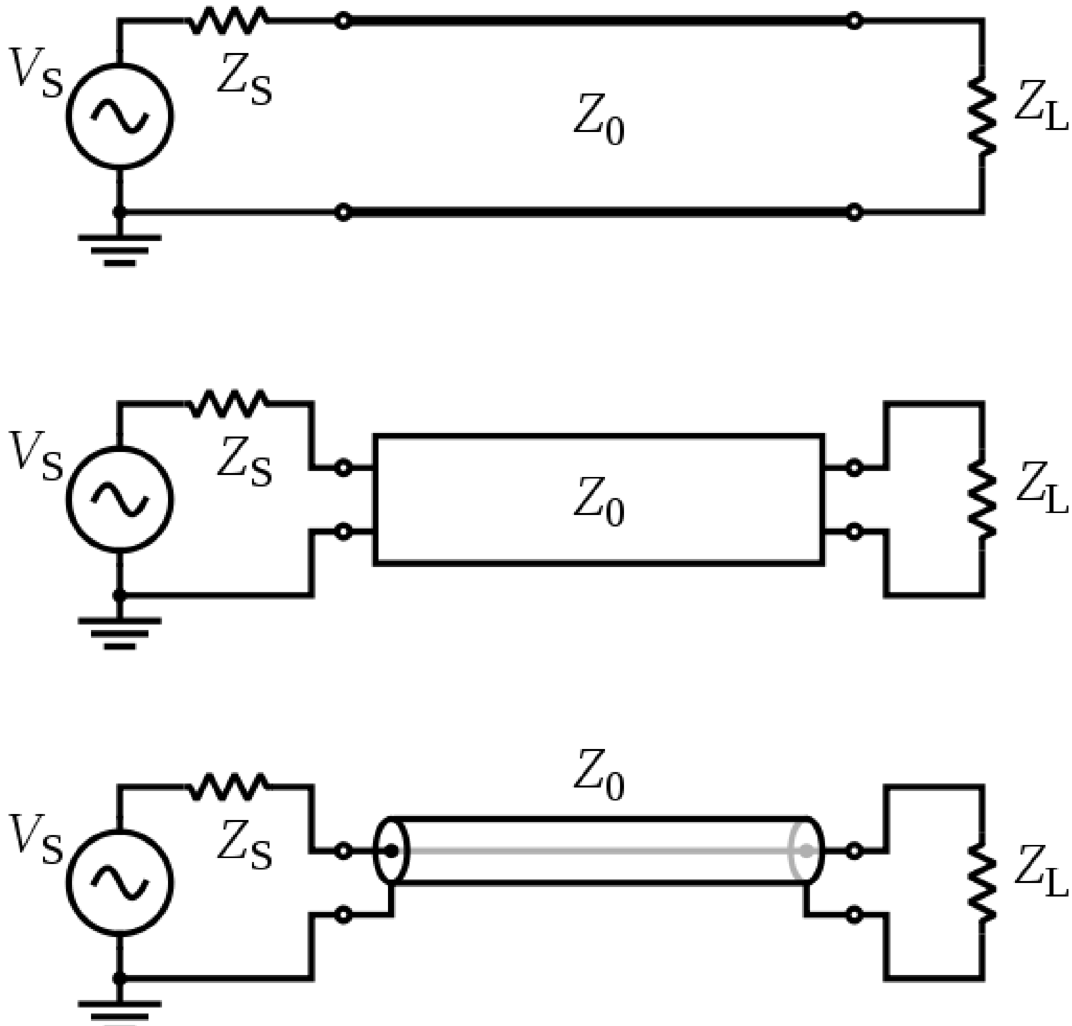
Mathematical analysis of the behaviour of electrical transmission lines grew out of the work of James Clerk Maxwell, Lord Kelvin and Oliver Heaviside. In 1855 Lord Kelvin formulated a diffusion model of the current in a submarine cable. The model correctly predicted the poor performance of the 1858 trans-Atlantic submarine telegraph cable. In 1885 Heaviside published the first papers that described his analysis of propagation in cables and the modern form of the telegrapher's equations.

Applicability

In many electric circuits, the length of the wires connecting the components can for the most part be ignored. That is, the voltage on the wire at a given time can be assumed to be the same at all points. However, when the voltage changes in a time interval comparable to the time it takes for the signal to travel down the wire, the length becomes important and the wire must be treated as a transmission line. Stated another way, the length of the wire is important when the signal includes frequency components with corresponding wavelengths comparable to or less than the length of the wire.

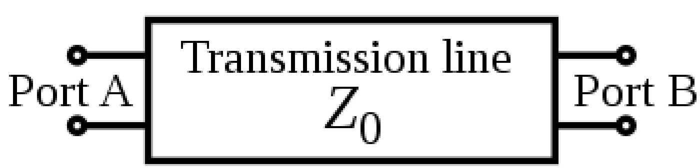
A common rule of thumb is that the cable or wire should be treated as a transmission line if the length is greater than 1/10 of the wavelength. At this length the phase delay and the interference of any reflections on the line become important and can lead to unpredictable behavior in systems which have not been carefully designed using transmission line theory.

The four terminal model



Variations on the schematic electronic symbol for a transmission line.

For the purposes of analysis, an electrical transmission line can be modelled as a two-port network (also called a quadrupole network), as follows:



In the simplest case, the network is assumed to be linear (i.e. the complex voltage across either port is proportional to the complex current flowing into it when there are no reflections), and the two ports are assumed to be interchangeable. If the transmission line is uniform along its length, then its behaviour is largely described by a single parameter called the *characteristic impedance*, symbol Z_0. This is the ratio of the complex voltage of a given wave to the complex current of the same wave at any point on the line. Typical values of Z_0 are 50 or 75 ohms for a coaxial cable, about 100 ohms for a twisted pair of wires, and about 300 ohms for a common type of untwisted pair used in radio transmission.

When sending power down a transmission line, it is usually desirable that as much power as possible will be absorbed by the load and as little as possible will be reflected back to the source. This can be ensured by making the load impedance equal to Z_0, in which case the transmission line is said to be *matched*.

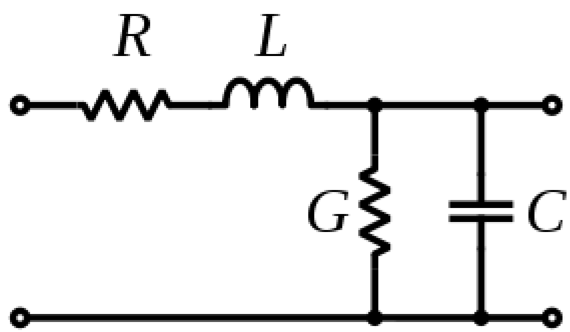
Some of the power that is fed into a transmission line is lost because of its resistance. This effect is called *ohmic* or *resistive* loss. At high frequencies, another effect called *dielectric loss* becomes significant, adding to the losses caused by resistance. Dielectric loss is caused when the insulating material inside the transmission line absorbs energy from the alternating electric field and converts it to heat. The Transmission Line is modeled with a Resistance(R) and Inductance(L) in Series with a Capacitance(C) and Conductance(G) in Parallel. The Resistance and Conductance contributes to the loss of the Transmission Line.

The total loss of power in a transmission line is often specified in decibels per metre (dB/m), and usually depends on the frequency of the signal. The manufacturer often supplies a chart showing the loss in dB/m at a range of frequencies. A loss of 3 dB corresponds approximately to a halving of the power.

High-frequency transmission lines can be defined as those designed to carry electromagnetic waves whose wavelengths are shorter than or comparable to the length of the line. Under these conditions, the approximations useful for calculations at lower frequencies are no longer accurate. This often occurs with radio, microwave and optical signals, metal mesh optical filters, and with the signals found in high-speed digital circuits.

Telegrapher's equations

The **Telegrapher's Equations** (or just **Telegraph Equations**) are a pair of linear differential equations which describe the voltage and current on an electrical transmission line with distance and time. They were developed by Oliver Heaviside who created the *transmission line model*, and are based on Maxwell's Equations.



Schematic representation of the elementary component of a transmission line.

The transmission line model represents the transmission line as an infinite series of two-port elementary components, each representing an infinitesimally short segment of the transmission line:

- The distributed resistance *R* of the conductors is represented by a series resistor (expressed in ohms per unit length).
- The distributed inductance *L* (due to the magnetic field around the wires, self-inductance, etc.) is represented by a series inductor (henries per unit length).
- The capacitance *C* between the two conductors is represented by a shunt capacitor C (farads per unit length).
- The conductance *G* of the dielectric material separating the two conductors is represented by a shunt resistor between the signal wire and the return wire (siemens per unit length).

The model consists of an *infinite series* of the elements shown in the figure, and that the values of the components are specified *per unit length* so the picture of the component can be misleading. *R*, *L*, *C*, and *G* may also be functions of frequency. An alternative notation is to use *R*', *L*', *C*' and *G*' to emphasize that the values are derivatives with respect to length. These quantities can also be known as the primary line constants to distinguish from the secondary line constants derived from them, these being the propagation constant, attenuation constant and phase constant.

The line voltage $V(x)$ and the current $I(x)$ can be expressed in the frequency domain as

$$\frac{\partial V(x)}{\partial x} = -(R + j\omega L)I(x)$$
$$\frac{\partial I(x)}{\partial x} = -(G + j\omega C)V(x)$$

When the elements *R* and *G* are negligibly small the transmission line is considered as a lossless structure. In this hypothetical case, the model depends only on the *L* and *C* elements which greatly simplifies the analysis. For a lossless transmission line, the second order steady-state Telegrapher's equations are:

$$\frac{\partial^2 V(x)}{\partial x^2} + \omega^2 LC \cdot V(x) = 0$$
$$\frac{\partial^2 I(x)}{\partial x^2} + \omega^2 LC \cdot I(x) = 0$$

These are wave equations which have plane waves with equal propagation speed in the forward and reverse directions as solutions. The physical significance of this is that electromagnetic waves propagate down transmission lines and in general, there is a reflected component that interferes with the original signal. These equations are fundamental to transmission line theory.

If *R* and *G* are not neglected, the Telegrapher's equations become:

$$\frac{\partial^2 V(x)}{\partial x^2} = \gamma^2 V(x)$$
$$\frac{\partial^2 I(x)}{\partial x^2} = \gamma^2 I(x)$$

where

$$\gamma = \sqrt{(R + j\omega L)(G + j\omega C)}$$

and the characteristic impedance is:

$$Z_0 = \sqrt{\frac{R + j\omega L}{G + j\omega C}}$$

The solutions for *V*(*x*) and *I*(*x*) are:

$$V(x) = V^+ e^{-\gamma x} + V^- e^{\gamma x}$$
$$I(x) = \frac{1}{Z_0}(V^+ e^{-\gamma x} - V^- e^{\gamma x})$$

The constants $V^{\pm}$and $I^{\pm}$must be determined from boundary conditions. For a voltage pulse $V_{\mathrm{in}}(t)$, starting at *x* = 0 and moving in the positive *x*-direction, then the transmitted pulse $V_{\mathrm{out}}(x,t)$at position *x* can be obtained by computing the Fourier Transform, $\tilde{V}(\omega)$, of $V_{\mathrm{in}}(t)$, attenuating each frequency component by $e^{-\mathrm{Re}(\gamma)x}$, advancing its phase by $-\mathrm{Im}(\gamma)x$, and taking the inverse Fourier Transform. The real and imaginary parts of γ can be computed as

$$\mathrm{Re}(\gamma) = (a^2+b^2)^{1/4}\cos(\mathrm{atan2}(b,a)/2)$$
$$\mathrm{Im}(\gamma) = (a^2+b^2)^{1/4}\sin(\mathrm{atan2}(b,a)/2)$$

where atan2 is the two-parameter arctangent, and

$$a \equiv \omega^2 LC\left[\left(\frac{R}{\omega L}\right)\left(\frac{G}{\omega C}\right)-1\right]$$
$$b \equiv \omega^2 LC\left(\frac{R}{\omega L}+\frac{G}{\omega C}\right)$$

For small losses and high frequencies, to first order in $R / \omega L$ and $G / \omega C$ one obtains

$$\mathrm{Re}(\gamma) \approx \frac{\sqrt{LC}}{2}\left(\frac{R}{L}+\frac{G}{C}\right)$$
$$\mathrm{Im}(\gamma) \approx \omega\sqrt{LC}$$

Noting that an advance in phase by $-\omega\delta$ is equivalent to a time delay by δ, $V_{out}(t)$ can be simply computed as

$$V_{\text{out}}(x,t) \approx V_{\text{in}}(t-\sqrt{LC}x)e^{-\frac{\sqrt{LC}}{2}\left(\frac{R}{L}+\frac{G}{C}\right)x}$$

Input impedance of lossless transmission line

The characteristic impedance Z_0 of a transmission line is the ratio of the amplitude of a **single** voltage wave to its current wave. Since most transmission lines also have a reflected wave, the characteristic impedance is generally **not** the impedance that is measured on the line.

For a lossless transmission line, it can be shown that the impedance measured at a given position l from the load impedance Z_L is

$$Z_{\text{in}}(l) = Z_0\frac{Z_L + jZ_0\tan(\beta l)}{Z_0 + jZ_L\tan(\beta l)}$$

where $\beta = \frac{2\pi}{\lambda}$ is the wavenumber.

In calculating β, the wavelength is generally different inside the transmission line to what it would be in free-space and the velocity constant of the material the transmission line is made of needs to be taken into account when doing such a calculation.

Special cases

Half wave length

For the special case where $\beta l = n\pi$ where n is an integer (meaning that the length of the line is a multiple of half a wavelength), the expression reduces to the load impedance so that

$$Z_{\text{in}} = Z_L$$

for all n. This includes the case when $n = 0$, meaning that the length of the transmission line is negligibly small compared to the wavelength. The physical significance of this is that the transmission line can be ignored (i.e. treated as a wire) in either case.

Quarter wave length

For the case where the length of the line is one quarter wavelength long, or an odd multiple of a quarter wavelength long, the input impedance becomes

$$Z_{\text{in}} = \frac{Z_0^2}{Z_L}$$

Matched load

Another special case is when the load impedance is equal to the characteristic impedance of the line (i.e. the line is *matched*), in which case the impedance reduces to the characteristic impedance of the line so that

$$Z_{\text{in}} = Z_L = Z_0$$

for all l and all λ.

Short

For the case of a shorted load (i.e. $Z_L = 0$), the input impedance is purely imaginary and a periodic function of position and wavelength (frequency)

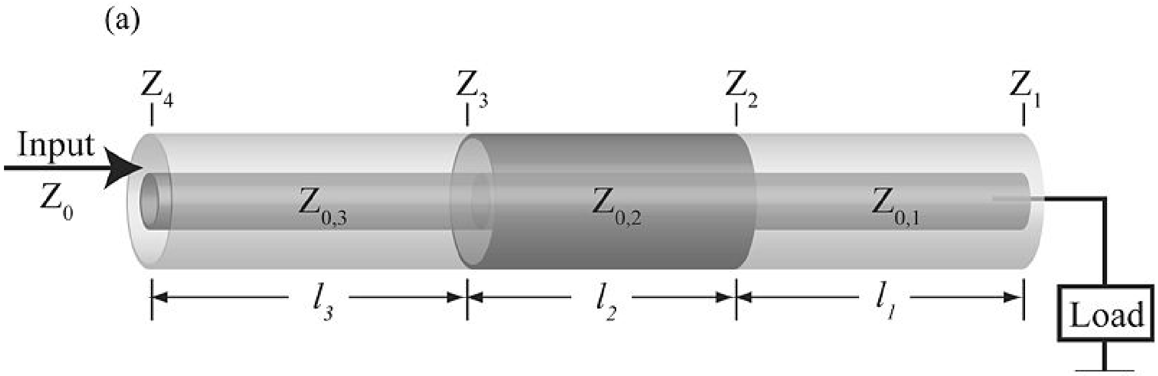
$$Z_{\text{in}}(l) = jZ_0 \tan(\beta l)$$

Open

For the case of an open load (i.e. $Z_L = \infty$), the input impedance is once again imaginary and periodic

$$Z_{\text{in}}(l) = -jZ_0 \cot(\beta l)$$

Stepped transmission line

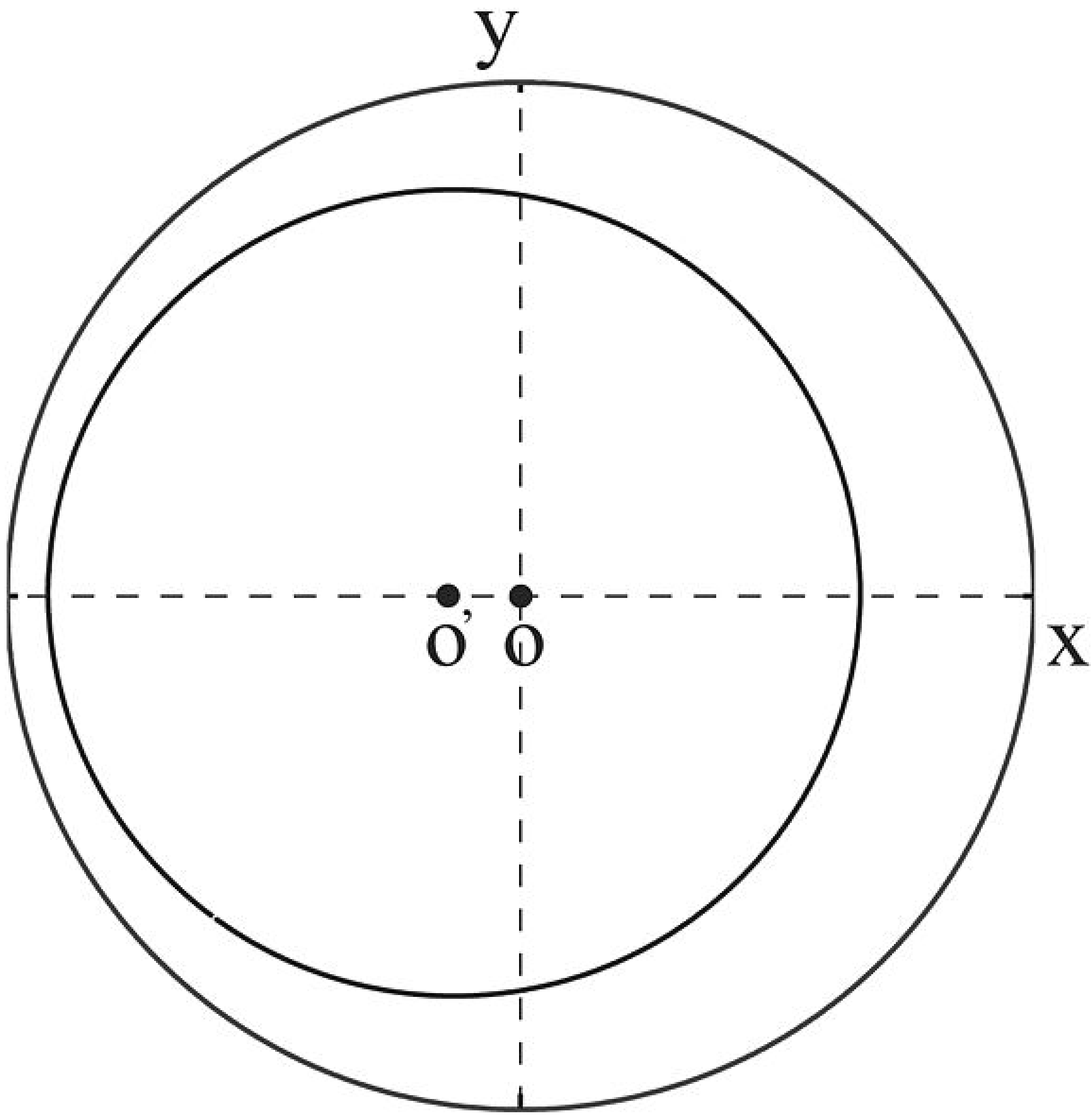


A simple example of stepped transmission line consisting of three segments.

Stepped transmission line is used for broad range impedance matching. It can be considered as multiple transmission line segments connected in serial, with the characteristic impedance of each individual element to be, $Z_{0,i}$. And the input impedance can be obtained from the successive application of the chain relation

$$Z_{\text{i+1}} = Z_{0,\text{i}} \frac{Z_i + jZ_{0,\text{i}} \tan(\beta_i l_i)}{Z_{0,\text{i}} + jZ_i \tan(\beta_i l_i)}$$

where β_i is the wave number of the *i*th transmission line segment and l_i is the length of this segment, and Z_i is the front-end impedance that loads the *i*th segment.



The impedance transformation circle along a transmission line whose characteristic impedance $Z_{0,i}$ is smaller than that of the input cable Z_0. And as a result, the impedance curve is off-centered towards the -x axis. Conversely, if $Z_{0,i} > Z_0$, the impedance curve should be off-centered towards the +x axis.

Because the characteristic impedance of each transmission line segment $Z_{0,i}$ is often different from that of the input cable Z_0, the impedance transformation circle is off centered along the x axis of the Smith Chart whose impedance representation is usually normalized against Z_0.

Practical types

Coaxial cable

Coaxial lines confine virtually all of the electromagnetic wave to the area inside the cable. Coaxial lines can therefore be bent and twisted (subject to limits) without negative effects, and they can be strapped to conductive supports without inducing unwanted currents in them. In radio-frequency applications up to a few gigahertz, the wave propagates in the transverse electric and magnetic mode (TEM) only, which means that the electric and magnetic fields are both perpendicular to the direction of propagation (the electric field is radial, and the magnetic field is circumferential). However, at frequencies for which the wavelength (in the dielectric) is significantly shorter than the circumference of the cable, transverse electric (TE) and transverse magnetic (TM) waveguide modes can also propagate. When more than one mode can exist, bends and other irregularities in the cable geometry can cause power to be transferred from one mode to another.

The most common use for coaxial cables is for television and other signals with bandwidth of multiple megahertz. In the middle 20th century they carried long distance telephone connections.

Microstrip

A microstrip circuit uses a thin flat conductor which is parallel to a ground plane. Microstrip can be made by having a strip of copper on one side of a printed circuit board (PCB) or ceramic substrate while the other side is a continuous ground plane. The width of the strip, the thickness of the insulating layer (PCB or ceramic) and the dielectric constant of the insulating layer determine the characteristic impedance. Microstrip is an open structure whereas coaxial cable is a closed structure.

Stripline

A stripline circuit uses a flat strip of metal which is sandwiched between two parallel ground planes. The insulating material of the substrate forms a dielectric. The width of the strip, the thickness of the substrate and the relative permittivity of the substrate determine the characteristic impedance of the strip which is a transmission line.

Balanced lines

A balanced line is a transmission line consisting of two conductors of the same type, and equal impedance to ground and other circuits. There are many formats of balanced lines, amongst the most common are twisted pair, star quad and twin-lead.

Twisted pair

Twisted pairs are commonly used for terrestrial telephone communications. In such cables, many pairs are grouped together in a single cable, from two to several thousand. The format is also used for data network distribution inside buildings, but in this case the cable used is more expensive with much tighter controlled parameters and either two or four pairs per cable.

Star quad

Star quad is another balanced format used at low frequencies. Applications include 4-wire telephony and microphone circuits.

Twin-lead

Twin-lead consists of a pair of conductors held apart by a continuous insulator.

Lecher lines

Lecher lines are a form of parallel conductor that can be used at UHF for creating resonant circuits. They are a convenient practical format that fills the gap between lumped components (used at HF/VHF) and resonant cavities (used at UHF/SHF).

Single-wire line

Unbalanced lines were formerly much used for telegraph transmission, but this form of communication has now fallen into disuse. Cables are similar to twisted pair in that many cores are bundled into the same cable but only one conductor is provided per circuit and there is no twisting. All the circuits on the same route use a common path for the return current (earth return). There is a power transmission version of single-wire earth return in use in many locations.

Waveguide

Waveguides are rectangular or circular metallic tubes inside which an electromagnetic wave is propagated and is confined by the tube. Waveguides are not capable of transmitting the transverse electromagnetic mode found in copper lines and must use some other mode. Consequently, they cannot be directly connected to cable and a mechanism for launching the waveguide mode must be provided at the interface.

Optical fiber

Optical fibers are a solid transparent fiber of glass or polymer which transmits a signal at optical, or near infrared, wavelengths. They form the backbone of all modern terrestrial communications networks due to the very high bandwidths that can be achieved. Optical fiber are another variety of waveguide.

General applications

Signal transfer

Electrical transmission lines are very widely used to transmit high frequency signals over long or short distances with minimum power loss. One familiar example is the down lead from a TV or radio aerial to the receiver.

Pulse generation

Transmission lines are also used as pulse generators. By charging the transmission line and then discharging it into a resistive load, a rectangular pulse equal in length to twice the electrical length of the line can be obtained, although with half the voltage. A Blumlein transmission line is a related pulse forming device that overcomes this limitation. These are sometimes used as the pulsed energy sources for radar transmitters and other devices.

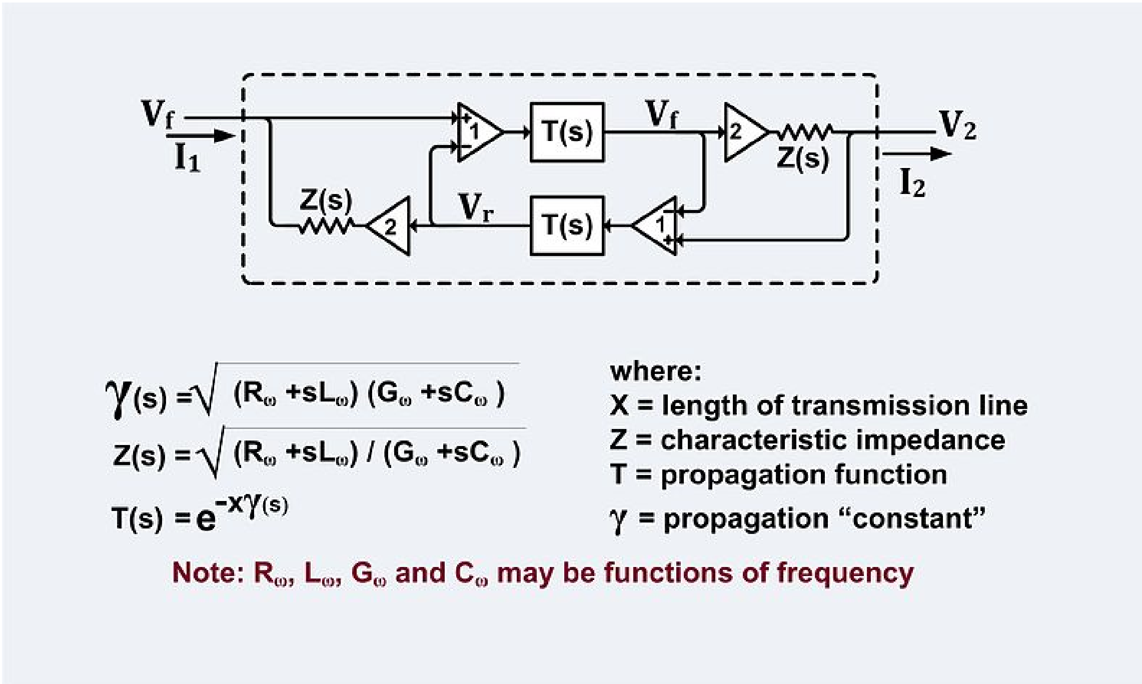
Stub filters

If a short-circuited or open-circuited transmission line is wired in parallel with a line used to transfer signals from point A to point B, then it will function as a filter. The method for making stubs is similar to the method for using Lecher lines for crude frequency measurement, but it is 'working backwards'. One method recommended in the RSGB's radiocommunication handbook is to take an open-circuited length of transmission line wired in parallel with the feeder delivering signals from an aerial. By cutting the free end of the transmission line, a minimum in the strength of the signal observed at a receiver can be found. At this stage the stub filter will reject this frequency and the odd harmonics, but if the free end of the stub is shorted then the stub will become a filter rejecting the even harmonics.

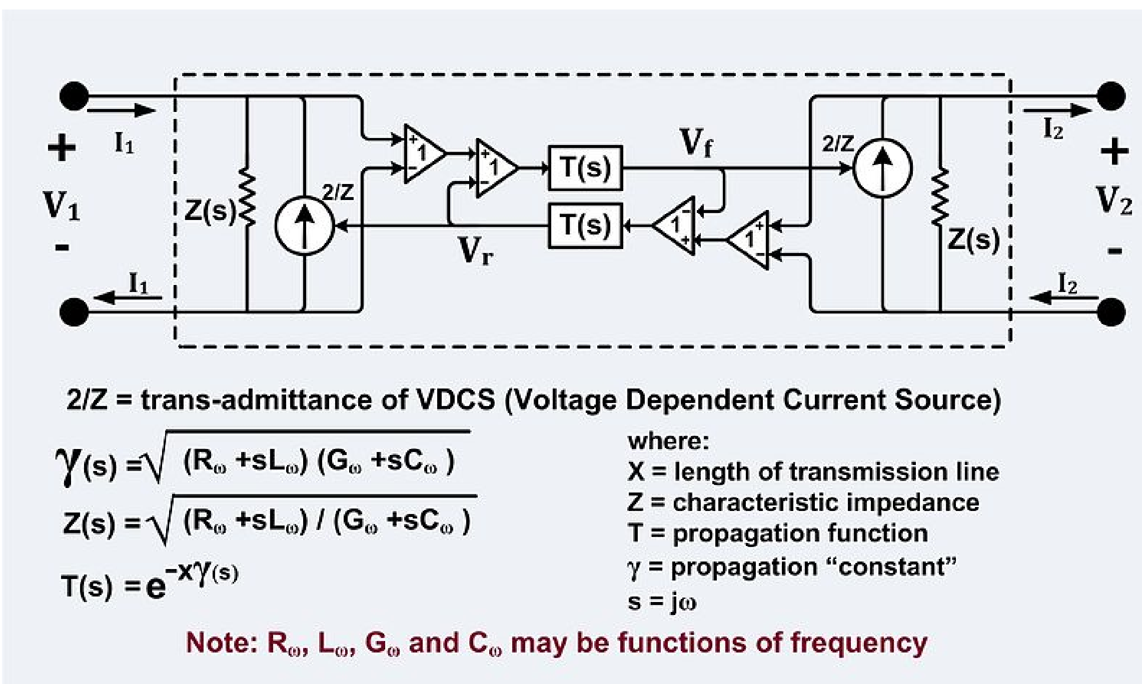
Acoustic transmission lines

An acoustic transmission line is the acoustic analog of the electrical transmission line, typically thought of as a rigid-walled tube that is long and thin relative to the wavelength of sound present in it.

Solutions of the Telegrapher's Equations as Circuit Components



Equivalent circuit of a transmission line described by the Telegrapher's equations.



Solutions of the Telegrapher's Equations as Components in the Equivalent Circuit of a Balanced Transmission Line Two-Port Implementation.

The solutions of the telegrapher's equations can be inserted directly into a circuit as components. The circuit in the left figure implements the solutions of the telegrapher's equations.

The right hand circuit is derived from the left hand circuit by source transformations. It also implements the solutions of the telegrapher's equations.

The solution of the telegrapher's equations can be expressed as an ABCD type *Two-port network* with the following defining equations

$$V_1 = V_2 cosh(\gamma x) + I_2 Z sinh(\gamma x)$$
$$I_1 = V_2 \frac{1}{Z} sinh(\gamma x) + I_2 cosh(\gamma x)$$

The symbols: E_s, E_L, I_s, I_L, l in the source book have been replaced by the symbols : V_1, V_2, I_1, I_2, x in the preceding two equations.

The ABCD type two-port gives V_1 and I_1 as functions of V_2 and I_2. Both of the circuits above, when solved for V_1 and I_1 as functions of V_2 and I_2 yield exactly the same equations.

In the right hand circuit, all voltages except the port voltages are with respect to ground and the differential amplifiers have unshown connections to ground. An example of a transmission line modeled by this circuit would be a balanced transmission line such as a telephone line. The impedances Z(s), the voltage dependent current sources (VDCSs) and the difference amplifiers (the triangle with the number "1") account for the interaction of the transmission line with the external circuit. The T(s) blocks account for delay, attenuation, dispersion and whatever happens to the signal in transit. One of the T(s) blocks carries the *forward wave* and the other carries the *backward wave*. The circuit, as depicted, is fully symmetric, although it is not drawn that way. The circuit depicted is equivalent to a transmission line connected from V_1 to V_2 in the sense that V_1, V_2, I_1 and I_2 would be same whether this circuit or an actual transmission line was connected between V_1 and V_2. There is no implication that there are actually amplifiers inside the transmission line.

Every two-wire or balanced transmission line has an implicit (or in some cases explicit) third wire which may be called shield, sheath, common, Earth or ground. So every two-wire balanced transmission line has two modes which are nominally called the differential and common modes. The circuit shown on the right only models the differential mode.

In the left hand circuit, the voltage doublers, the difference amplifiers and impedances Z(s) account for the interaction of the transmission line with the external circuit. This circuit, as depicted, is also fully symmetric, and also not drawn that way. This circuit is a useful equivalent for an unbalanced transmission line like a coaxial cable or a micro strip line.

These are not the only possible equivalent circuits.

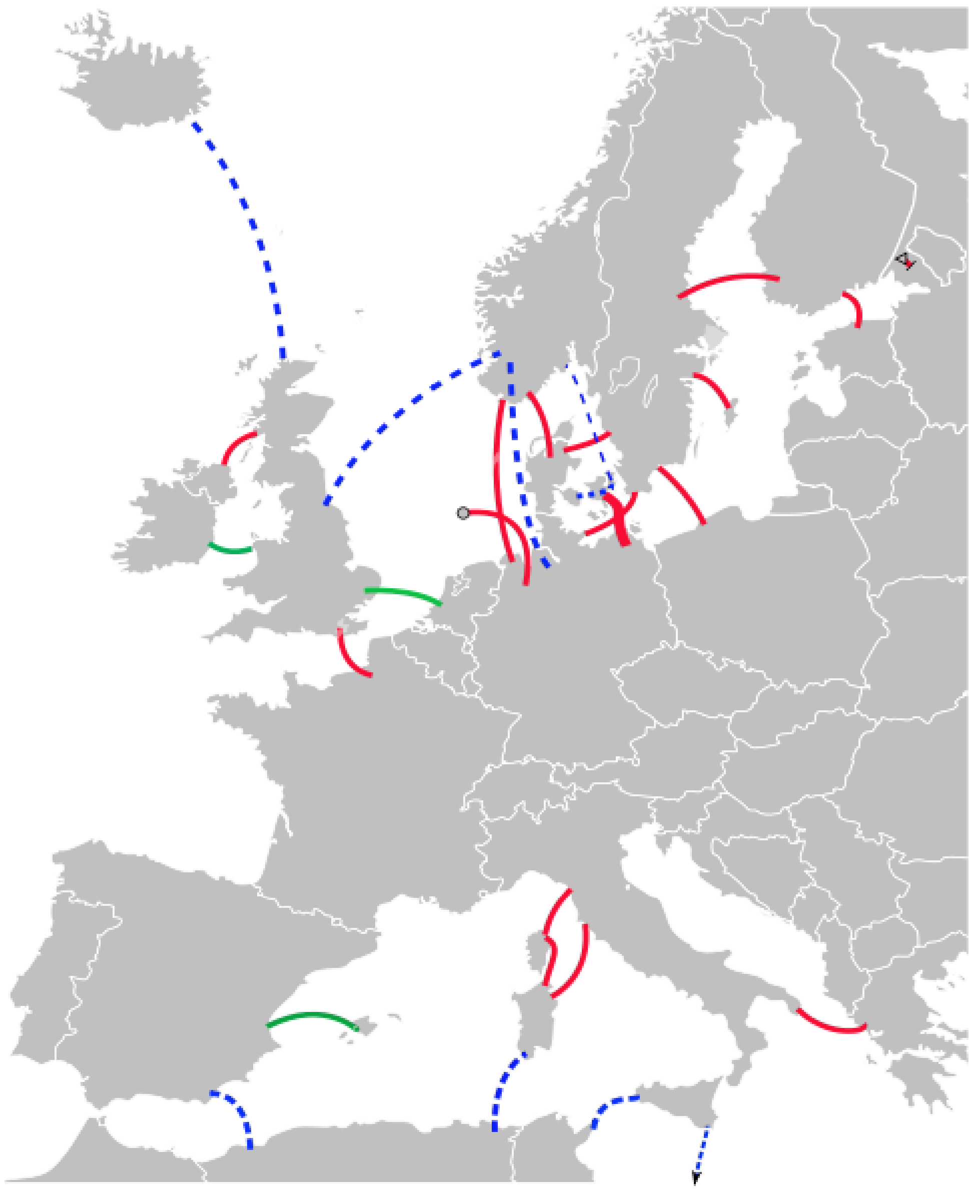
Chapter- 9

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).



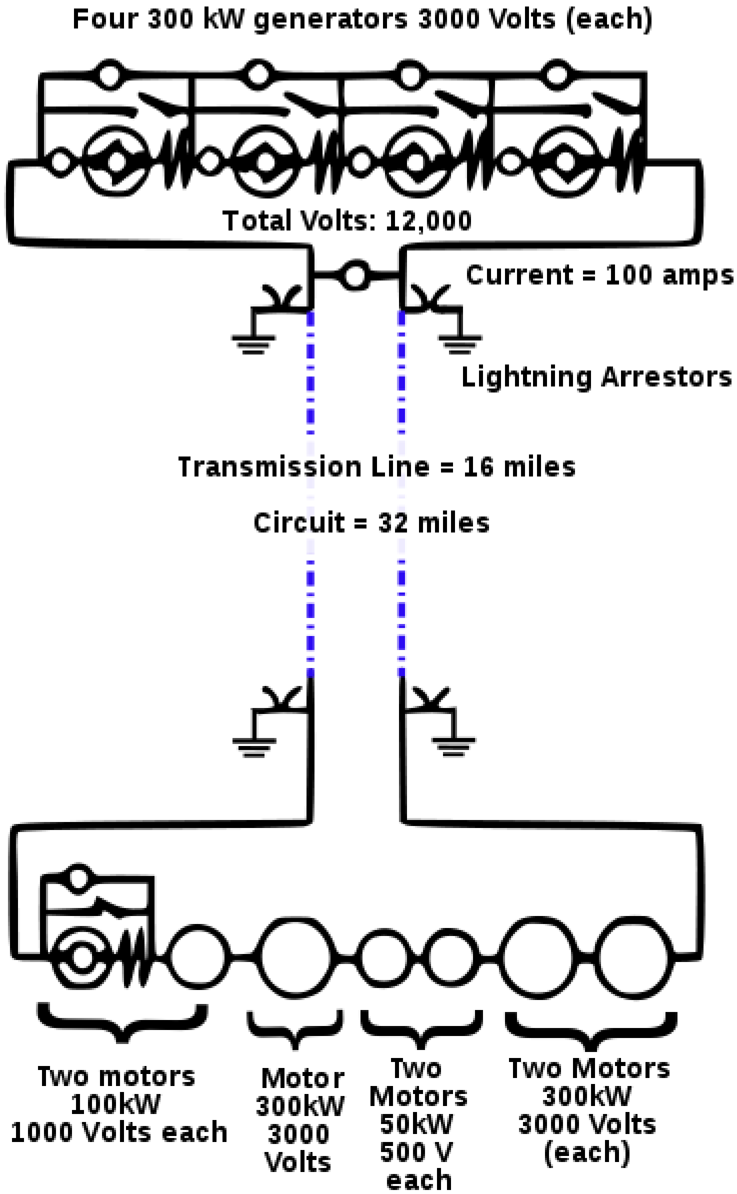
Existing links
Under construction
Proposed
Many of these transfer power from renewable sources such as hydro and wind.

High voltage transmission

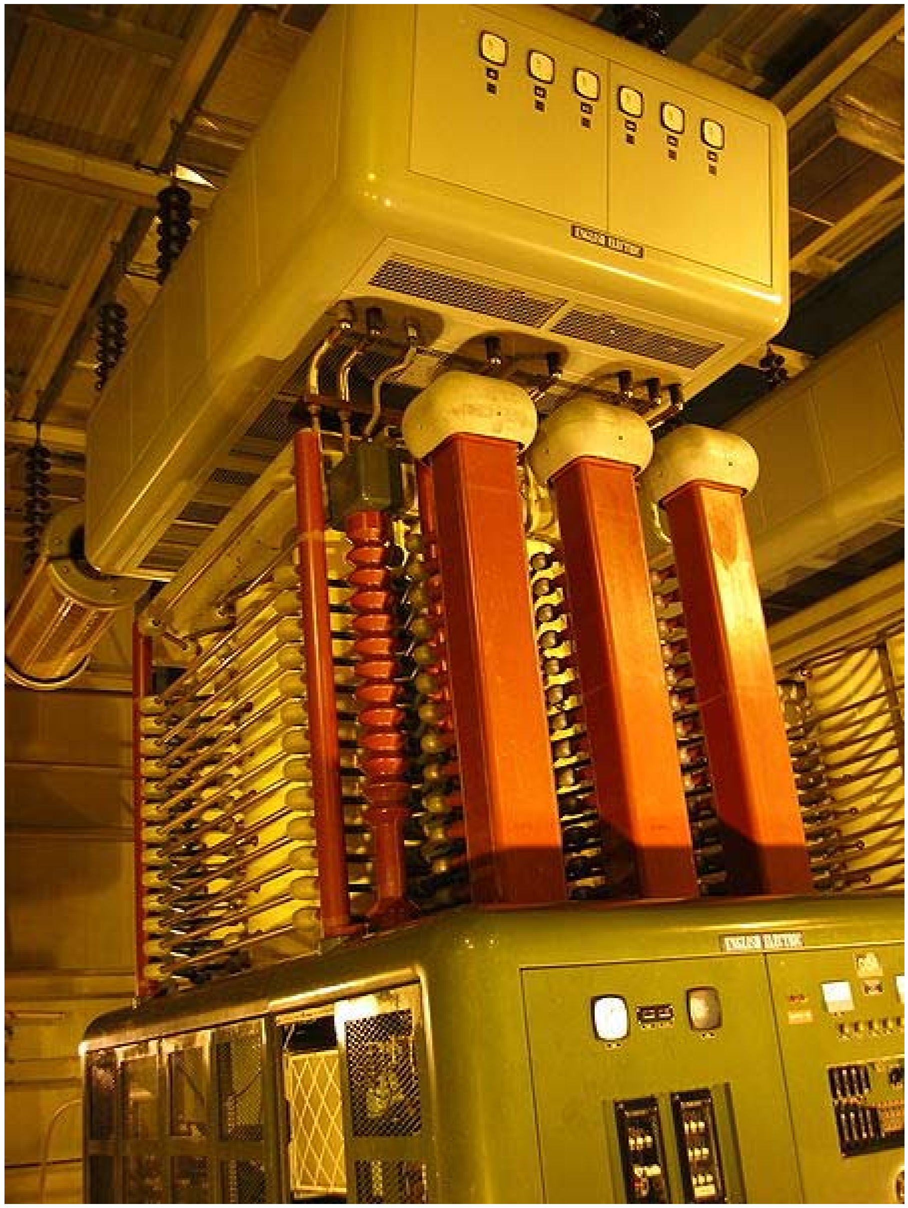
High voltage is used for electric power transmission to reduce the energy lost in the resistance of the wires. For a given quantity of power transmitted, higher voltage reduces the transmission power loss. The power lost as heat in the wires is proportional to the square of the current. So if a given 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).

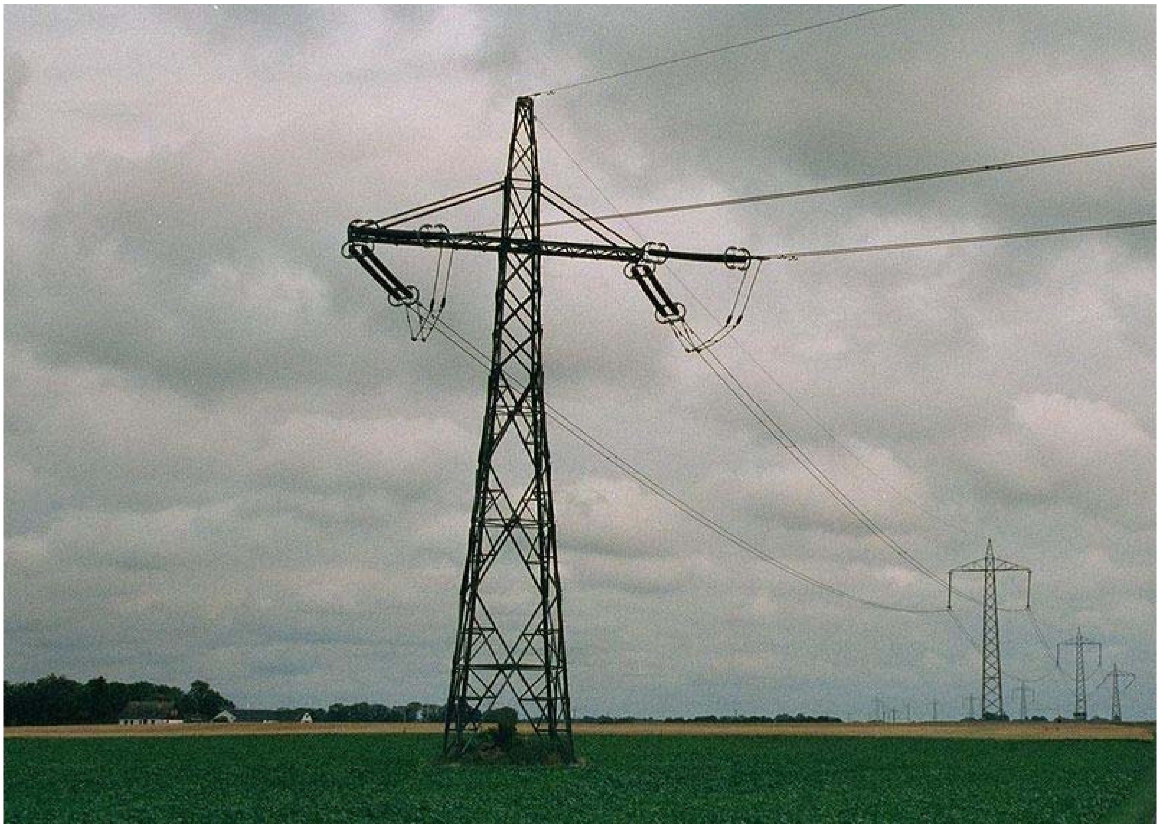
History of HVDC transmission



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 high voltage cables have a high electrical capacitance, since the conductors are surrounded by a relatively thin layer of insulation and a metal sheath. 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

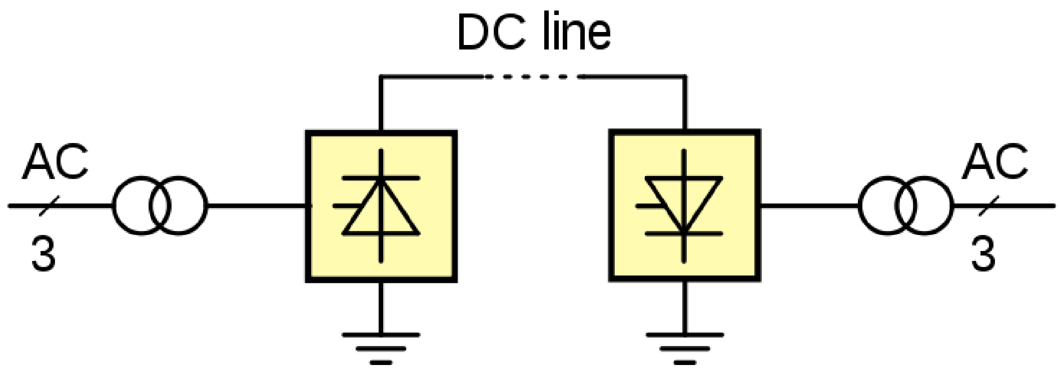
Rectification and inversion use essentially the same machinery. Many substations (*Converter Stations*) are set up in such a way that they can act as both rectifiers and inverters. At the AC end a set of transformers, often three physically separated single-phase transformers, isolate the station from 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:

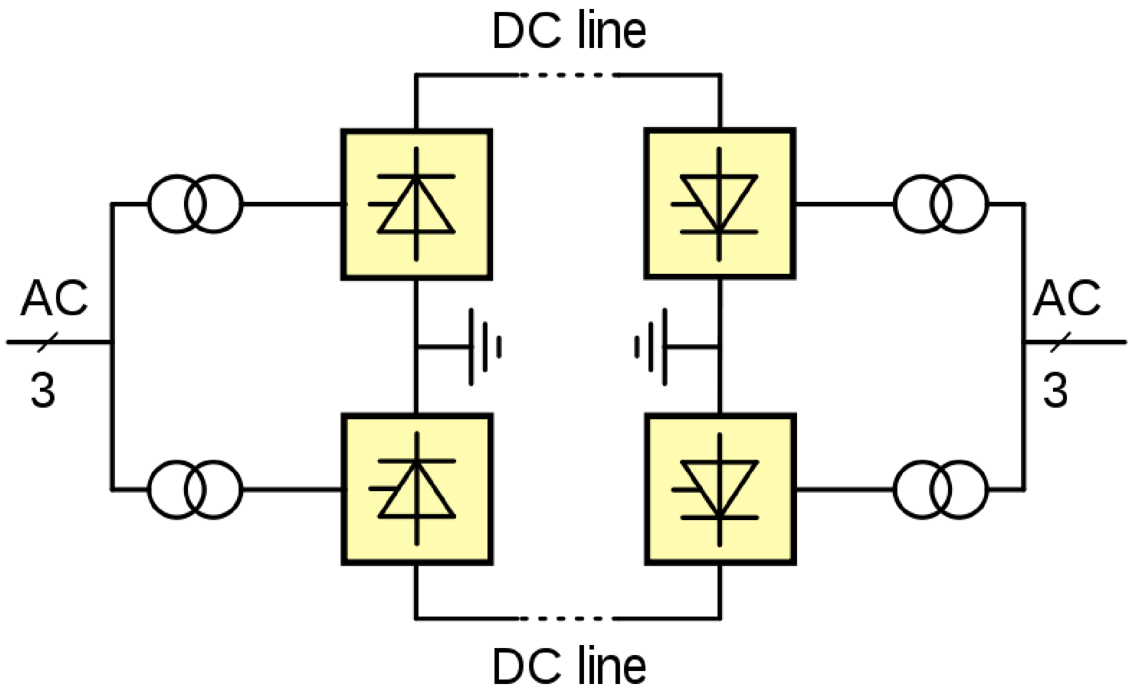
- Electrochemical corrosion of long buried metal objects such as pipelines
- Underwater earth-return electrodes in seawater may produce chlorine or otherwise affect water chemistry.
- An unbalanced current path may result in a net magnetic field, which can affect magnetic navigational compasses for ships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



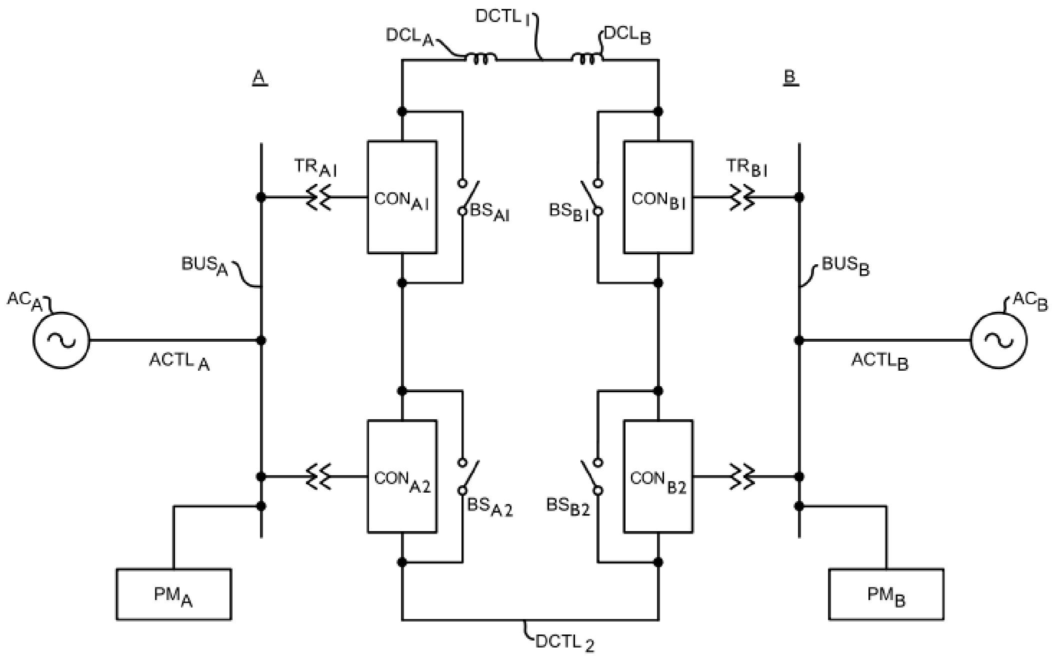
Block diagram of a bipolar system that also has an earth return

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 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.