Handbook of Transformers and Electrical Generators

Maud Bostic

Felicity Salerno

First Edition, 2012

ISBN 978-81-323-0931-4

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

Table of Contents

Chapter-1

Transformer

Pole-mounted power distribution transformer with center-tapped secondary winding (note use of grounded conductor, right, as one leg of the primary feeder). It transforms the high voltage of the overhead distribution wires to the lower voltage used in house wiring.

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

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

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

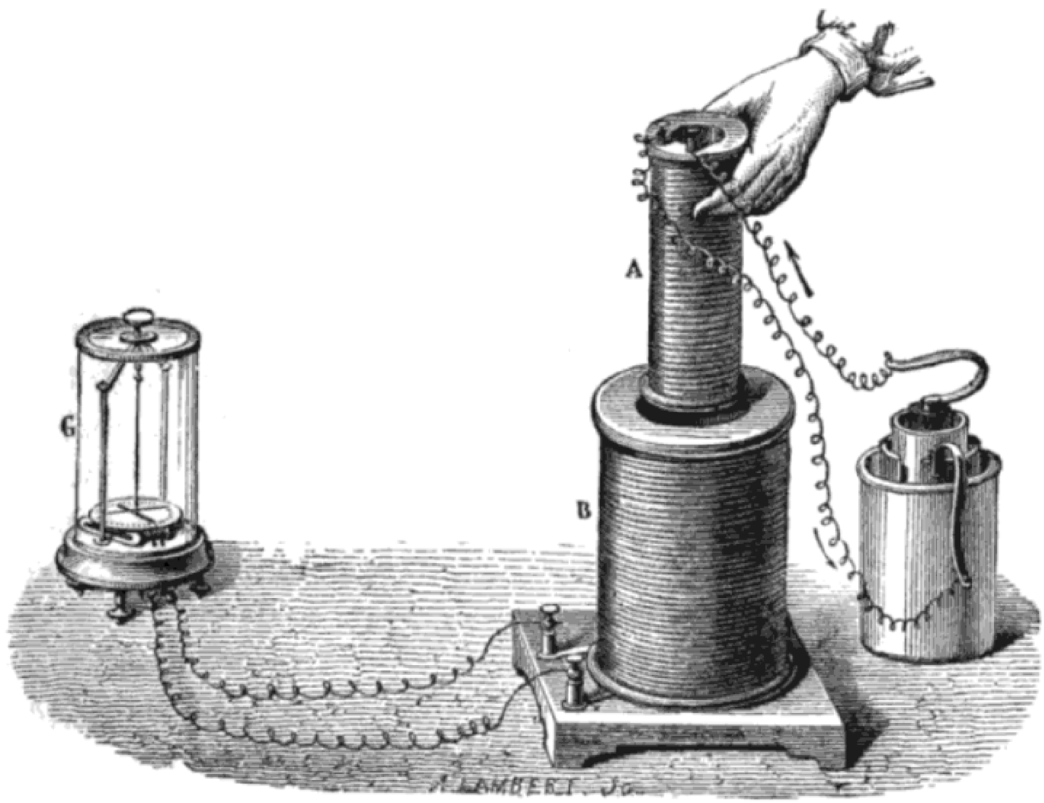
By appropriate selection of the ratio of turns, a transformer thus allows an alternating current (AC) voltage to be "stepped up" by making N_s greater than N_p, or "stepped down" by making N_s less than N_p.

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

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

History

Discovery



Faraday's experiment with induction between coils of wire

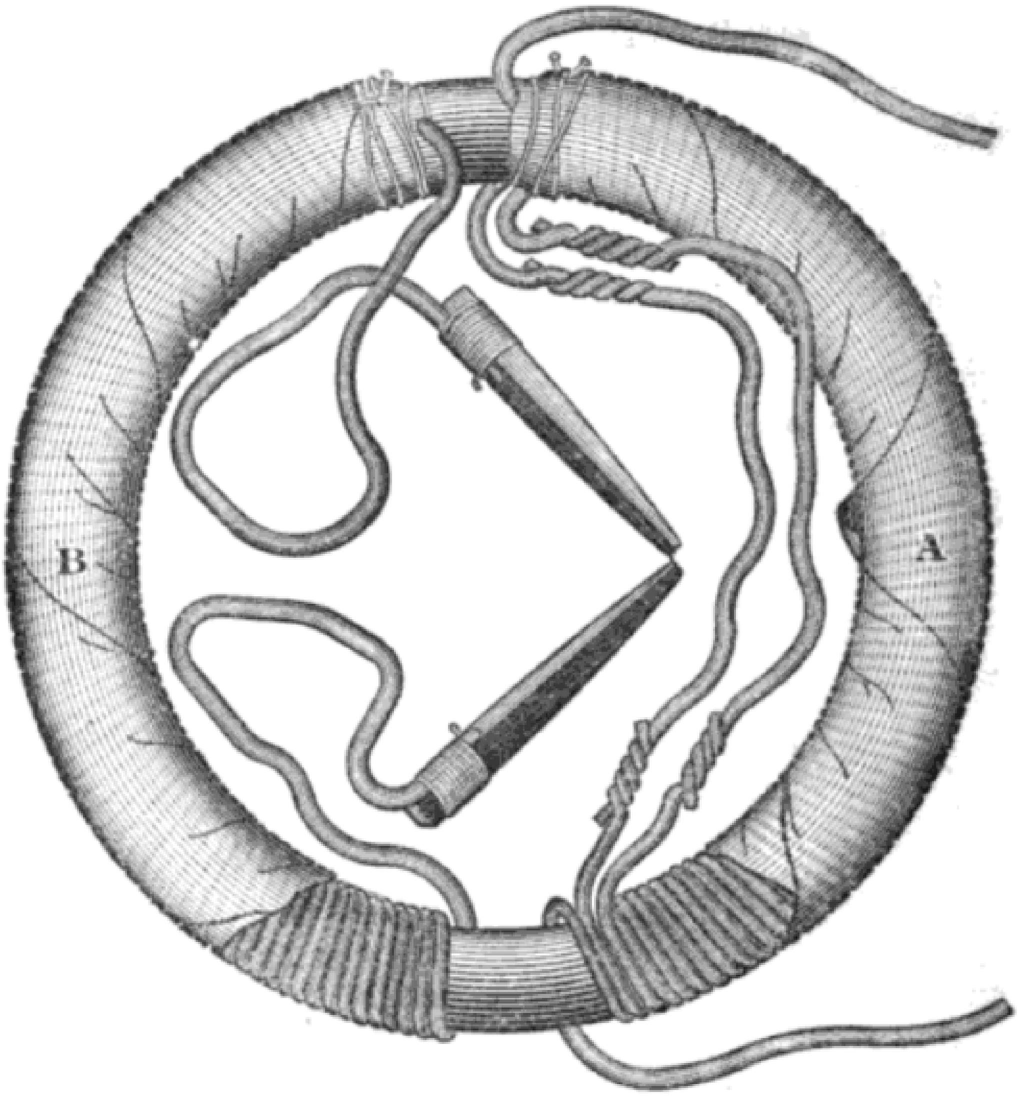
The phenomenon of electromagnetic induction was discovered independently by Michael Faraday and Joseph Henry in 1831. However, Faraday was the first to publish the results of his experiments and thus receive credit for the discovery. The relationship between electromotive force (EMF) or "voltage" and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

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

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

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

Induction coils



Faraday's ring transformer

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

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

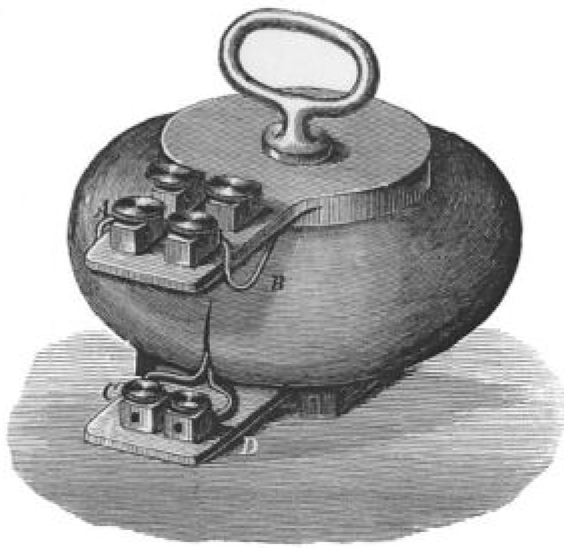
In 1878, the Ganz Company in Hungary began manufacturing equipment for electric lighting and, by 1883, had installed over fifty systems in Austria-Hungary. Their systems used alternating current exclusively and included those comprising both arc and incandescent lamps, along with generators and other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

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

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

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

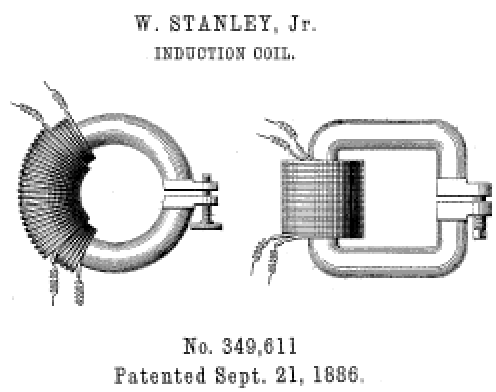
Closed-core transformers and the introduction of parallel connection



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

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

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



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

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

Other early transformers

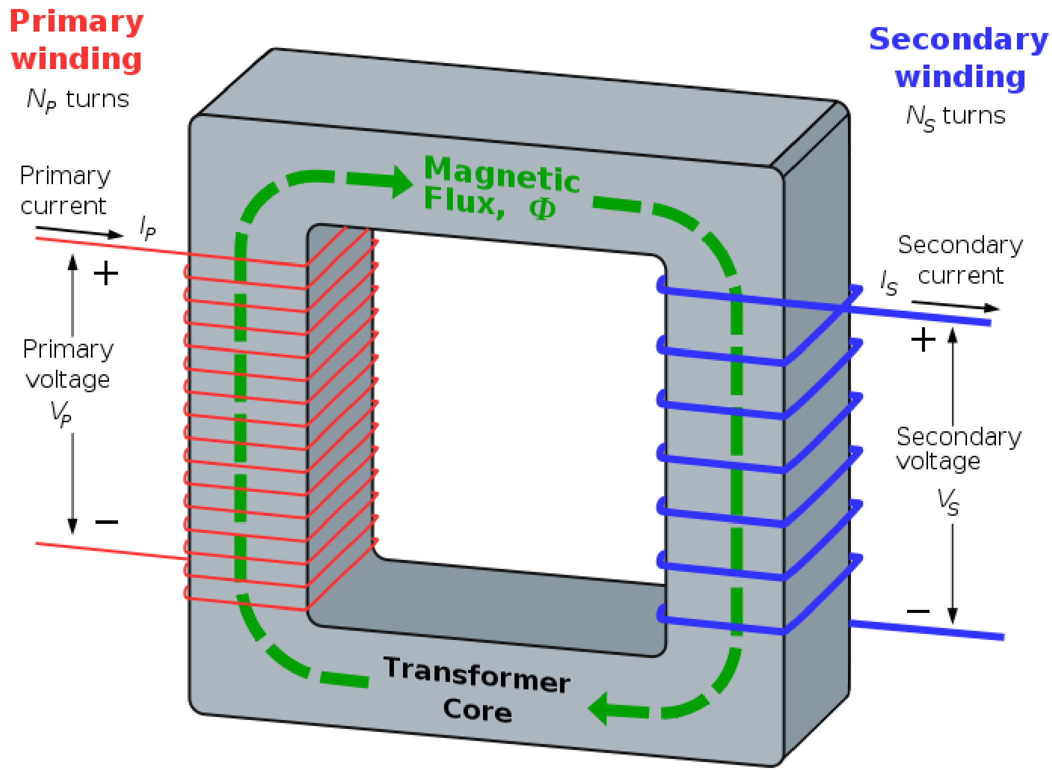
In 1889, Russian-born engineer Mikhail Dolivo-Dobrovolsky developed the first three-phase transformer at the Allgemeine Elektricitäts-Gesellschaft ("General Electricity Company") in Germany.

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

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

Basic principles

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



An ideal transformer

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

Induction law

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

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

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

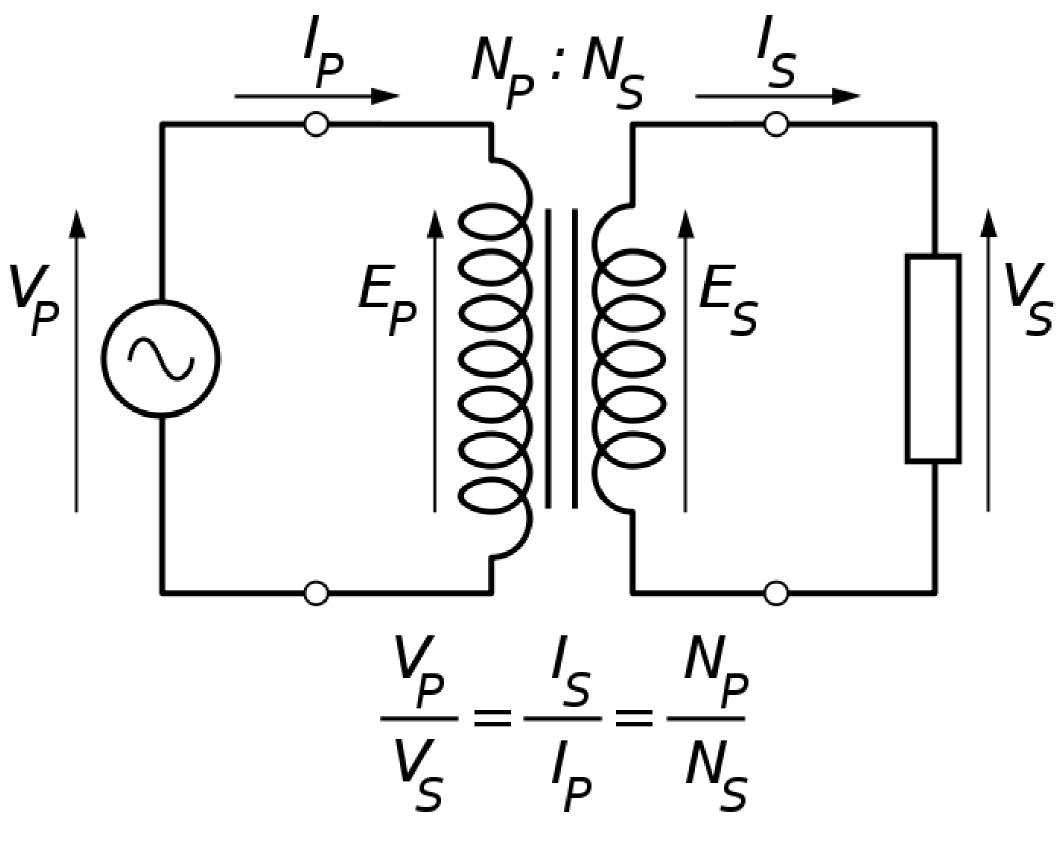
$$V_p = N_p \frac{d\Phi}{dt}.$$

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

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

N_p/N_s is known as the *turns ratio*, and is the primary functional characteristic of any transformer. In the case of step-up transformers, this may sometimes be stated as the reciprocal, N_s/N_p. *Turns ratio* is commonly expressed as an irreducible fraction or ratio: for example, a transformer with primary and secondary windings of, respectively, 100 and 150 turns is said to have a turns ratio of 2:3 rather than 0.667 or 100:150.

Ideal power equation



The ideal transformer as a circuit element

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

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

giving the ideal transformer equation

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

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

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

Detailed operation

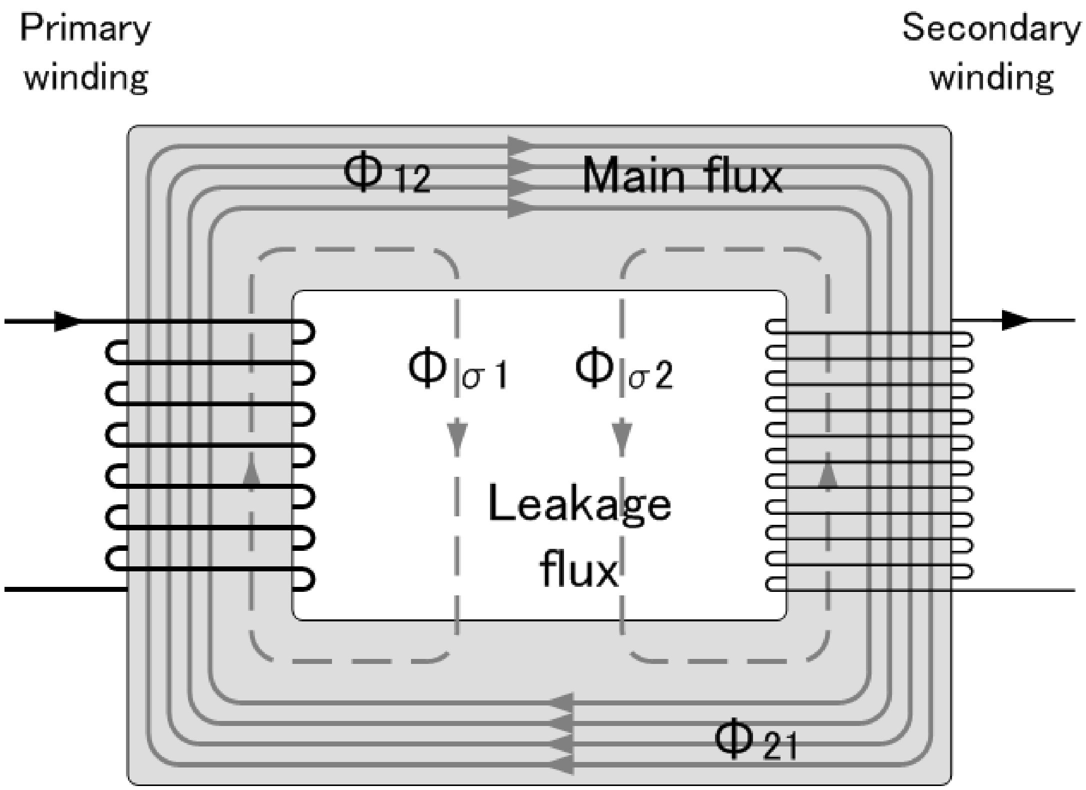
The simplified description above neglects several practical factors, in particular the primary current required to establish a magnetic field in the core, and the contribution to the field due to current in the secondary circuit.

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

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

Practical considerations

Leakage flux



Leakage flux of a transformer

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

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

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

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

Effect of frequency

Transformer universal EMF equation

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

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

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

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

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

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

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

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

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

Energy losses

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

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

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

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

Winding resistance

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

Hysteresis losses

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

Eddy currents

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

Magnetostriction

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

Mechanical losses

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

Stray losses

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

Dot convention

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

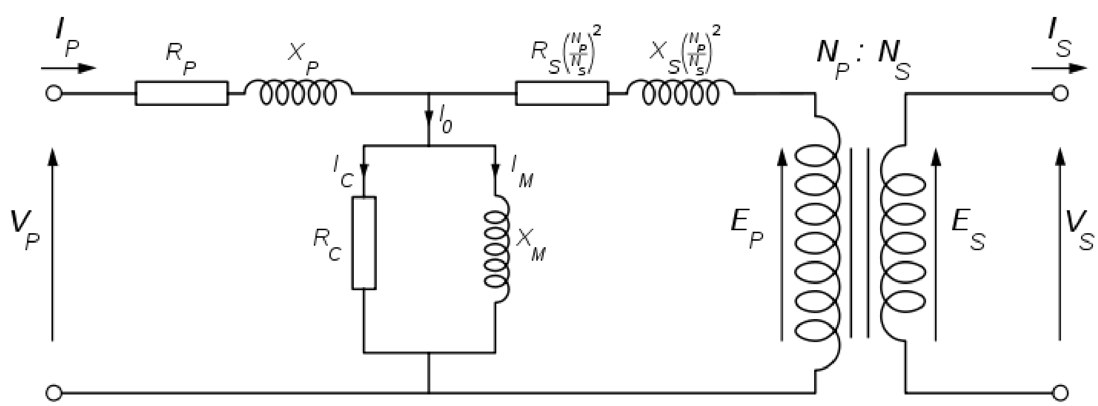
Equivalent circuit

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

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

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

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



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

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

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

Types

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

Autotransformer

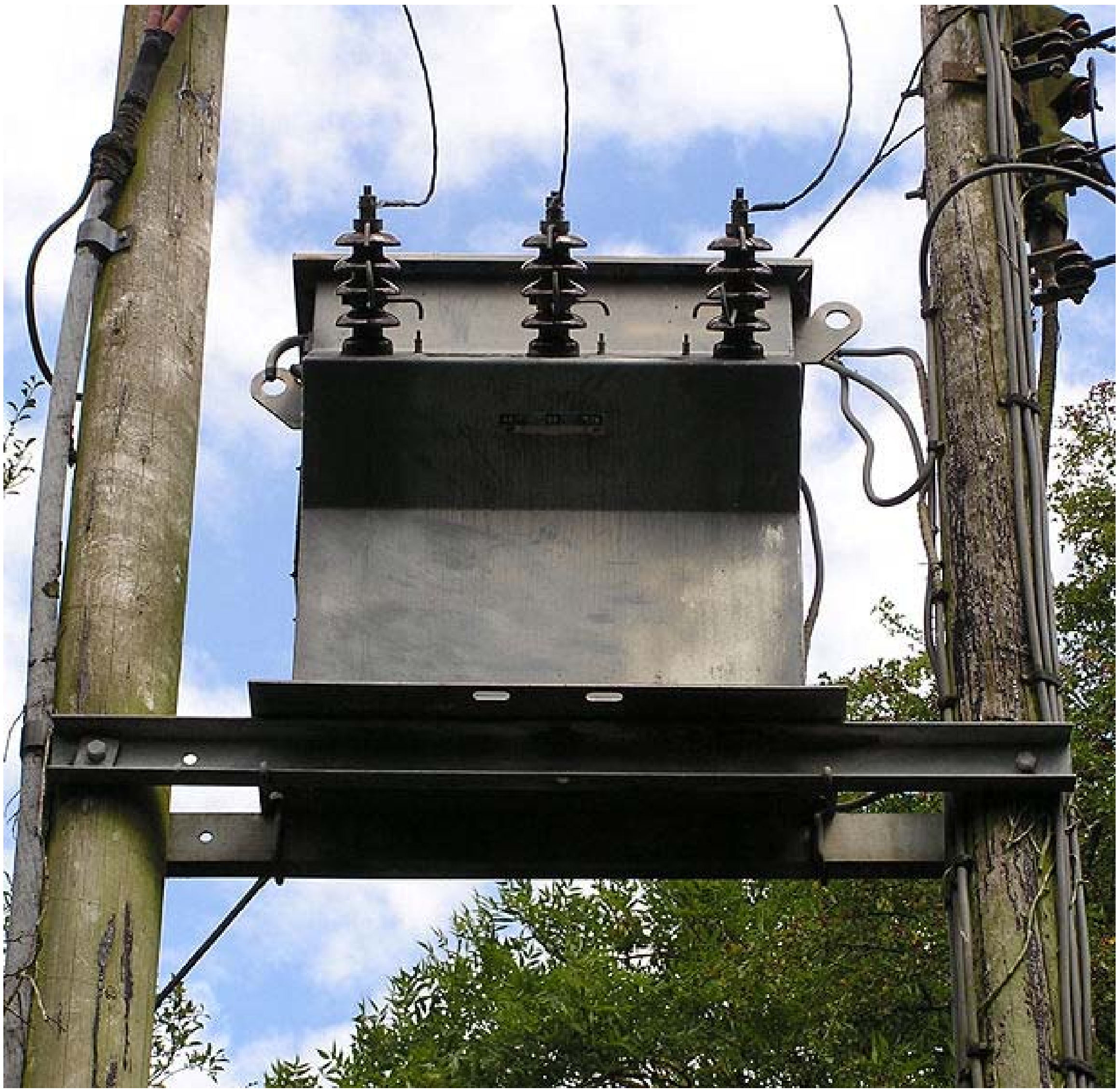
A variable autotransformer

In an autotransformer portions of the same winding act as both the primary and secondary. The winding has at least three taps where electrical connections are made. An autotransformer can be smaller, lighter and cheaper than a standard dual-winding transformer however the autotransformer does not provide electrical isolation.

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

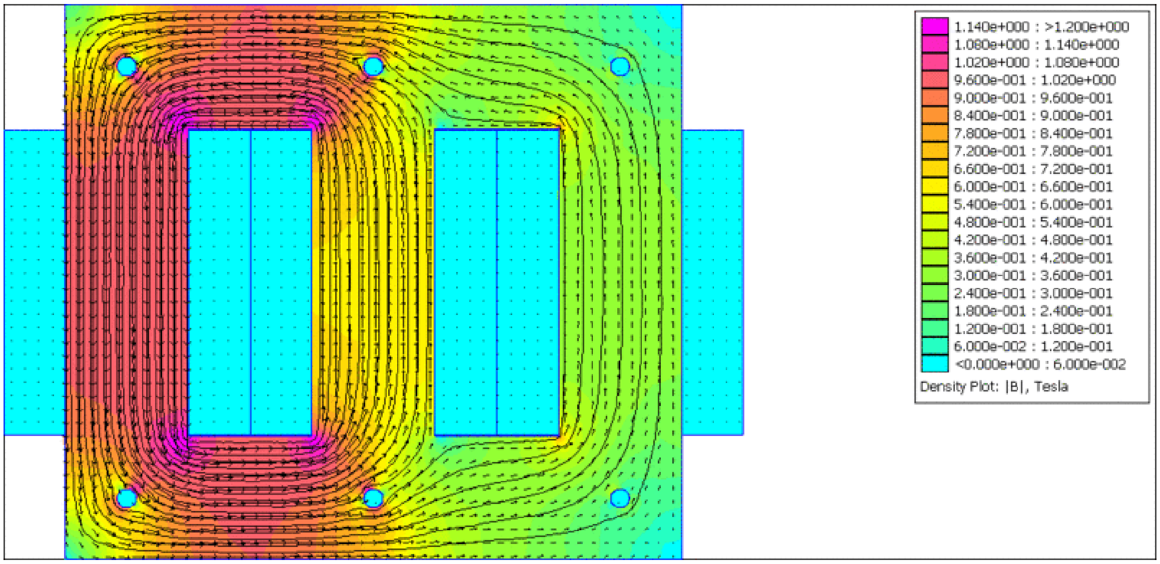
A variable autotransformer is made by exposing part of the winding coils and making the secondary connection through a sliding brush, giving a variable turns ratio. Such a device is often referred to by the trademark name *variac*.

Polyphase transformers



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

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



Screenshot of a FEM simulation of the magnetic flux inside a three-phase power transformer.

Leakage transformers

Leakage transformer

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

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

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

Resonant transformers

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

Audio transformers

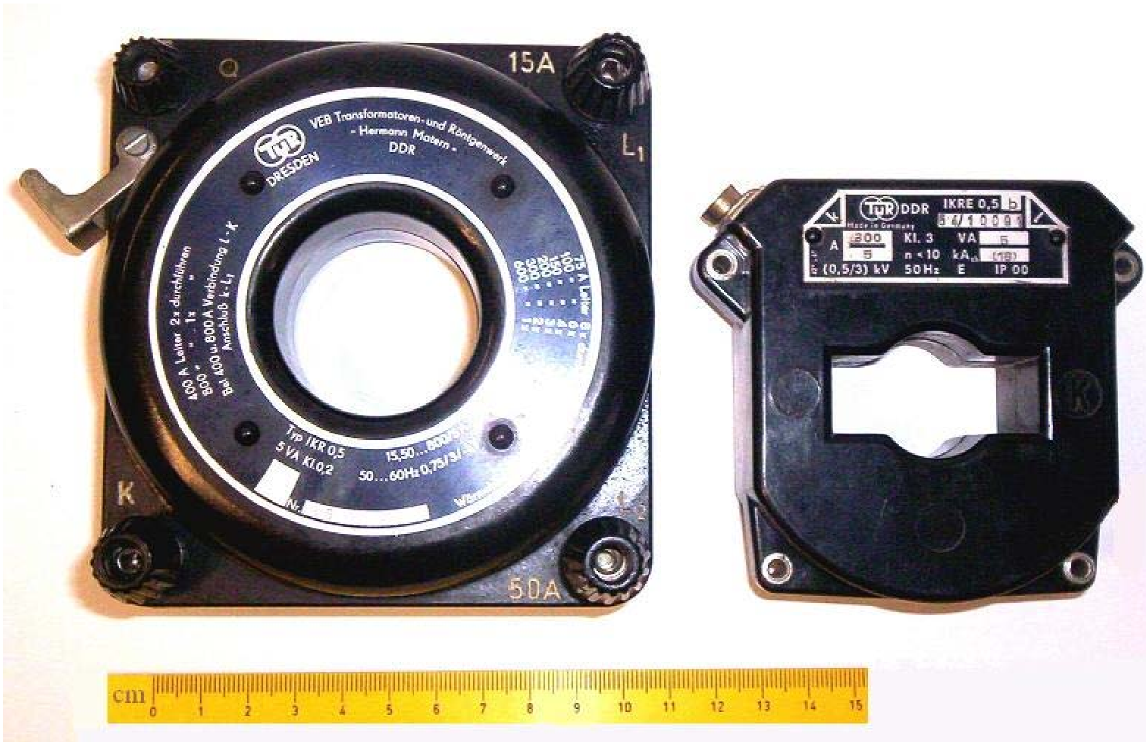
Audio transformers are those specifically designed for use in audio circuits. They can be used to block radio frequency interference or the DC component of an audio signal, to split or combine audio signals, or to provide impedance matching between high and low impedance circuits, such as between a high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

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

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

Instrument transformers

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



Current transformers, designed for placing around conductors

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

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

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

Classification

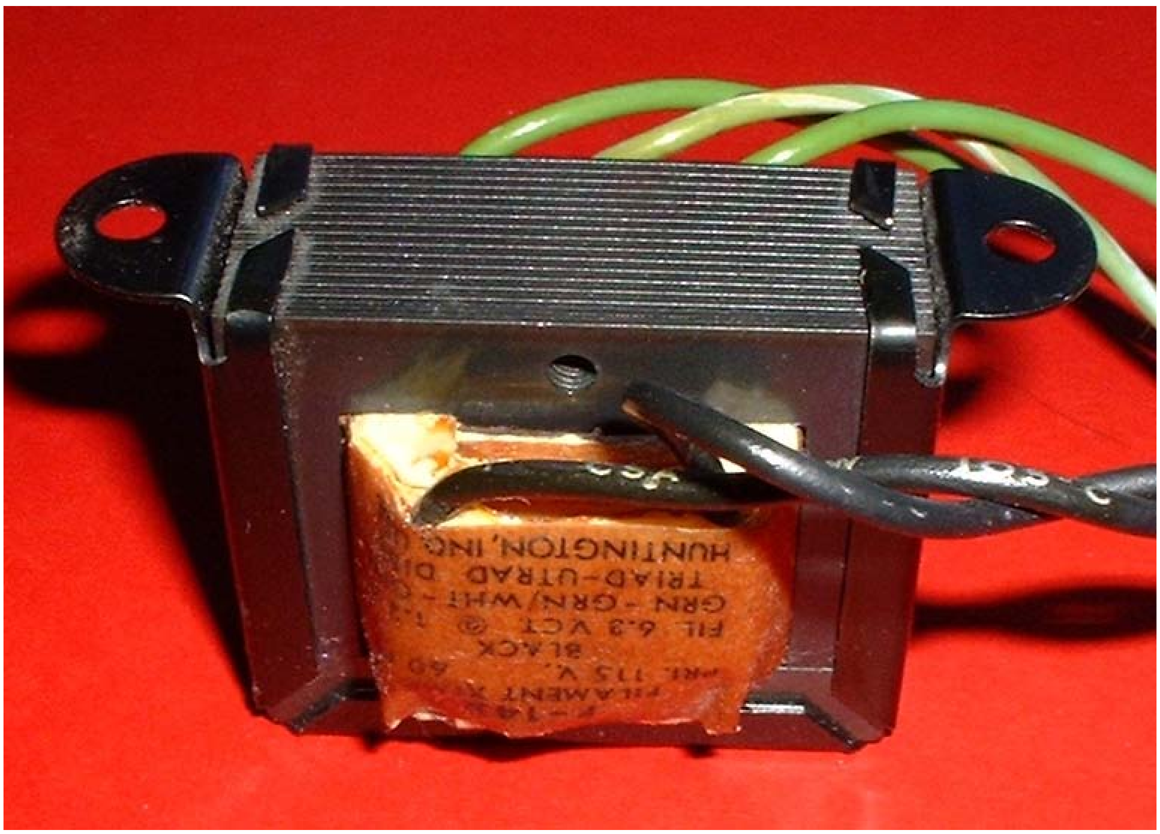
Transformers can be classified in many different ways; an incomplete list is:

- *By power capacity*: from a fraction of a volt-ampere (VA) to over a thousand MVA;
- *By frequency range*: power-, audio-, or radio frequency;
- *By voltage class*: from a few volts to hundreds of kilovolts;

- *By cooling type*: air-cooled, oil-filled, fan-cooled, or water-cooled;
- *By application*: such as power supply, impedance matching, output voltage and current stabilizer, or circuit isolation;
- *By purpose*: distribution, rectifier, arc furnace, amplifier output, etc.;
- *By winding turns ratio*: step-up, step-down, isolating with equal or near-equal ratio, variable, multiple windings.

Construction

Cores

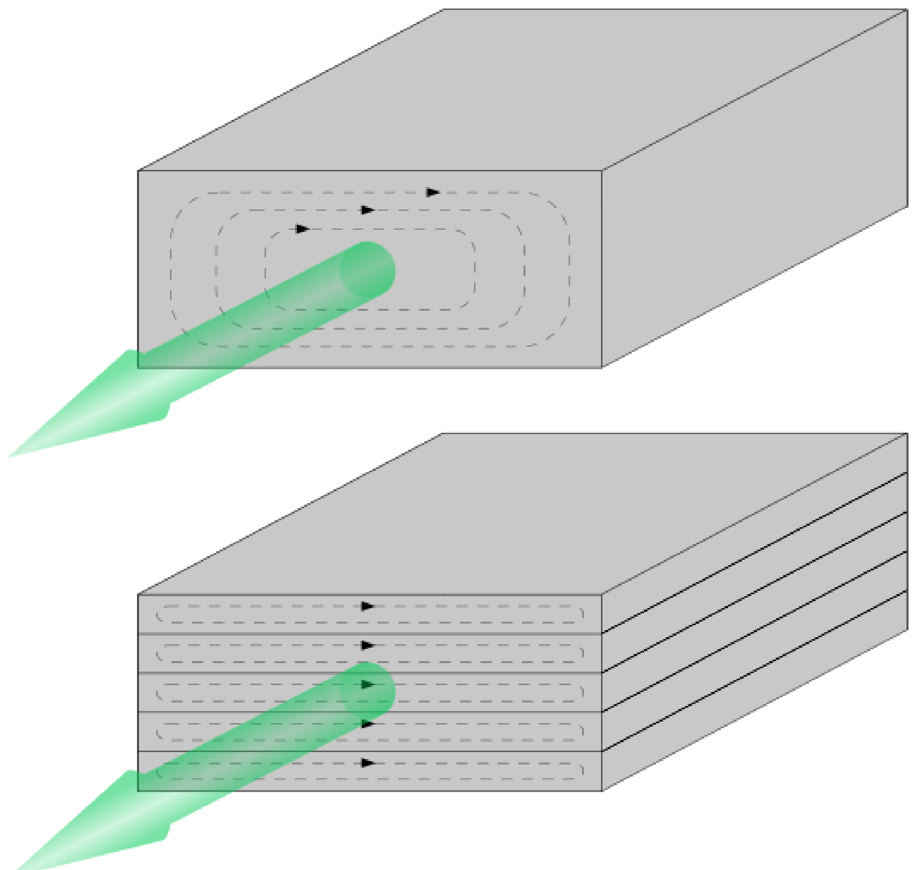


Laminated core transformer showing edge of laminations at top of photo

Laminated steel cores

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

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



Laminating the core greatly reduces eddy-current losses

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

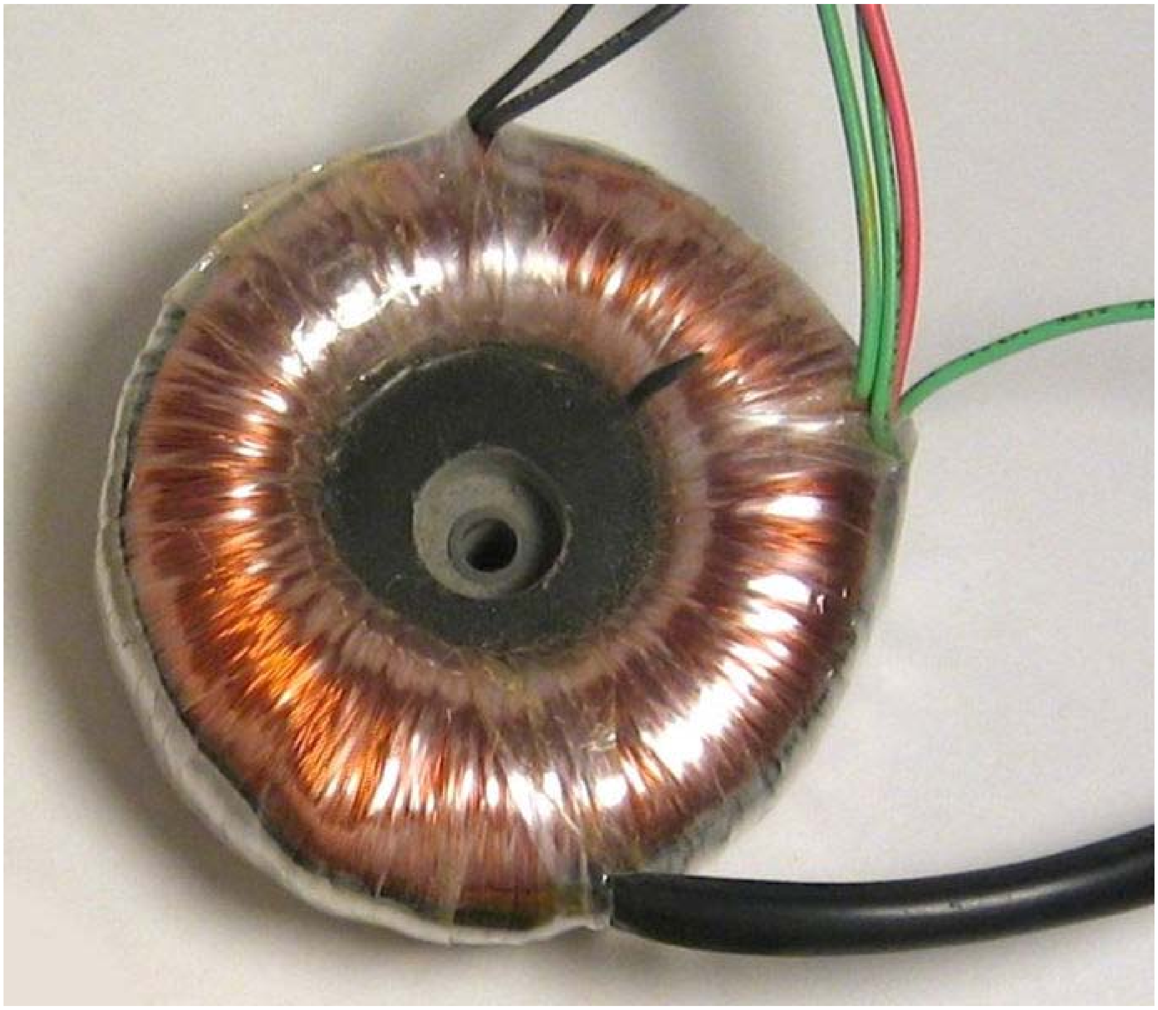
A steel core's remanence means that it retains a static magnetic field when power is removed. When power is then reapplied, the residual field will cause a high inrush current until the effect of the remaining magnetism is reduced, usually after a few cycles of the applied alternating current. Overcurrent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

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

Solid cores

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

Toroidal cores



Small toroidal core transformer

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

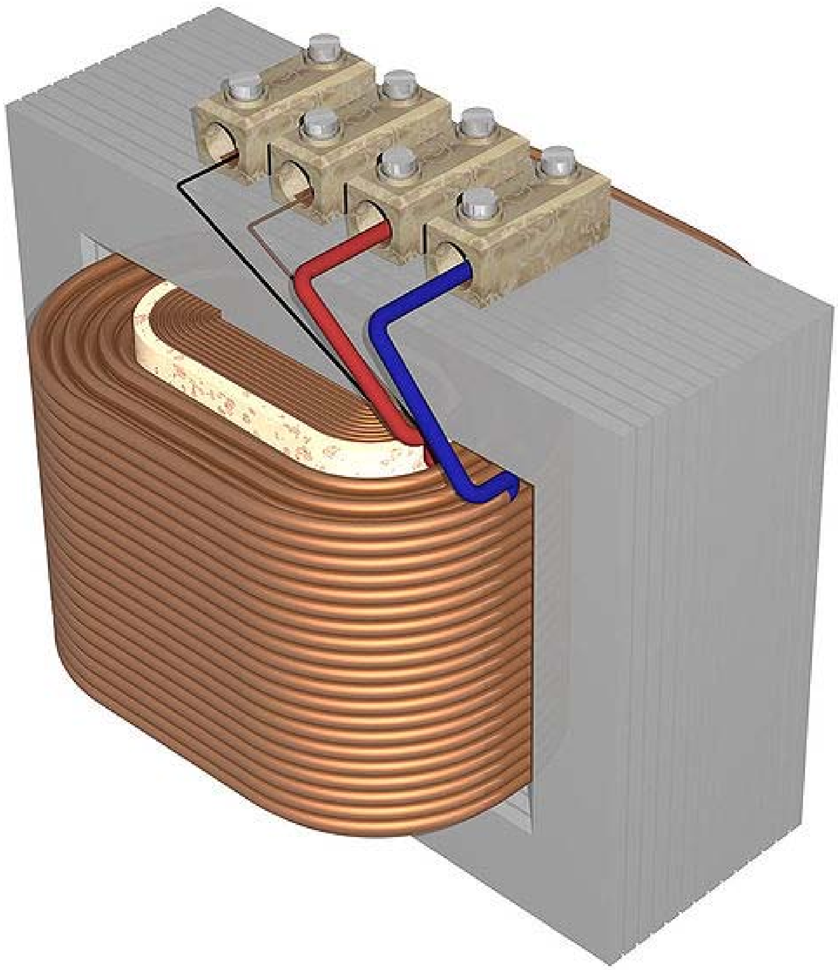
Toroidal transformers are more efficient than the cheaper laminated E-I types for a similar power level. Other advantages compared to E-I types, include smaller size (about half), lower weight (about half), less mechanical hum (making them superior in audio amplifiers), lower exterior magnetic field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

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

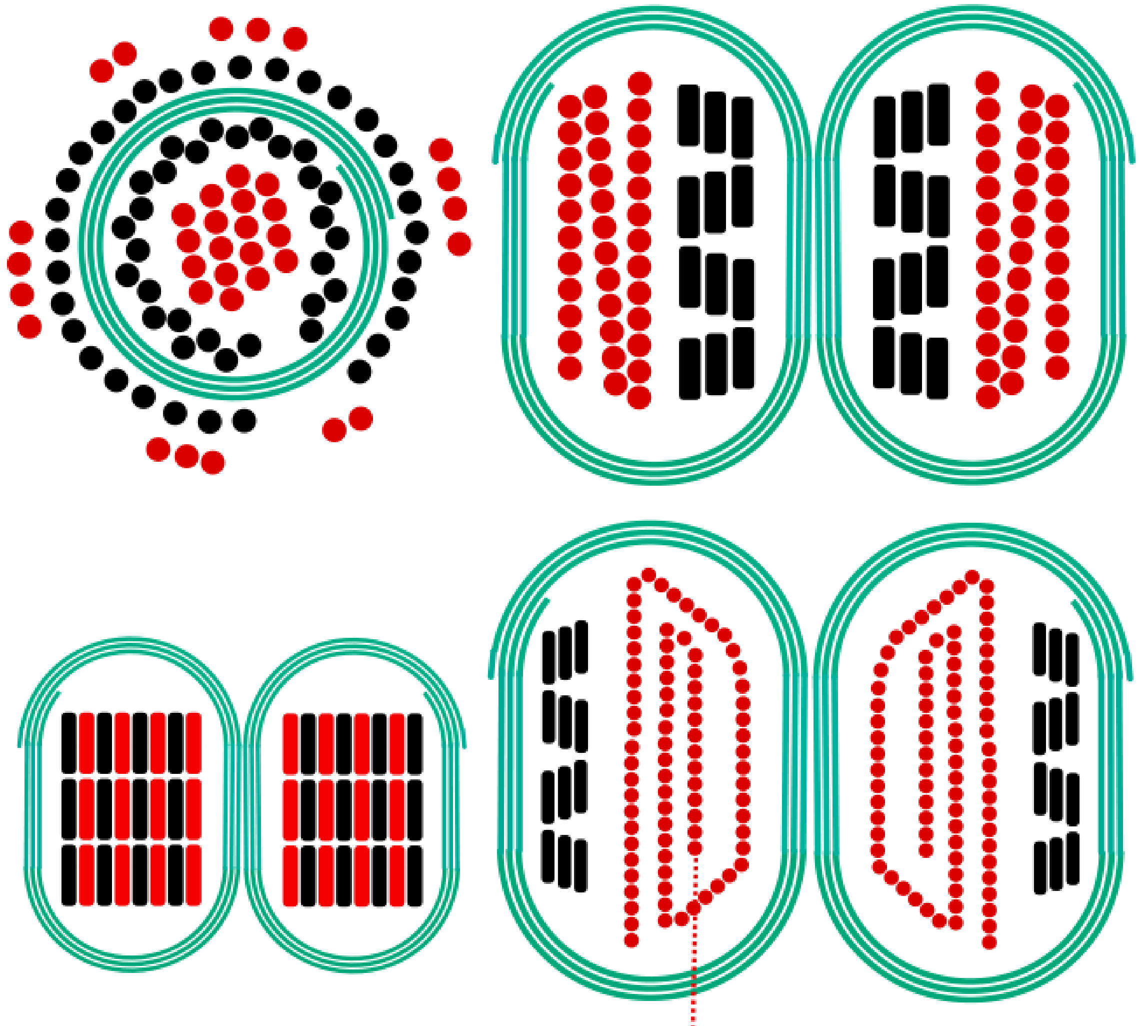
Air cores

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

Windings



Windings are usually arranged concentrically to minimize flux leakage.



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

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

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

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

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

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

Coolant

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

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

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

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

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

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

Insulation drying

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

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

Terminals

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

Applications

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

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

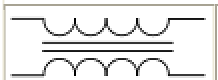
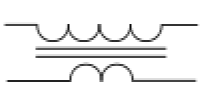
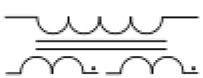
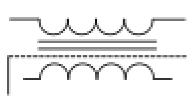
Transformers are also used extensively in electronic products to step down the supply voltage to a level suitable for the low voltage circuits they contain. The transformer also electrically isolates the end user from contact with the supply voltage.

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

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

Chapter-2

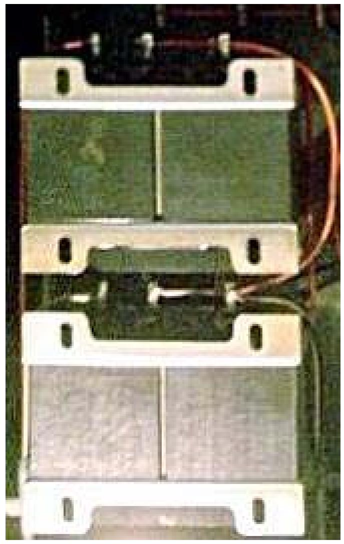
Transformer Types

Circuit symbols	
	Transformer with two windings and iron core.
	Step-down or step-up transformer. The symbol shows which winding has more turns, but not usually the exact ratio.
	Transformer with three windings. The dots show the relative configuration of the windings.
	Transformer with electrostatic screen preventing capacitive coupling between the windings.

A variety of types of electrical transformer are made for different purposes. Despite their design differences, the various types employ the same basic principle as discovered in 1831 by Michael Faraday, and share several key functional parts.

Power transformers

Laminated core

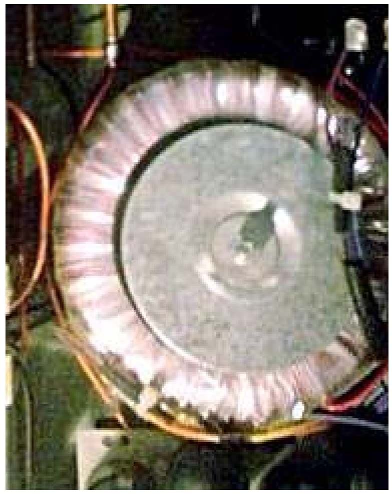


Laminated Core Transformer

This is the most common type of transformer, widely used in appliances to convert mains voltage to low voltage to power electronics

- Widely available in power ratings ranging from mW to MW
- Insulated lamination minimizes eddy current losses
- Small appliance and electronic transformers may use a split bobbin, giving a high level of insulation between the windings
- Rectangular core
- Core laminate stampings are usually in EI shape pairs. Other shape pairs are sometimes used
- Mu-metal shields can be fitted to reduce EMI (electromagnetic interference)
- A screen winding is occasionally used between the 2 power windings
- Small appliance and electronics transformers may have a thermal cut out built in
- Occasionally seen in low profile format for use in restricted spaces
- Laminated core made with silicon steel with high permeability

Toroidal



Toroidal Transformer

Doughnut shaped toroidal transformers are used to save space compared to EI cores, and sometimes to reduce external magnetic field. These use a ring shaped core, copper windings wrapped round this ring (and thus threaded through the ring during winding), and tape for insulation.

Toroidal transformers compared to EI core transformers:

- Lower external magnetic field
- Smaller for a given power rating
- Higher cost in most cases, as winding requires more complex and slower equipment
- Less robust
- Central fixing is either
    - bolt, large metal washers and rubber pads
    - bolt and potting resin
- Over-tightening the central fixing bolt may short the windings
- Greater inrush current at switch-on

Autotransformer

An autotransformer has only a single winding, which is tapped at some point along the winding. AC or pulsed voltage is applied across a portion of the winding, and a higher (or lower) voltage is produced across another portion of the same winding. The higher voltage will be connected to the ends of the winding, and the lower voltage from one end to a tap. For example, a transformer with a tap at the center of the winding can be used with 230 V across the entire winding, and 115 volts between one end and the tap. It can be connected to a 230 V supply to drive 115 V equipment, or reversed to drive 230 V equipment from 115 V. Since the current in the windings is lower, the transformer is smaller, lighter cheaper and more efficient. For voltage ratios not exceeding about 3:1, an autotransformer is cheaper, lighter, smaller and more efficient than an isolating (two-winding) transformer of the same rating. Large three-phase autotransformers are used in electric power distribution systems, for example, to interconnect 33 kV and 66 kV sub-transmission networks.

Variac

By exposing part of the winding coils of an autotransformer, and making the secondary connection through a sliding carbon brush, an autotransformer with a near-continuously variable turns ratio can be obtained, allowing for wide voltage adjustment in very small increments.

Induction regulator

The induction regulator is similar in design to a wound-rotor induction motor but it is essentially a transformer whose output voltage is varied by rotating its secondary relative to the primary i.e. rotating the angular position of the rotor.

It can be seen as a power transformer exploiting rotating magnetic fields.

The major advantage of the induction regulator is that unlike variacs, they are practical for transformers over 5 kVA.

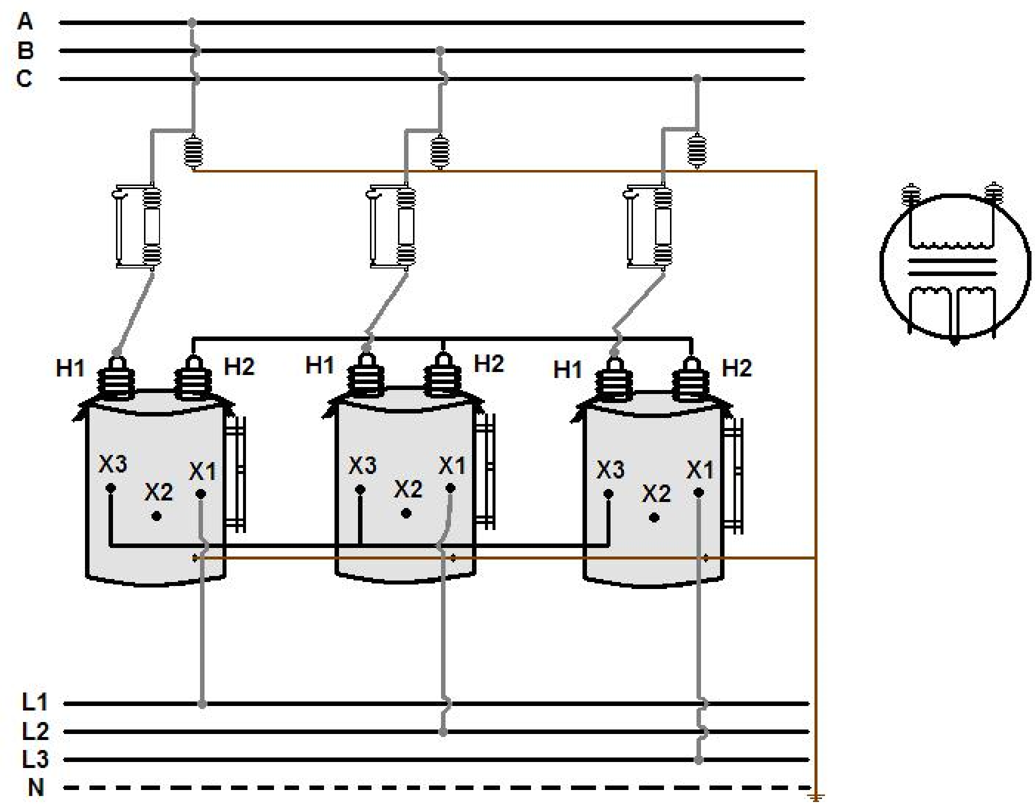
Hence, such regulators find windspread use in high-voltage laboratories.

Stray field transformer

A stray field transformer has a significant stray field or a (sometimes adjustable) magnetic bypass in its core. It can act as a transformer with inherent current limitation due to its lower coupling between the primary and the secondary winding, which is unwanted in most other cases. The output and input currents are low enough to prevent thermal overload under each load condition - even if the secondary is shorted.

Stray field transformers are used for arc welding and high voltage discharge lamps (cold cathode fluorescent lamps, series connected up to 7.5 kV AC working voltage). It acts both as voltage transformer and magnetic ballast.

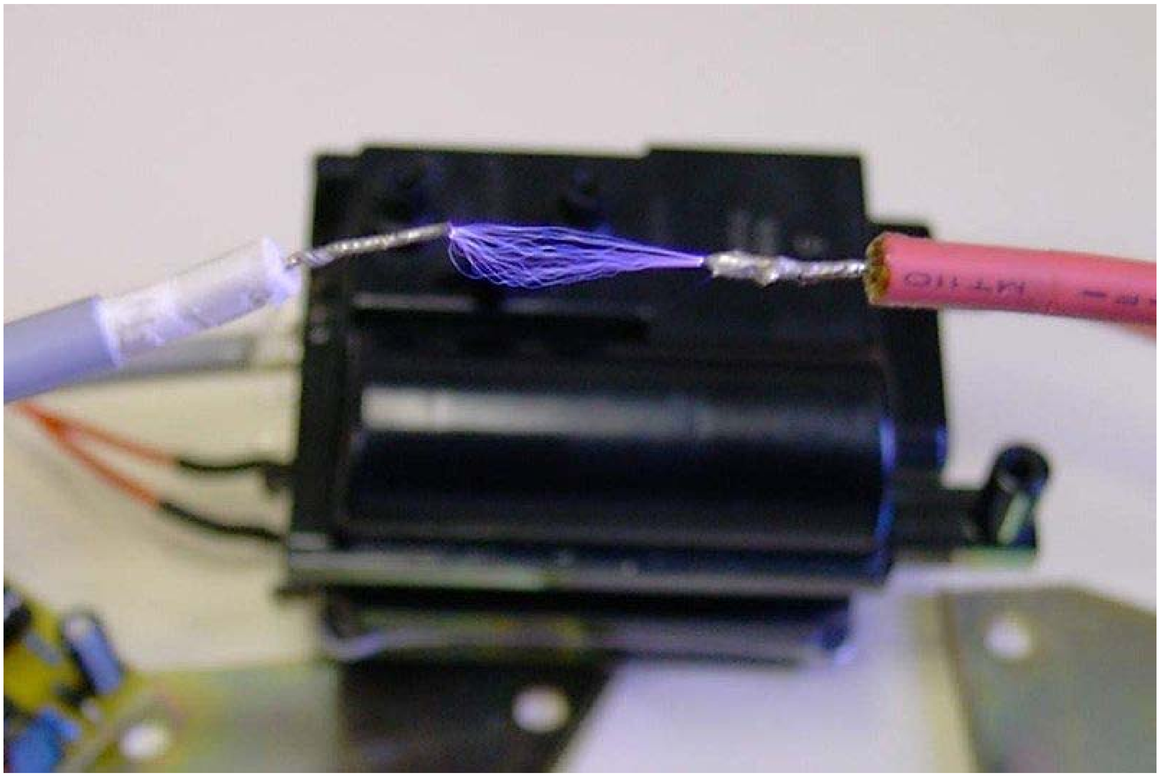
Polyphase transformers



Example of Y Y Connection

For three-phase power, three separate single-phase transformers can be used, or all three phases can be connected to a single polyphase transformer. The three primary windings are connected together and the three secondary windings are connected together. The most common connections are Y-Delta, Delta-Y, Delta-Delta and Y-Y. A vector group indicates the configuration of the windings and the phase angle difference between them. If a winding is connected to earth (grounded), the earth connection point is usually the center point of a Y winding. If the secondary is a Delta winding, the ground may be connected to a center tap on one winding (high leg delta) or one phase may be grounded (corner grounded delta). A special purpose polyphase transformer is the zigzag transformer. There are many possible configurations that may involve more or fewer than six windings and various tap connections.

Resonant transformers



A 25 kV flyback transformer being used to generate an arc.

A resonant transformer operates at the resonant frequency of one or more of its coils and (usually) an external capacitor. The resonant coil, usually the secondary, acts as an inductor, and is connected in series with a capacitor. When the primary coil is driven by a periodic source of alternating current, such as a square or sawtooth wave at the resonant frequency, each pulse of current helps to build up an oscillation in the secondary coil. Due to resonance, a very high voltage can develop across the secondary, until it is limited by some process such as electrical breakdown. These devices are used to generate high alternating voltages, and the current available can be much larger than that from electrostatic machines such as the Van de Graaff generator or Wimshurst machine.

Examples:

- Tesla coil
- Oudin coil (or Oudin resonator; named after its inventor Paul Oudin)
- D'Arsonval apparatus
- Ignition coil or induction coil used in the ignition system of a petrol engine
- Flyback transformer of a CRT television set or video monitor.
- Electrical breakdown and insulation testing of high voltage equipment and cables. In the latter case, the transformer's secondary is resonated with the cable's capacitance.

Other applications of resonant transformers are as coupling between stages of a superheterodyne receiver, where the selectivity of the receiver is provided by the tuned transformers of the intermediate-frequency amplifiers.

Constant voltage transformer

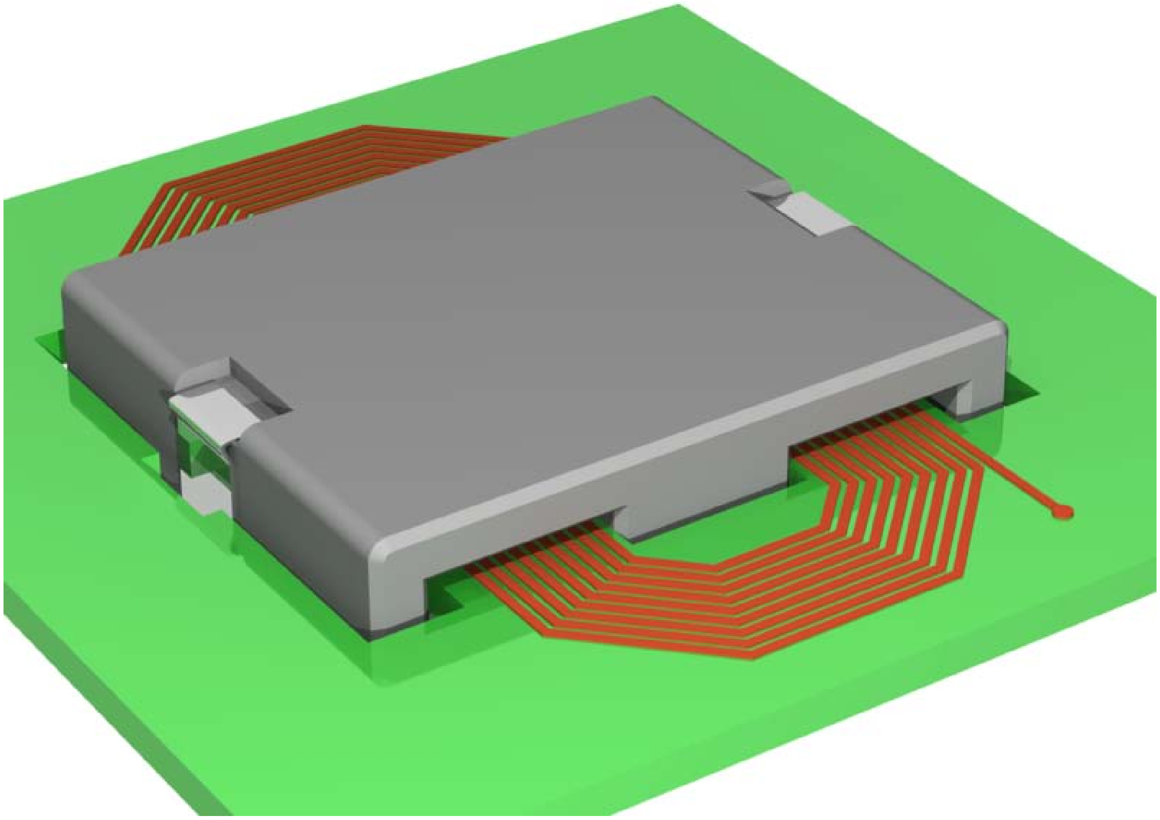
By arranging particular magnetic properties of a transformer core, and installing a ferro-resonant tank circuit (a capacitor and an additional winding), a transformer can be arranged to automatically keep the secondary winding voltage relatively constant for varying primary supply without additional circuitry or manual adjustment. Ferro-resonant transformers run hotter than standard power transformers, because regulating action depends on core saturation, which reduces efficiency. The output waveform is heavily distorted unless careful measures are taken to prevent this. Saturating transformers provide a simple rugged method to stabilize an AC power supply.

Ferrite core

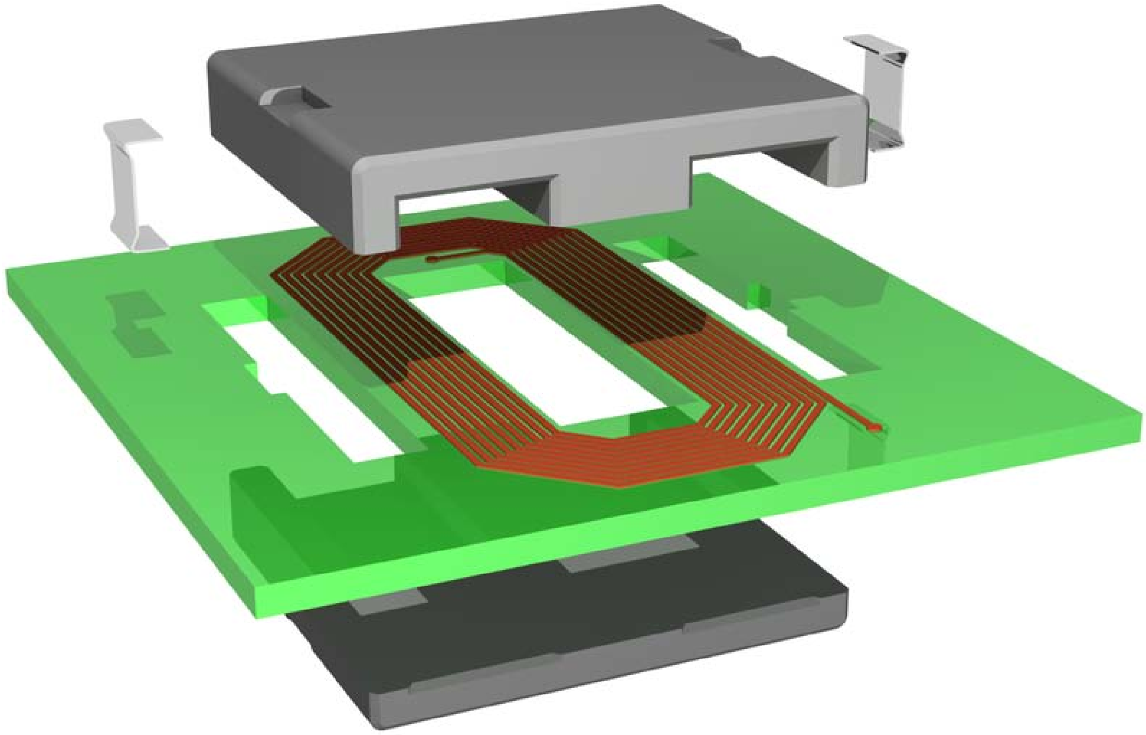
Ferrite core power transformers are widely used in switched-mode power supplies (SMPSs). The powder core enables high-frequency operation, and hence much smaller size-to-power ratio than laminated-iron transformers.

Ferrite transformers are not used as power transformers at mains frequency since laminated iron cores cost less than an equivalent ferrite core.

Planar transformer



A planar transformer



Exploded view: the spiral primary "winding" on one side of the PCB (the spiral secondary "winding" is on the other side of the PCB)

Manufacturers etch spiral patterns on a printed circuit board to form the "windings" of a **planar transformer**. (Manufacturers literally wind pieces of wire on some core or bobbin to form the windings of other kinds of transformers).

Some planar transformers are commercially sold as discrete components—the transformer is the only thing on that printed circuit board. Other planar transformers are one of many components on one large printed circuit board.

- much thinner than other transformers, for low-profile applications (even when several PCBs are stacked)
- almost all use a ferrite planar core

Oil cooled transformer

For large transformers used in power distribution or electrical substations, the core and coils of the transformer are immersed in oil which cools and insulates. Oil circulates through ducts in the coil and around the coil and core assembly, moved by convection. The oil is cooled by the outside of the tank in small ratings, and in larger ratings an air-cooled radiator is used. Where a higher rating is required, or where the transformer is used in a building or underground, oil pumps are used to circulate the oil and an oil-to-water heat exchanger may also be used. Formerly, indoor transformers required to be fire-resistant used PCB liquids; since these are now banned, substitute fire-resistant liquids such as silicone oils are instead used.

Cast resin transformers

Cast-resin power transformers encase the windings in epoxy resin. These transformers simplify installation since they are dry, without cooling oil, and so require no fire-proof valut for indoor installations. The epoxy protects the windings from dust and corrosive atmospheres. However, because the molds for casting the coils are only available in fixed sizes, the design of the transformers is less flexible, which may make them more costly if customized features (voltage, turns ratio, taps) are required.

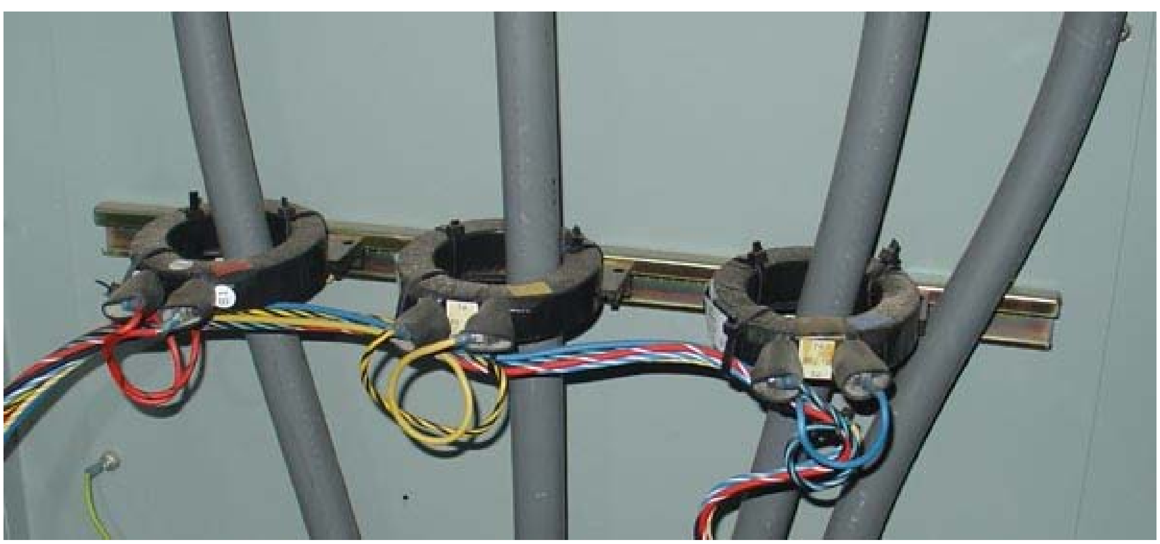
Isolating Transformer

Most transformers isolate, meaning the secondary winding is not connected to the primary. But this isn't true of all transformers.

However the term 'isolating transformer' is normally applied to mains transformers providing isolation rather than voltage transformation. They are simply 1:1 laminated core transformers. Extra voltage tappings are sometimes included, but to earn the name 'isolating transformer' it is expected that they will usually be used at 1:1 ratio.

Instrument transformers

Current transformers



Current transformers used in metering equipment for three-phase 400 ampere electricity supply

A current transformer (CT) is a measurement device designed to provide a current in its secondary coil proportional to the current flowing in its primary. Current transformers are commonly used in metering and protective relays in the electrical power industry where they allow safe measurement of large currents, often in the presence of high voltages. The current transformer safely isolates measurement and control circuitry from the high voltages typically present on the circuit being measured.

Current transformers are often constructed by passing a single primary turn (either an insulated cable or an uninsulated bus bar) through a well-insulated toroidal core wrapped with many turns of wire. The CT is typically described by its current ratio from primary to secondary. For example, a 4000:5 CT would provide an output current of 5 amperes when the primary was passing 4000 amperes. The secondary winding can be single ratio or have several tap points to provide a range of ratios. Care must be taken that the secondary winding is not disconnected from its load while current flows in the primary, as this will produce a dangerously high voltage across the open secondary and may permanently affect the accuracy of the transformer.

Specially constructed wideband CTs are also used, usually with an oscilloscope, to measure high frequency waveforms or pulsed currents within pulsed power systems. One type provides a voltage output that is proportional to the measured current; another, called a Rogowski coil, requires an external integrator in order to provide a proportional output.

Voltage transformers

Voltage transformers (VT) or potential transformers (PT) are another type of instrument transformer, used for metering and protection in high-voltage circuits. They are designed to present negligible load to the supply being measured and to have a precise voltage ratio to accurately step down high voltages so that metering and protective relay equipment can be operated at a lower potential. Typically the secondary of a voltage transformer is rated for 69 V or 120 V at rated primary voltage, to match the input ratings of protective relays.

The transformer winding high-voltage connection points are typically labeled as H_1, H_2 (sometimes H_0 if it is internally grounded) and X_1, X2 and sometimes an X_3 tap may be present. Sometimes a second isolated winding (Y_1, Y_2, Y_3) may also be available on the same voltage transformer. The high side (primary) may be connected phase to ground or phase to phase. The low side (secondary) is usually phase to ground.

The terminal identifications (H_1, X_1, Y_1, etc.) are often referred to as polarity. This applies to current transformers as well. At any instant terminals with the same suffix numeral have the same polarity and phase. Correct identification of terminals and wiring is essential for proper operation of metering and protective relays.

Some meters operate directly on the secondary service voltages at or below 600 V. VTs are typically used for higher voltages (for example, 765 kV for power transmission) , or where isolation is desired between the meter and the measured circuit.

Pulse transformers

A **pulse transformer** is a transformer that is optimised for transmitting rectangular electrical pulses (that is, pulses with fast rise and fall times and a relatively constant amplitude). Small versions called *signal* types are used in digital logic and telecommunications circuits, often for matching logic drivers to transmission lines. Medium-sized *power* versions are used in power-control circuits such as camera flash controllers. Larger *power* versions are used in the electrical power distribution industry to interface low-voltage control circuitry to the high-voltage gates of power semiconductors. Special high voltage pulse transformers are also used to generate high power pulses for radar, particle accelerators, or other high energy pulsed power applications.

To minimise distortion of the pulse shape, a pulse transformer needs to have low values of leakage inductance and distributed capacitance, and a high open-circuit inductance. In power-type pulse transformers, a low coupling capacitance (between the primary and secondary) is important to protect the circuitry on the primary side from high-powered transients created by the load. For the same reason, high insulation resistance and high breakdown voltage are required. A good transient response is necessary to maintain the rectangular pulse shape at the secondary, because a pulse with slow edges would create switching losses in the power semiconductors.

The product of the peak pulse voltage and the duration of the pulse (or more accurately, the voltage-time integral) is often used to characterise pulse transformers. Generally speaking, the larger this product, the larger and more expensive the transformer.

Pulse transformers by definition have a duty cycle of less than 0.5, whatever energy stored in the coil during the pulse must be "dumped" out before the pulse is fired again.

RF transformers

There are several types of transformer used in radio frequency (RF) work. Steel laminations are not suitable for RF.

Air-core transformers

These are used for high frequency work. The lack of a core means very low inductance. Such transformers may be nothing more than a few turns of wire soldered onto a printed circuit board.

Ferrite-core transformers

Widely used in intermediate frequency (IF) stages in superheterodyne radio receivers. are mostly tuned transformers, containing a threaded ferrite slug that is screwed in or out to adjust IF tuning. The transformers are usually canned for stability and to reduce interference.

Transmission-line transformers

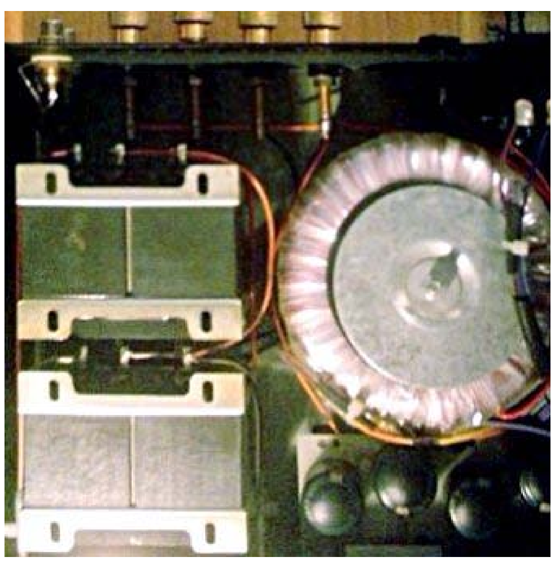
For radio frequency use, transformers are sometimes made from configurations of transmission line, sometimes bifilar or coaxial cable, wound around ferrite or other types of core. This style of transformer gives an extremely wide bandwidth but only a limited number of ratios (such as 1:9, 1:4 or 1:2) can be achieved with this technique.

The core material increases the inductance dramatically, thereby raising its Q factor. The cores of such transformers help improve performance at the lower frequency end of the band. RF transformers sometimes used a third coil (called a tickler winding) to inject feedback into an earlier (detector) stage in antique regenerative radio receivers.

Baluns

Baluns are transformers designed specifically to connect between balanced and unbalanced circuits. These are sometimes made from configurations of transmission line and sometimes bifilar or coaxial cable and are similar to transmission line transformers in construction and operation.

Audio transformers



Transformers in a tube amplifier. Output transformers are on the left. The power supply toroidal transformer is on right.

Audio transformers are usually the factor which limit sound quality when used; electronic circuits with wide frequency response and low distortion are relatively simple to design.

Transformers are also used in DI boxes to convert high-impedance instrument signals (e.g. bass guitar) to low impedance signals to enable them to be connected to a microphone input on the mixing console.

A particularly critical component is the output transformer of an audio power amplifier. Valve circuits for quality reproduction have long been produced with no other (inter-stage) audio transformers, but an output transformer is needed to couple the relatively high impedance (up to a few hundred ohms depending upon configuration) of the output valve(s) to the low impedance of a loudspeaker. (The valves can deliver a low current at a high voltage; the speakers require high current at low voltage.) Most solid-state power amplifiers need no output transformer at all.

For good low-frequency response a relatively large iron core is required; high power handling increases the required core size. Good high-frequency response requires carefully designed and implemented windings without excessive leakage inductance or stray capacitance. All this makes for an expensive component.

Early transistor audio power amplifiers often had output transformers, but they were eliminated as designers discovered how to design amplifiers without them.

Loudspeaker transformers

In the same way that transformers are used to create high voltage power transmission circuits that minimize transmission losses, loudspeaker transformers can be used to allow many individual loudspeakers to be powered from a single audio circuit operated at higher-than normal loudspeaker voltages. This application is common in industrial public address applications. Such circuits are commonly referred to as constant voltage speaker systems, although the audio waveform is a changing voltage. Such systems are also known by other terms such as **25-**, **70-** and **100-volt speaker systems**, referring to the nominal voltage of the loudspeaker line.

At the audio amplifier, a large audio transformer may be used to step-up the low impedance, low-voltage output of the amplifier to the designed line voltage of the loudspeaker circuit. At the distant loudspeaker location, a smaller step-down transformer returns the voltage and impedance to ordinary loudspeaker levels. The loudspeaker transformers commonly have multiple primary taps, allowing the volume at each speaker to be adjusted in discrete steps.

Output transformer

Valve (tube) amplifiers almost always use an output transformer to match the high load impedance requirement of the valves (several kilohms) to a low impedance speaker.

Small signal transformers

Moving coil phonograph cartridges produce a very small voltage. In order for this to be amplified with a reasonable signal-noise ratio, a transformer is usually used to convert the voltage to the range of the more common moving-magnet cartridges.

Microphones may also be matched to their load with a small transformer, which is mumetal shielded to minimise noise pickup. These transformers are less widely used today, as transistorized buffers are now cheaper.

Interstage and coupling transformers

In a push-pull amplifier, an inverted signal is required and is obtained from a transformer with a center-tapped winding, used to drive two active devices in opposite phase. These phase splitting transformers are not much used today.

Homemade and obsolete transformers

Transformer kits

Transformers may be wound at home using commercial transformer kits, which contain laminations & bobbin. Alternatively, ready made transformers may be disassembled and rewound. These approaches are occasionally used by home constructors but are usually avoided where possible due to the number of hours required to hand wind a transformer.

Firm clamping of laminations and varnish help to avoid buzz.

100% homemade

It is possible to make the transformer laminations by hand too. Such transformers are encountered at times in 3rd world countries, using laminations cut from scrap sheet steel, paper slips between the laminations, and string to tie the assembly together. The result works, but is usually noisy due to poor clamping of laminations.

- picture
- device in use

Hedgehog

Hedgehog transformers are occasionally encountered in homemade 1920s radios. They are homemade audio interstage coupling transformers.

Enamelled copper wire is wound round the central half of the length of a bundle of insulated iron wire (eg florists' wire), to make the windings. The ends of the iron wires are then bent around the electrical winding to complete the magnetic circuit, and the whole is wrapped with tape or string to hold it together.

Variocouplers

Variocouplers (sometimes called variometers) are RF transformers with two windings and variable coupling between the windings. They were standard equipment in 1920s radio sets.

Pancake coil variocouplers were common in 1920s radios for variable RF coupling. The two planar coils were arranged to swing away from each other and for the angle between them to increase to 90 degrees, thus giving wide variation in coupling. No core was used. These were mostly used to control reaction. The pancake structure was a means to minimize stray capacitance.

In another design of variocoupler, two coils were wound on two circular bands, and housed one inside the other, with provision for rotating the inner coil. Coupling varies as one coil is rotated between 0 and 90 degrees from the other. These had higher stray capacitance than the pancake type.

Not transformers

Items which may be mistaken for transformers, but which are not always transformers.

Wall warts: small power supplies with integral mains plug. These can contain a transformer and other circuitry. Most use a laminated iron transformer, but an increasing number now contain a small switched-mode power supply. These are smaller and much lighter.

Halogen lighting transformers: Toroidal transformers are sometimes used for this task, but most halogen 'transformers' are switched-mode power supplies.

Transformers rely on a linear relationship between the currents in primary and secondary circuits. Interesting and useful power control devices such as the saturable reactor and the magnetic amplifier rely on controlled saturation of a ferromagnetic core. Such devices can provide considerable power amplification without use of transistors or vacuum tubes. Although they resemble transformers with cores and sets of windings, the operating principles and purposes are different.

Chapter-3

Balun

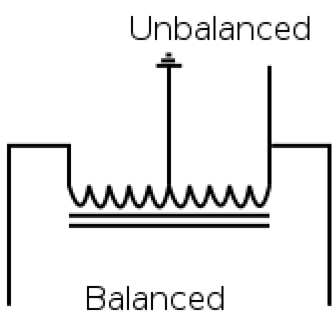
Pair of AC&E 120 Ohm twisted pair (Krone IDC) to 75 Ohm coaxial cable balun transformers. Actual length is about 3cm.

2 balun matching transformers

A **balun**, is a type of electrical transformer that can convert electrical signals that are balanced about ground (differential) to signals that are unbalanced (single-ended) and vice versa. They are also often used to connect lines of differing impedance. The origin of the word balun is **bal**(ance) + **un**(balance).

Baluns can take many forms and their presence is not always obvious. They always use electromagnetic coupling for their operation.

Types of balun

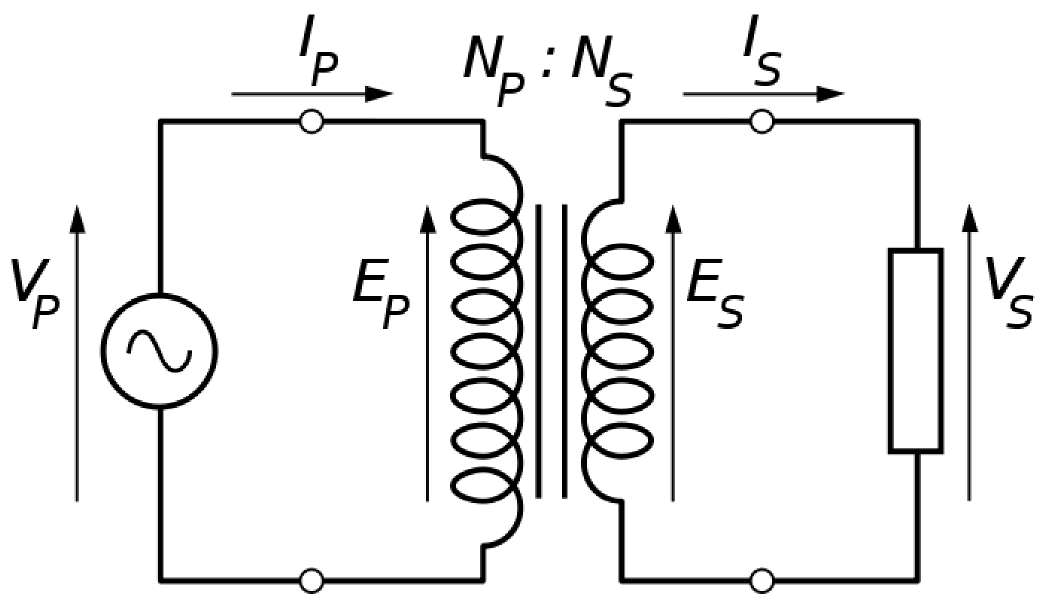


Autotransformer 4:1 wideband balun using two windings on a ferrite rod.

Autotransformer type

In an autotransformer, two coils on a ferrite rod can be used as a balun by winding the individual strands of enameled wire comprising the coil very tightly together. This winding can take one of two forms: either the two windings must be wound such that the two form a single layer where each turn is touching each of the adjacent turns of the other winding; or the two wires are twisted together before being wound into the coil.

The two windings are joined to become a single coil. The end of one of the windings on one side of the coil is connected to the end of the other winding on the other side of the coil. This point then becomes the ground for the unbalanced circuit. One of the remaining ends is connected to the ungrounded side of the unbalanced circuit, and one side of the balanced circuit. Finally, the other side of the balanced circuit is connected to the remaining end.



$$\frac{V_P}{V_S} = \frac{I_S}{I_P} = \frac{N_P}{N_S}$$

Isolated transformer

Classical transformer type

Isolated transformers have a real impedance at a resonance frequency where self-inductance and self-capacitance for each individual winding cancel themselves out.

Transmission-line transformer type

Baluns can be considered as simple forms of transmission line transformers.

A more complex (and subtle) type results when the transformer type (magnetic coupling) is combined with the transmission line type (electro-magnetic coupling). This is where whole transmission lines are used as windings, resulting in devices capable of very wideband operation. This whole class known generally as "Transmission Line Transformers" spawn their own huge variety. Very commonly, they use small ferrite cores in toroidal or "binocular" shapes. Something as simple as 10 turns of coaxial cable coiled up on a diameter about the size of a dinner plate makes an extremely effective choke balun for frequencies from about 10 MHz to beyond 30 MHz. The magnetic material may be "air", but it is a transmission line transformer.

Homemade 1:1 balun using a toroidal core and coaxial cable. This simple RF choke works as a balun by preventing signals passing along the outside of the braid. Such a device can be used to cure television interference by acting as a braid-breaker.

The Guanella transmission line transformer is often combined with a balun to act as an impedance matching transformer. Putting balancing aside a 1:4 transformer of this type consists of a 75 Ohm transmission line divided in parallel into two 150 Ohm cables, which are then combined in series for 300 Ohm. It is implemented as a specific wiring around the ferrite core of the balun.

Delay line type

A large class of baluns uses connected transmission lines of specific lengths, with no obvious "transformer" part. These are usually built for (narrow) frequency ranges where the lengths involved are some multiple of a quarter wavelength of the intended frequency in the transmission line medium. A common application is in making a coaxial connection to a balanced antenna, and designs include many types involving coaxial loops and variously connected "stubs".

One easy way to make a balun is a one-half wavelength ($\lambda/2$) length of coaxial cable. The inner core of the cable is linked at each end to one of the balanced connections for a feeder or dipole. One of these terminals should be connected to the inner core of the coaxial feeder. All three braids should be connected together. This then forms a 4:1 balun which works at only one frequency.

Another narrow band design is to use a $\lambda/4$ length of metal pipe. The coaxial cable is placed inside the pipe; at one end the braid is wired to the pipe while at the other end no connection is made to the pipe. The balanced end of this balun is at the end where the pipe is wired to the braid. The $\lambda/4$ conductor acts as a transformer converting the infinite impedance at the unconnected end into a zero impedance at the end connected to the braid. Hence any current entering the balun through the connection, which goes to the braid at the end with the connection to the pipe, will flow into the pipe. This balun design is not good for low frequencies because of the long length of pipe that will be needed. An easy way to make such a balun is to paint the outside of the coax with conductive paint, then to connect this paint to the braid.

Balun alternatives

An RF choke can be used in place of a balun. If a coil is made using coaxial cable near to the feed point of a balanced antenna then the RF current that flows on the outer surface of the coaxial cable can be attenuated. One way of doing this would be to wrap a lossy material, such as ferrite around the coaxial cable;

Applications

A balun's function is generally to achieve compatibility between systems, and as such, finds extensive application in modern communications, particularly in realising frequency conversion mixers to make cellular phone and data transmission networks possible. They are also used to convert an E1 carrier signal from coaxial cable to UTP CAT-5 cable.

Radio and television

A 75-to-300 ohm balun built into the antenna plug.

In television, amateur radio, and other antenna installations and connections, baluns convert between 300 ohm ribbon cable or 450 ohm ladder line (balanced) and 75 Ω coaxial cable (unbalanced) or to directly connect a balanced antenna to (unbalanced) coax. To avoid EMC problems it is a good idea to connect a centre fed dipole antenna to coaxial cable via a balun. Match 300 Ω twin-lead cable to 75 Ω coaxial cable

In electronic communications, baluns convert Twinax cables to Category 5 cables, and back, or they convert between coaxial cable and ladder line.

In measuring the impedance or radiation pattern of a balanced antenna using a coaxial cable, it is important to place a balun between the cable and the antenna feed. Unbalanced currents that may otherwise flow on the cable will make the measured antenna impedance sensitive to the configuration of the feed cable, and the radiation pattern of small antennas may be distorted by radiation from the cable.

Baluns are present in radars, transmitters, satellites, in every telephone network, and probably in most wireless network modem/routers used in homes. It can be combined with transimpedance amplifiers to compose high-voltage amplifiers out of low-voltage components.

Video

While not as high as most RF applications, baseband video still uses frequencies up to several megahertz. Since this bandwidth is now well within range of modern twisted-pair cables, they are now being used to send video which would otherwise run over coaxial cable. Many better security cameras now have both a balanced UTP output and an unbalanced coaxial one via an internal balun, though any camera can be used with an external balun. A balun is also used on the video recorder end to convert back from the 100-ohm balanced to 75-ohm unbalanced. A balun of this type has a BNC connector with two screw terminals. VGA/DVI baluns are baluns with electronic circuitry used to connect VGA/DVI sources (laptop, DVD, etc.) to VGA/DVI display devices over long runs of CAT-5/CAT-6 cable. Runs over 130 m (400 ft) may lose quality due to attenuation and variations in the arrival time of each signal. A skew control and special low skew or skew free cable is used for runs over 130 m (400 ft).

Audio

Three audio baluns (transformers).

In audio applications, baluns convert between high impedance unbalanced and low impedance balanced lines.

Except for the connections, the three devices in the image are electrically identical, but only the leftmost two can be used as baluns. The device on the left would normally be used to connect a high impedance source, such as a guitar, into a balanced microphone input, serving as a passive DI unit. The one in the centre is for connecting a low impedance balanced source, such as a microphone, into a guitar amplifier. The one at the right is not a balun, as it provides only impedance matching.

In power line communications, baluns are used in coupling signals onto a power line.

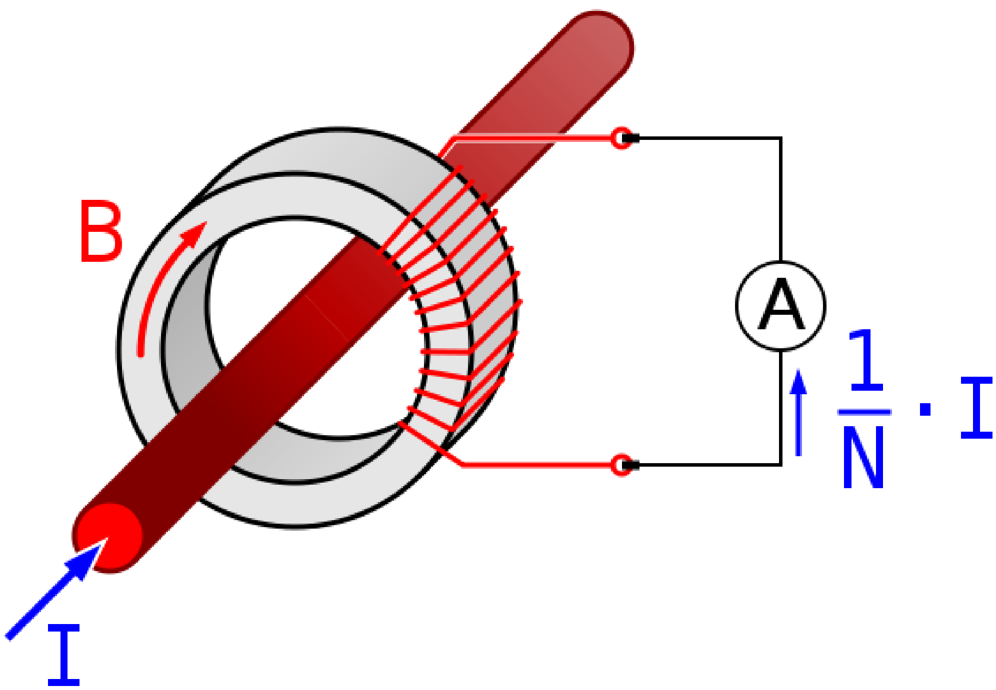
Chapter-4

Current Transformer

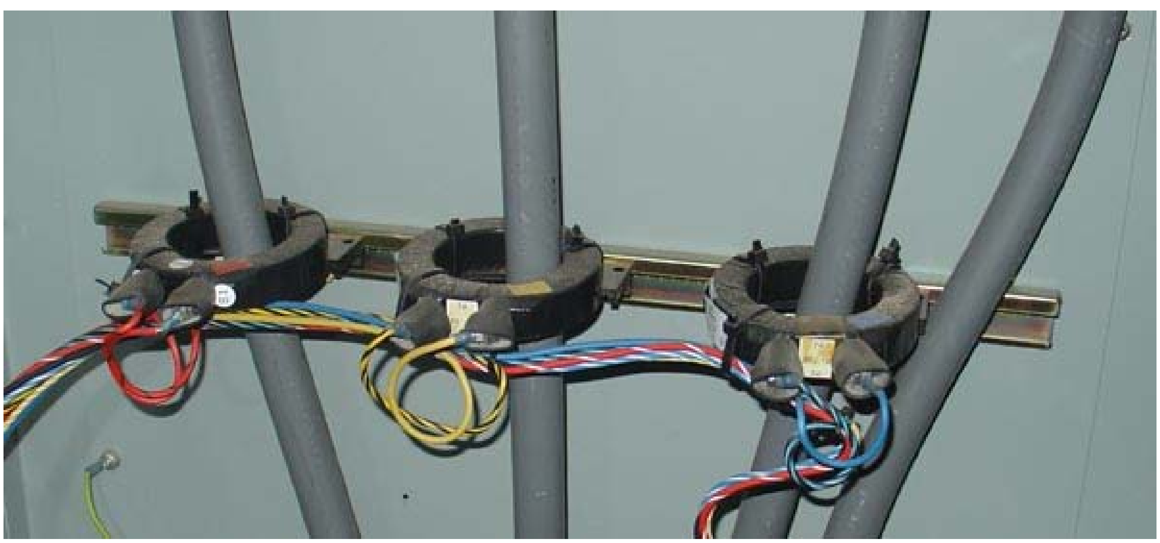
A CT for operation on a 110 kV grid

In electrical engineering, a **current transformer** (**CT**) is used for measurement of electric currents. Current transformers, together with **voltage transformers** (**VT**) (**potential transformers** (**PT**)), are known as **instrument transformers**. When current in a circuit is too high to directly apply to measuring instruments, a current transformer produces a reduced current accurately proportional to the current in the circuit, which can be conveniently connected to measuring and recording instruments. A current transformer also isolates the measuring instruments from what may be very high voltage in the monitored circuit. Current transformers are commonly used in metering and protective relays in the electrical power industry.

Design



SF_6 110 kV current transformer TGFM series, Russia



Current transformers used in metering equipment for three-phase 400 ampere electricity supply

Like any other transformer, a current transformer has a primary winding, a magnetic core, and a secondary winding. The alternating current flowing in the primary produces a magnetic field in the core, which then induces a current in the secondary winding circuit. A primary objective of current transformer design is to ensure that the primary and secondary circuits are efficiently coupled, so that the secondary current bears an accurate relationship to the primary current.

The most common design of CT consists of a length of wire wrapped many times around a silicon steel ring passed over the circuit being measured. The CT's primary circuit therefore consists of a single 'turn' of conductor, with a secondary of many hundreds of turns. The primary winding may be a permanent part of the current transformer, with a heavy copper bar to carry current through the magnetic core. Window-type current transformers are also common, which can have circuit cables run through the middle of an opening in the core to provide a single-turn primary winding. When conductors passing through a CT are not centered in the circular (or oval) opening, slight inaccuracies may occur.

Shapes and sizes can vary depending on the end user or switchgear manufacturer. Typical examples of low voltage single ratio metering current transformers are either ring type or plastic moulded case. High-voltage current transformers are mounted on porcelain bushings to insulate them from ground. Some CT configurations slip around the bushing of a high-voltage transformer or circuit breaker, which automatically centers the conductor inside the CT window.

The primary circuit is largely unaffected by the insertion of the CT. The rated secondary current is commonly standardized at 1 or 5 amperes. For example, a 4000:5 CT would provide an output current of 5 amperes when the primary was passing 4000 amperes. The secondary winding can be single ratio or multi ratio, with five taps being common for multi ratio CTs. The load, or burden, of the CT should be of low resistance. If the voltage time integral area is higher than the core's design rating, the core goes into saturation towards the end of each cycle, distorting the waveform and affecting accuracy.

Usage

Current transformers are used extensively for measuring current and monitoring the operation of the power grid. Along with voltage leads, revenue-grade CTs drive the electrical utility's watt-hour meter on virtually every building with three-phase service and single-phase services greater than 200 amp.

The CT is typically described by its current ratio from primary to secondary. Often, multiple CTs are installed as a "stack" for various uses. For example, protection devices and revenue metering may use separate CTs to provide isolation between metering and protection circuits, and allows current transformers with different characteristics (accuracy, overload performance) to be used for the different purposes.

Safety precautions

Care must be taken that the secondary of a current transformer is not disconnected from its load while current is flowing in the primary, as the transformer secondary will attempt to continue driving current across the effectively infinite impedance. This will produce a high voltage across the open secondary (into the range of several kilovolts in some cases), which may cause arcing. The high voltage produced will compromise operator and equipment safety and permanently affect the accuracy of the transformer.

Accuracy

The accuracy of a CT is directly related to a number of factors including:

- Burden
- Burden class/saturation class
- Rating factor
- Load
- External electromagnetic fields
- Temperature and
- Physical configuration.
- The selected tap, for multi-ratio CTs

For the IEC standard, accuracy classes for various types of measurement are set out in IEC 60044-1, Classes 0.1, 0.2s, 0.2, 0.5, 0.5s, 1, and 3. The class designation is an approximate measure of the CT's accuracy. The ratio (primary to secondary current) error of a Class 1 CT is 1% at rated current; the ratio error of a Class 0.5 CT is 0.5% or less. Errors in phase are also important especially in power measuring circuits, and each class has an allowable maximum phase error for a specified load impedance. Current transformers used for protective relaying also have accuracy requirements at overload currents in excess of the normal rating to ensure accurate performance of relays during system faults.

Burden

The load, or burden, in a CT metering circuit is the (largely resistive) impedance presented to its secondary winding. Typical burden ratings for IEC CTs are 1.5 VA, 3 VA, 5 VA, 10 VA, 15 VA, 20 VA, 30 VA, 45 VA & 60 VA. As for ANSI/IEEE burden ratings are B-0.1, B-0.2, B-0.5, B-1.0, B-2.0 and B-4.0. This means a CT with a burden rating of B-0.2 can tolerate up to 0.2 Ω of impedance in the metering circuit before its output current is no longer a fixed ratio to the primary current. Items that contribute to the burden of a current measurement circuit are switch-blocks, meters and intermediate conductors. The most common source of excess burden in a current measurement circuit is the conductor between the meter and the CT. Often, substation meters are located significant distances from the meter cabinets and the excessive length of small gauge conductor creates a large resistance. This problem can be solved by using CT with 1 ampere secondaries which will produce less voltage drop between a CT and its metering devices (used for remote measurement).

Knee-point voltage

The **knee-point voltage** of a current transformer is the magnitude of the secondary voltage after which the output current ceases to follow the input current. This means that the one-to-one or proportional relationship between the input and output is no longer within rated accuracy. The output current increases abruptly even with small increment in the input, if the voltage across the secondary terminals exceeds the knee-point voltage. The knee-point voltage is not applicable for metering current transformers, the concept of knee point voltage is pertinent to protect current transformers only since they are necessarily exposed to high currents during faults.

Rating factor

Rating factor is a factor by which the nominal full load current of a CT can be multiplied to determine its absolute maximum measurable primary current. Conversely, the minimum primary current a CT can accurately measure is "light load," or 10% of the nominal current (there are, however, special CTs designed to measure accurately currents as small as 2% of the nominal current). The rating factor of a CT is largely dependent upon ambient temperature. Most CTs have rating factors for 35 degrees Celsius and 55 degrees Celsius. It is important to be mindful of ambient temperatures and resultant rating factors when CTs are installed inside pad-mounted transformers or poorly ventilated mechanical rooms. Recently, manufacturers have been moving towards lower nominal primary currents with greater rating factors. This is made possible by the development of more efficient ferrites and their corresponding hysteresis curves. This is a distinct advantage over previous CTs because it increases their range of accuracy, since the CTs are most accurate between their rated current and rating factor.

Special designs

Specially constructed *wideband current transformers* are also used (usually with an oscilloscope) to measure waveforms of high frequency or pulsed currents within pulsed power systems. One type of specially constructed wideband transformer provides a voltage output that is proportional to the measured current. Another type (called a Rogowski coil) requires an external integrator in order to provide a voltage output that is proportional to the measured current. Unlike CTs used for power circuitry, wideband CTs are rated in output volts per ampere of primary current.

Chapter-5

Transformer Oil and Transformer Oil Testing

Transformer oil

Transformer oil or **insulating oil** is usually a highly-refined mineral oil that is stable at high temperatures and has excellent electrical insulating properties. It is used in oil-filled transformers, some types of high voltage capacitors, fluorescent lamp ballasts, and some types of high voltage switches and circuit breakers. Its functions are to insulate, suppress corona and arcing, and to serve as a coolant.

Explanation

The oil helps cool the transformer. Because it also provides part of the electrical insulation between internal live parts, transformer oil must remain stable at high temperatures for an extended period. To improve cooling of large power transformers, the oil-filled tank may have external radiators through which the oil circulates by natural convection. Very large or high-power transformers (with capacities of thousands of KVA) may also have cooling fans, oil pumps, and even oil-to-water heat exchangers.

Large, high voltage transformers undergo prolonged drying processes, using electrical self-heating, the application of a vacuum, or both to ensure that the transformer is completely free of water vapor before the cooling oil is introduced. This helps prevent corona formation and subsequent electrical breakdown under load.

Oil filled transformers with a **conservator** (an oil tank above the transformer) tend to be equipped with Buchholz relays. These are safety devices that detect the build up of gases (such as acetylene) inside the transformer (a side effect of corona or an electric arc in the windings) and switch off the transformer. Transformers without conservators are usually equipped with sudden pressure relays, which perform a similar function as the Buchholz relay.

The flash point (min) and pour point (max) are 140 °C and −6 °C respectively. The dielectric strength of new untreated oil is 12 MV/m (RMS) and after treatment it should be >24 MV/m (RMS).

Oil transformer

Large transformers for indoor use must either be of the dry type, that is, containing no liquid, or use a less-flammable liquid.

Well into the 1970s, polychlorinated biphenyls (PCB)s were often used as a dielectric fluid since they are not flammable. They are toxic, and under incomplete combustion, can form highly toxic products such as furan. Starting in the early 1970s, concerns about the toxicity of PCBs have led to their banning in many countries.

Today, non-toxic, stable silicon-based or fluorinated hydrocarbons are used, where the added expense of a fire-resistant liquid offsets additional building cost for a transformer vault. Combustion-resistant vegetable oil-based dielectric coolants and synthetic pentaerythritol tetra fatty acid (C7, C8) esters are also becoming increasingly common as alternatives to naphthenic mineral oil. Esters are non-toxic to aquatic life, readily biodegradable, and have a lower volatility and a higher flash points than mineral oil.

Transformer Oil Testing

Transformer oils are subject to electrical and mechanical stresses while a transformer is in operation. In addition there are contaminations caused due to chemical interactions with windings and other solid insulations, catalyzed by high operating temperature. As a result the original chemical properties of transformer oil changes gradually, rendering it ineffective for its intended purpose after many years. Hence this oil has to be periodically tested to ascertain its basic electrical properties, and make sure it is suitable for further use or necessary actions like filtration/regeneration has to be done. These tests can be divided into:

1. Dissolved gas analysis
2. Furan analysis
3. PCB analysis
4. General electrical & physical tests:

- Color & Appearance
- Breakdown Voltage
- Water Content
- Acidity (Neutralization Value)
- Dielectric Dissipation Factor
- Resistivity
- Sediments & Sludge
- Interfacial Tension
- Flash Point
- Pour Point
- Density
- Kinematic Viscosity

The details of conducting these tests is available in standards released by IEC, ASTM, IS, BS, and testing can be done by either of the methods. The Furan and DGA tests are specifically not for determining the quality of transformer oil, but for determining any abnormalities in the internal windings of the transformer or the paper insulation of the transformer, which cannot be otherwise detected without a complete overhaul of the transformer. Suggested intervals for these test are:

- General and physical tests - bi-yearly
- Dissolved gas analysis - yearly
- Furan testing - once every 2 years, subject to the transformer being in operation for min 5 years.

On-site transformer oil testing

As in most countries transformer oil testing is mandatory, suppliers of test equipment have developed portable devices for on-site transformer oil testing.

To determine the insulating property of the dielectric oil, an oil sample is taken from the device under test, and its **breakdown voltage** is measured on-site according the following test sequence:

- In the vessel, two standard-compliant test electrodes with a typical clearance of 2.5 mm are surrounded by the insulating oil.
- During the test, a test voltage is applied to the electrodes. The test voltage is continuously increased up to the breakdown voltage with a constant slew rate of e.g. 2 kV/s.
- Breakdown occures in an electric arc, leading to a collapse of the test voltage.
- Immediately after ignition of the arc, the test voltage is switched off automatically.
- Ultra fast switch off is crucial, as the energy that is brought into the oil and is burning it during the breakdown, must be limited to keep the additional pollution by carbonisation as low as possible.
- The root mean square value of the test voltage is measured at the very instant of the breakdown and is reported as the breakdown voltage.
- After the test is completed, the insulating oil is stirred automatically and the test sequence is performed repeatedly.
- The resulting breakdown voltage is calculated as mean value of the individual measurements.

Transformer oil testing

The insulation oil of voltage- and current-transformers fulfills the purpose of insulating as well as cooling. Thus, the dielectric quality of transformer oil is a matter of secure operation of a transformer.

Since transformer oil deteriorates in its isolation and cooling behaviour due to ageing and pollution by dust particles or humidity, and due to its vital role, transformer oil must be subject to oil tests on a regular basis.

Voltage breakdown during transformer oil testing

In most countries such tests are even mandatory. Transformer oil testing sequences and procedures are defined by various international standards.

Periodic execution of transformer oil testing is as well in the very interest of energy supplying companies, as potential damage to the transformer insulation can be avoided by well timed substitution of the transformer oil. Lifetime of plant can be substantially increased and the requirement for new investment may be delayed.

Transformer oil testing procedure

To assess the insulating property of dielectric transformer oil, a sample of the transformer oil is taken and its breakdown voltage is measured.

- The transformer oil is filled in the vessel of the testing device. Two standard-compliant test electrodes with a typical clearance of 2.5 mm are surrounded by the dielectric oil.
- A test voltage is applied to the electrodes and is continuously increased up to the breakdown voltage with a constant, standard-compliant slew rate of e.g. 2 kV/s.
- At a certain voltage level breakdown occures in an electric arc, leading to a collapse of the test voltage.
- An instant after ignition of the arc, the test voltage is switched off automatically by the testing device. Ultra fast switch off is highly desirable, as the carbonisation due to the electric are must be limited to keep the additional pollution as low as possible.
- The transformer oil testing device measures and reports the root mean square value of the breakdown voltage.
- After the transformer oil test is completed, the insultaion oil is stirred automatically and the test sequence is performed repeatedly. (Typically 5 Repetitions, depending on the standard)
- As a result the breakdown voltage is calculated as mean value of the individual measurements.

Conclusion: The lower the resulting breakdown voltage, the poorer the quality of the transformer oil!

On-site transformer oil testing

Recently time consuming testing procedures in test labs have been replaced by on-site oil testing procedures. There are various manufacturers of portable oil testers.

With low weight devices in the range of 20 to 40 kg tests up to 100 kV rms can be performed and reported on-site automatically. Some of them are even battery-powered and come with all sorts of accessories.

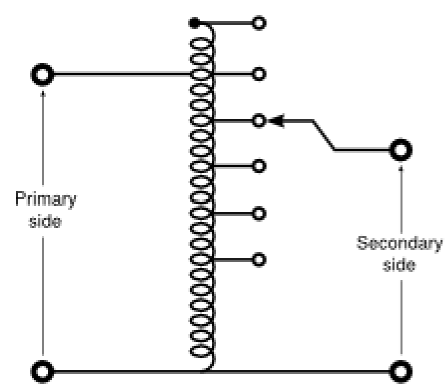
Chapter-6

Autotransformer

An **autotransformer** (sometimes called ***autoformer***) is an electrical transformer with only one winding. The *auto* prefix refers to the single coil rather than any automatic mechanism. In an autotransformer portions of the same winding act as both the primary and secondary. The winding has at least three taps where electrical connections are made. An autotransformer can be smaller, lighter and cheaper than a standard dual-winding transformer however the autotransformer does not provide electrical isolation.

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

Operation



Single-phase tapped autotransformer with output voltage range of 40%–115% of input

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

One end of the winding is usually connected in common to both the voltage source and the electrical load. The other end of the source and load are connected to taps along the winding. Different taps on the winding correspond to different voltages, measured from the common end. In a step-down transformer the source is usually connected across the entire winding while the load is connected by a tap across only a portion of the winding. In a step-up transformer, conversely, the load is attached across the full winding while the source is connected to a tap across a portion of the winding.

As in an **ordinary transformer**, the ratio of secondary to primary voltages is equal to the ratio of the number of turns of the winding they connect to. For example, connecting the load between the middle and bottom of the autotransformer will reduce the voltage by 50%. Depending on the application, that portion of the winding used solely in the higher-voltage (lower current) portion may be wound with wire of a smaller gauge, though the entire winding is directly connected.

Limitations

An autotransformer does not provide electrical isolation between its windings as an ordinary transfomer does. A failure of the insulation of the windings of an autotransformer can result in full input voltage applied to the output. This is an important safety consideration when deciding to use an autotransformer in a given application. Furthermore, if the neutral side of the input is not at ground voltage, the neutral side of the output will not be either.

Because it requires both fewer windings and a smaller core, an autotransformer for power applications is typically lighter and less costly than a two-winding transformer, up to a voltage ratio of about 3:1; beyond that range, a two-winding transformer is usually more economical.

In three phase power transmission applications, autotransformers have the limitations of not suppressing harmonic currents and as acting as another source of ground fault currents. A large three-phase autotransformer may have a "buried" delta winding, not connected to the outside of the tank, to absorb some harmonic currents.

In practice, transformer losses mean that autotransformers are not perfectly reversible; one designed for stepping down a voltage will deliver slightly less voltage than required if used to step up. The difference is usually slight enough to allow reversal where the actual voltage level is not critical. This is true of isolated winding transformers too.

Like multiple-winding transformers, autotransformers operate on time-varying magnetic fields and so cannot be used directly on DC.

Applications

Autotransformers are frequently used in power applications to interconnect systems operating at different voltage classes, for example 138 kV to 66 kV for transmission. Another application is in industry to adapt machinery built (for example) for 480 V supplies to operate on a 600 V supply. They are also often used for providing conversions between the two common domestic mains voltage bands in the world (100-130 and 200-250). The links between the UK 400 kV and 275 kV 'Super Grid' networks are normally three phase autotransformers with taps at the common neutral end.

On long rural power distribution lines, special autotransformers with automatic tap-changing equipment are inserted as voltage regulators, so that customers at the far end of the line receive the same average voltage as those closer to the source. The variable ratio of the autotransformer compensates for the voltage drop along the line.

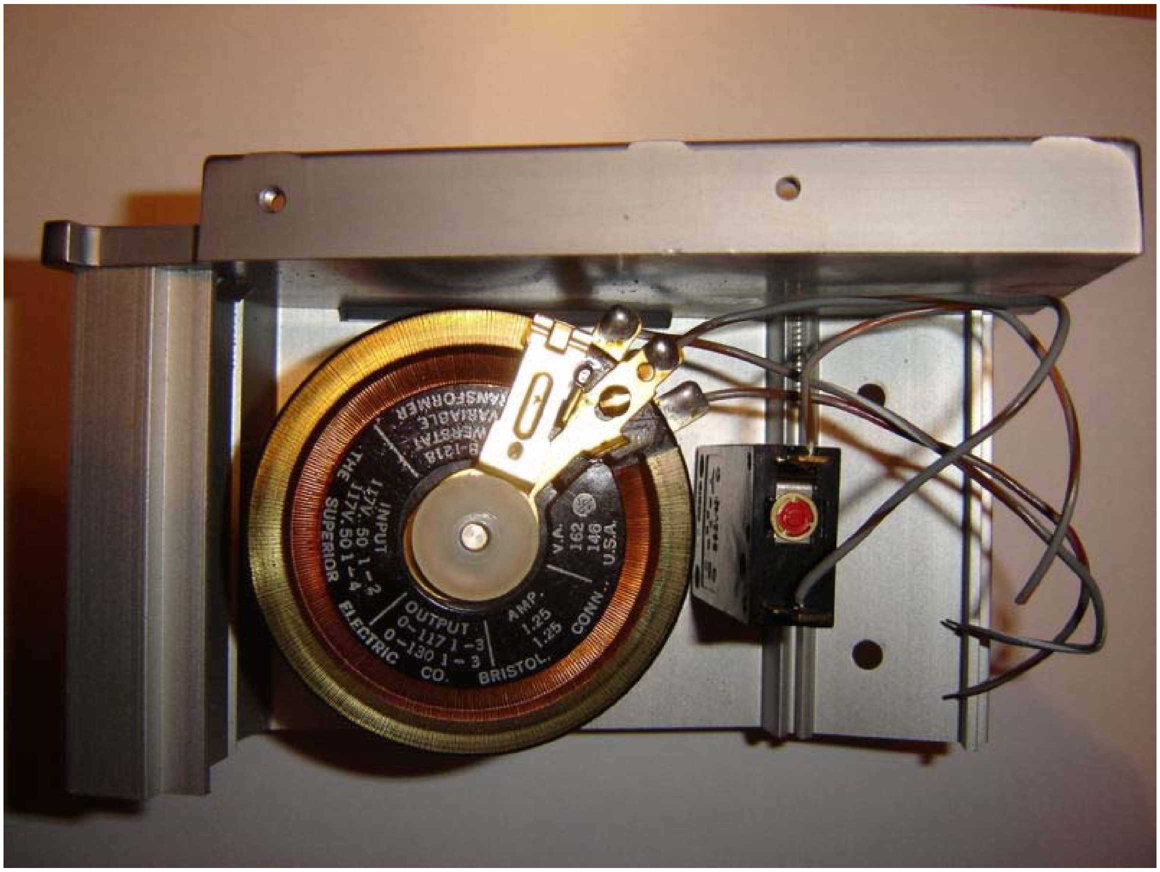
A special form of autotransformer called a *zig zag* is used to provide grounding (earthing) on three-phase systems that otherwise have no connection to ground (earth). A zig-zag transformer provides a path for current that is common to all three phases (so-called *zero sequence* current).

In audio applications, tapped autotransformers are used to adapt speakers to constant-voltage audio distribution systems, and for impedance matching such as between a low-impedance microphone and a high-impedance amplifier input.

In UK railway applications, it is common to power the trains at 25 kV AC. To increase the distance between electricity supply Grid feeder points they can be arranged to supply a 25-0-25 kV supply with the third wire (opposite phase) out of reach of the train's overhead collector pantograph. The 0 V point of the supply is connected to the rail while one 25 kV point is connected to the overhead contact wire. At frequent (about 10 km) intervals, an autotransformer links the contact wire to rail and to the second (antiphase) supply conductor. This system increases usable transmission distance, reduces induced interference into external equipment and reduces cost. A variant is occasionally seen where the supply conductor is at a different voltage to the contact wire with the autotransformer ratio modified to suit.

Variable autotransformers

A variable autotransformer, with a sliding-brush secondary connection and a toroidal core. Cover has been removed to show copper windings and brush.



Variable Transformer - part of Tektronix 576 Curve Tracer

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

As with two-winding transformers, autotransformers may be equipped with many taps and automatic switchgear to allow them to act as automatic voltage regulators, to maintain a steady voltage at the customers' service during a wide range of load conditions. They can also be used to simulate low line conditions for testing. Another application is a lighting dimmer that doesn't produce the EMI typical of most thyristor dimmers.

By exposing part of the winding coils and making the secondary connection through a sliding brush, an almost continuously variable turns ratio can be obtained, allowing for very smooth control of voltage. Applicable only for relatively low voltage designs, this device is known as a variable AC transformer, or commonly by the trade name of *Variac*.

From 1934 to 2002, **Variac** was a U.S. trademark of General Radio for a variable autotransformer intended to conveniently vary the output voltage for a steady AC input voltage. In 2004, Instrument Service Equipment applied for and obtained the *Variac* trademark for the same type of product.

Chapter-7

Tesla Coil

Tesla coil

Tesla coil at Questacon - the National Science and Technology center in Canberra, Australia

Uses	Application in educational demonstrations, novelty lighting, as well as music
Inventor	Nikola Tesla
Related items	Electrical transformer, electromagnetic field

A **Tesla coil** is a type of resonant transformer circuit invented by Nikola Tesla around 1891. It is used to produce high voltage, low current, high frequency alternating current electricity, although Tesla coils produce higher current than the other source of high voltage discharges, electrostatic machines. Tesla experimented with a number of different configurations and they consist of two, or sometimes three, coupled resonant electric circuits. Tesla used these coils to conduct innovative experiments in electrical lighting, phosphorescence, x-ray generation, high frequency alternating current phenomena, electrotherapy, and the transmission of electrical energy without wires.

The early Tesla coil transformer design employs a medium- to high-voltage power source, one or more high voltage capacitor(s), and a spark gap to excite a multiple-layer primary inductor with periodic bursts of high frequency current. The multiple-layer Tesla coil transformer secondary is excited by resonant inductive coupling, the primary and secondary circuits both being *tuned* so they resonate at the same frequency (typically, between 25 kHz and 2 MHz). The later and higher-power coil design has a single-layer primary and secondary. These Tesla coils are often used by hobbyists and at venues such as science museums to produce long sparks.

Tesla coil circuits were used commercially in sparkgap radio transmitters for wireless telegraphy until the 1920s, and in electrotherapy and pseudomedical devices such as violet ray. Today their main use is entertainment and educational displays. Tesla coils are built by many high-voltage enthusiasts, research institutions, science museums and independent experimenters. Although electronic circuit controllers have been developed, Tesla's original spark gap design is less expensive and has proven extremely reliable.

History

Tesla's coil

The "American Electrician" gives a description of an early Tesla coil wherein a glass battery jar, 15 x 20 cm (6 x 8 in) is wound with 60 to 80 turns of AWG No. 18 B & S magnet wire (0.823 mm^2). Into this is slipped a primary consisting of eight to ten turns of AWG No. 6 B & S wire (13.3 mm^2) and the whole combination immersed in a vessel containing linseed or mineral oil. (Norrie, pg. 34-35)

Tesla Coil Theory

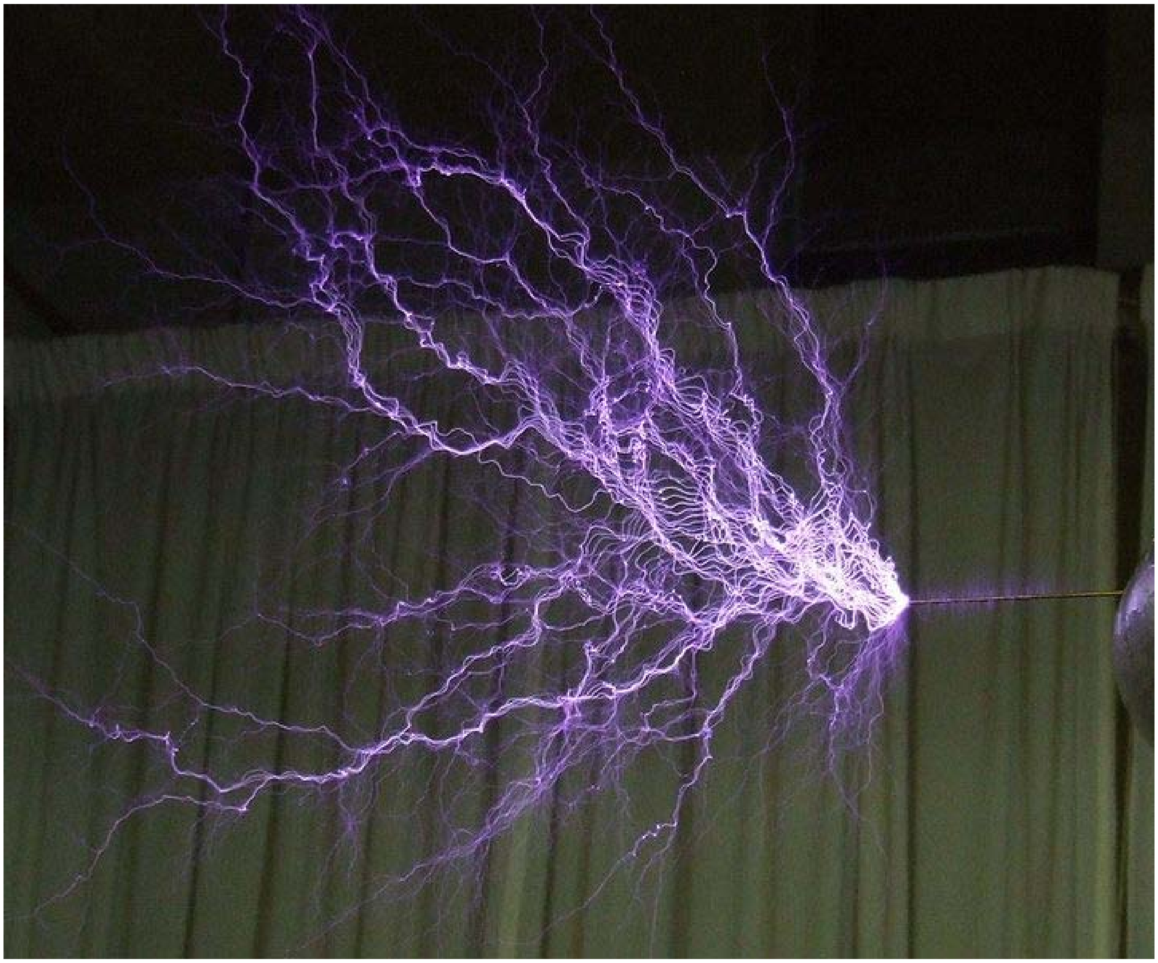
A Tesla coil transformer operates in a significantly different fashion than a conventional (i.e., iron core) transformer. In a conventional transformer, the windings are very tightly coupled, and voltage gain is determined by the ratio of the numbers of turns in the windings. This works well at normal voltages, however, at high voltages, the insulation between the two sets of windings is easily broken down, and this prevents iron cored transformers from running at extremely high voltages without damage.

With Tesla coils, unlike a conventional transformer, which may couple 97%+ of the magnetic fields between windings, a Tesla coil's windings are "loosely" coupled, with a large air gap, and thus the primary and secondary are typically sharing only 10–20% of their respective magnetic fields. Instead of a tight coupling, the coil transfers energy (via loose coupling) from one oscillating resonant circuit (the primary) to the other (the secondary) over a number of RF cycles.

As the primary energy transfers to the secondary, the secondary's output voltage increases until all of the available primary energy has been transferred to the secondary (less losses). Even with significant spark gap losses, a well designed Tesla coil can transfer over 85% of the energy initially stored in the primary capacitor to the secondary circuit. Thus the voltage gain of a Tesla coil can be significantly greater than a conventional transformer, since the air gap has a very high insulation.

With the loose coupling the voltage gain is instead proportional to the square root of the ratio of secondary and primary inductances.

Modern day Tesla coils



Electric discharge showing the lightning-like plasma filaments from a *Tesla coil*.

Modern high voltage enthusiasts usually build Tesla coils that are similar to some of Tesla's "later" air core designs. These typically consist of a primary tank circuit, a series LC (inductance-capacitance) circuit composed of a high voltage capacitor, spark gap and primary coil, and the secondary LC circuit, a series resonant circuit consisting of the secondary coil plus a terminal capacitance or "top load." In Tesla's more advanced design, the secondary LC circuit is composed of an air-core transformer secondary coil placed in series with a helical resonator. The helical coil is then connected to the terminal capacitance. Most modern coils use only a single helical coil comprising both the secondary and primary resonator. The terminal capacitance actually forms one 'plate' of a capacitor, the other 'plate' being the Earth (or "ground"). The primary LC circuit is tuned so that it resonates at the same frequency as the secondary LC circuit. The primary and secondary coils are magnetically coupled, creating a dual-tuned resonant air-core transformer. Earlier oil insulated Tesla coils needed large and long insulators at their high-voltage terminals to prevent discharge in air. Later version Tesla coils spread their electric fields over large distances to prevent high electrical stresses in the first place, thereby allowing operation in free air.

Tesla's 1902 design for his advanced magnifying transmitter used a top terminal consisting of a metal frame in the shape of a toroid, covered with hemispherical plates (constituting a very large conducting surface). The top terminal has relatively small capacitance, charged to as high a voltage as practicable. The outer surface of the elevated conductor is where the electrical charge chiefly accumulates. It has a large radius of curvature, or is composed of separate elements which, irrespective of their own radii of curvature, are arranged close to each other so that the outside ideal surface enveloping them has a large radius. This design allowed the terminal to support very high voltages without generating corona or sparks. Tesla, during his patent application process, described a variety of resonator terminals at the top of this later coil. Most Modern Tesla coils use simple toroids, typically fabricated from spun metal or flexible aluminum ducting, to control the high electrical field near the top of the secondary and to direct spark outward and away from the primary and secondary windings.

As pointed out above, more advanced Tesla coil transmitters involve a more tightly coupled air core resonance transformer network or "master oscillator" the output of which is then fed another resonator, sometimes called the "extra coil." The principle is that energy accumulates in the extra coil and the role of transformer secondary is played by the separate master oscillator secondary; the roles are not shared by a single secondary. In some modern three-coil Magnifying transmitter systems the extra coil is placed some distance from the transformer. Direct magnetic coupling to the upper secondary is not desirable, since the third coil is designed to be driven by injecting RF current directly into the bottom end.

This particular Tesla coil configuration consists of a secondary coil in close inductive relation with a primary, and one end of which is connected to a ground-plate, while its other end is led through a separate self-induction coil (whose connection should always be made at, or near, the geometrical center of that coil's circular aspect, in order to secure a symmetrical distribution of the current), and of a metallic cylinder carrying the current to the terminal. The primary coil may be excited by any desired source of high frequency current. The important requirement is that the primary and secondary sides must be tuned to the same resonant frequency to allow efficient transfer of energy between the primary and secondary resonant circuits. The conductor of the shaft to the terminal (topload) is in the form of a cylinder with smooth surface of a radius much larger than that of the spherical metal plates, and widens out at the bottom into a hood (which is slotted to avoid loss by eddy currents). The secondary coil is wound on a drum of insulating material, with its turns close together. When the effect of the small radius of curvature of the wire itself is overcome, the lower secondary coil behaves as a conductor of large radius of curvature, corresponding to that of the drum. The top of the extra coil may be extended up to the terminal U.S. Patent 1,119,732 and the bottom should be somewhat below the uppermost turn of the primary coil. This lessens the tendency of the charge to break out from the wire connecting both and to pass along the support.

A sword-like discharge characteristic of a Vacuum Tube Tesla Coil. This particular coil was constructed by Xellers of the instructables community.

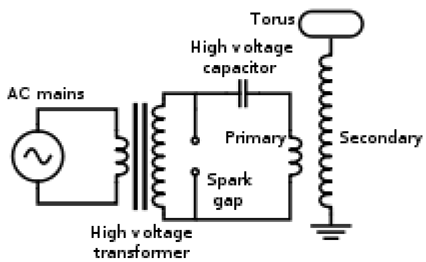
Modern day transistor or vacuum tube Tesla coils do not use a primary spark gap. Instead, the transistor(s) or vacuum tube(s) provide the switching or amplifying function necessary to generate RF power for the primary circuit. Solid-state Tesla coils use the lowest primary operating voltage, typically between 155 to 800 volts, and drive the primary winding using either a single, half-bridge, or full-bridge arrangement of bipolar transistors, MOSFETs or IGBTs to switch the primary current. Vacuum tube coils typically operate with plate voltages between 1500 and 6000 volts, while most spark gap coils operate with primary voltages of 6,000 to 25,000 volts. The primary winding of a traditional transistor Tesla coil is wound around only the bottom portion of the secondary (sometimes called the resonator). This helps to illustrate operation of the secondary as a pumped resonator. The primary *induces* alternating voltage into the bottommost portion of the secondary, providing regular "pushes" (similar to provided properly timed pushes to a playground swing). Additional energy is transferred from the primary to the secondary inductance and topload capacitance during each "push", and secondary output voltage builds (called *ring-up*). An electronic feedback circuit is usually used to adaptively synchronize the primary oscillator to the growing resonance in the secondary, and this is the only tuning consideration beyond the initial choice of a reasonable topload.

Demonstration of the Nevada Lightning Laboratory 1:12 scale prototype twin Tesla Coil at Maker Faire 2008.

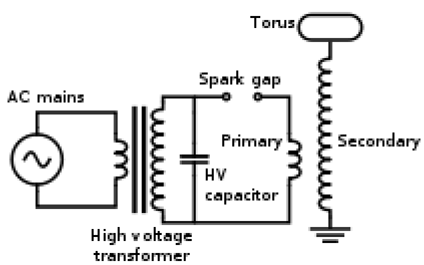
In a *dual resonant solid-state Tesla coil* (DRSSTC), the electronic switching of the solid-state Tesla coil is combined with the resonant primary circuit of a spark-gap Tesla coil. The resonant primary circuit is formed by connecting a capacitor in series with the primary winding of the coil, so that the combination forms a series tank circuit with a resonant frequency near that of the secondary circuit. Because of the additional resonant circuit, one manual and one adaptive tuning adjustment are necessary. Also, an interrupter is usually used to reduce the duty cycle of the switching bridge, in order to improve peak power capabilities; similarly, IGBTs are more popular in this application than bipolar transistors or MOSFETs, due to their superior power handling characteristics. Performance of a DRSSTC can be comparable to a medium power spark gap Tesla coil, and efficiency (as measured by spark length versus input power) can be significantly greater than a spark gap Tesla coil operating at the same input power.

Applications

Transmission



Typical Tesla Coil Schematic
This example circuit is designed to be driven by alternating currents. Here the spark gap shorts the high frequency across the first transformer. An inductance, not shown, protects the transformer. This design is favoured when a relatively fragile Neon Sign Transformer (NST) is used.



Alternate Tesla Coil Configuration
This circuit also driven by alternating currents. However, here the AC supply transformer must be capable of withstanding high voltages at high frequencies.

High voltage production

A large Tesla coil of more modern design often operates at very high peak power levels, up to many megawatts (millions of watts). It should therefore be adjusted and operated carefully, not only for efficiency and economy, but also for safety. If, due to improper tuning, the maximum voltage point occurs below the terminal, along the secondary coil, a discharge (spark) may break out and damage or destroy the coil wire, supports, or nearby objects.

Tesla experimented with these, and many other, circuit configurations. The Tesla coil primary winding, spark gap and tank capacitor are connected in series. In each circuit, the AC supply transformer charges the tank capacitor until its voltage is sufficient to break down the spark gap. The gap suddenly fires, allowing the charged tank capacitor to discharge into the primary winding. Once the gap fires, the electrical behavior of either circuit is identical. Experiments have shown that neither circuit offers any marked performance advantage over the other.

However, in the typical circuit (above), the spark gap's short circuiting action prevents high frequency oscillations from 'backing up' into the supply transformer. In the alternate circuit, high amplitude high frequency oscillations that appear across the capacitor also are applied to the supply transformer's winding. This can induce corona discharges between turns that weaken and eventually destroy the transformer's insulation. Experienced Tesla coil builders almost exclusively use the top circuit, often augmenting it with low pass filters (resistor and capacitor (RC) networks) between the supply transformer and spark gap to help protect the supply transformer. This is especially important when using transformers with fragile high voltage windings, such as Neon-sign transformers (NSTs). Regardless of which configuration is used, the HV transformer must be of a type that self-limits its secondary current by means of internal leakage inductance. A normal (low leakage inductance) high voltage transformer must use an external limiter (sometimes called a ballast) to limit current. NSTs are designed to have high leakage inductance to limit their short circuit current to a safe level.

Tuning precautions

The primary coil's resonant frequency should be tuned to that of the secondary, using low-power oscillations, then increasing the power until the apparatus has been brought under control. While tuning, a small projection (called a "breakout bump") is often added to the top terminal in order to stimulate corona and spark discharges (sometimes called streamers) into the surrounding air. Tuning can then be adjusted so as to achieve the longest streamers at a given power level, corresponding to a frequency match between the primary and secondary coil. Capacitive 'loading' by the streamers tends to lower the resonant frequency of a Tesla coil operating under full power. For a variety of technical reasons, toroids provide one of the most effective shapes for the top terminals of Tesla coils.

Air discharges

A small, later-type "*Tesla coil*" in operation. The output is giving 17-inch sparks. The diameter of the secondary is three inches. The power source is a 10000 V, 60 Hz current limited supply.

While generating discharges, electrical energy from the secondary and toroid is transferred to the surrounding air as electrical charge, heat, light, and sound. The electric currents that flow through these discharges are actually due to the rapid shifting of quantities of charge from one place (the top terminal) to other places (nearby regions of air). The process is similar to charging or discharging a capacitor. The current that arises from shifting charges within a capacitor is called a displacement current. Tesla coil discharges are formed as a result of displacement currents as pulses of electrical charge are rapidly transferred between the high voltage toroid and nearby regions within the air (called space charge regions). Although the space charge regions around the toroid are invisible, they play a profound role in the appearance and location of Tesla coil discharges.

When the spark gap fires, the charged capacitor discharges into the primary winding, causing the primary circuit to oscillate. The oscillating primary current creates a magnetic field that couples to the secondary winding, transferring energy into the secondary side of the transformer and causing it to oscillate with the toroid capacitance. The energy transfer occurs over a number of cycles, and most of the energy that was originally in the primary side is transferred into the secondary side. The greater the magnetic coupling between windings, the shorter the time required to complete the energy transfer. As energy builds within the oscillating secondary circuit, the amplitude of the toroid's RF voltage rapidly increases, and the air surrounding the toroid begins to undergo dielectric breakdown, forming a corona discharge.

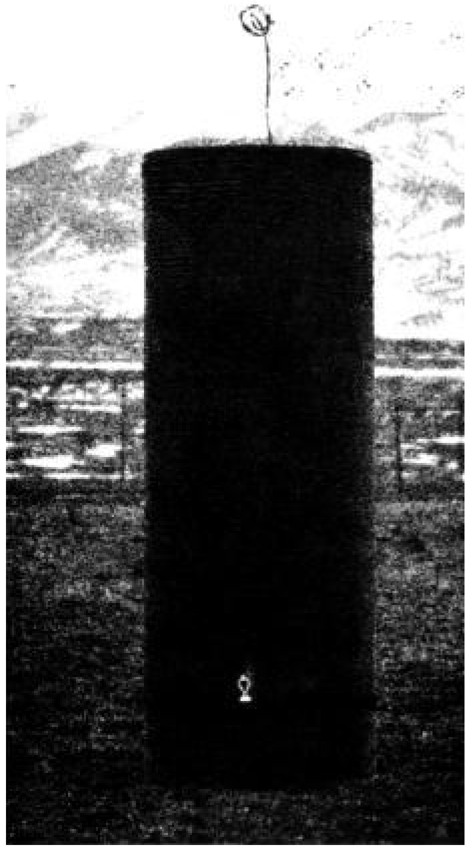
As the secondary coil's energy (and output voltage) continue to increase, larger pulses of displacement current further ionize and heat the air at the point of initial breakdown. This forms a very conductive "root" of hotter plasma, called a leader, that projects outward from the toroid. The plasma within the leader is considerably hotter than a corona discharge, and is considerably more conductive. In fact, it has properties that are similar to an electric arc. The leader tapers and branches into thousands of thinner, cooler, hairlike discharges (called streamers). The streamers look like a bluish 'haze' at the ends of the more luminous leaders, and it is the streamers that actually transfer charge between the leaders and toroid to nearby space charge regions. The displacement currents from countless streamers all feed into the leader, helping to keep it hot and electrically conductive.

The primary break rate of sparking Tesla coils is slow compared to the resonant frequency of the resonator-topload assembly. When the switch closes, energy is transferred from the primary LC circuit to the resonator where the voltage rings up over a short period of time up culminating in the electrical discharge. In a spark gap Tesla coil the primary-to-secondary energy transfer process happens repetitively at typical pulsing rates of 50–500 times per second, and previously formed leader channels don't get a chance to fully cool down between pulses. So, on successive pulses, newer discharges can build upon the hot pathways left by their predecessors. This causes incremental growth of the leader from one pulse to the next, lengthening the entire discharge on each successive pulse. Repetitive pulsing causes the discharges to grow until the average energy that's available from the Tesla coil during each pulse balances the average energy being lost in the discharges (mostly as heat). At this point, dynamic equilibrium is reached, and the discharges have reached their maximum length for the Tesla coil's output power level. The unique combination of a rising high voltage Radio Frequency envelope and repetitive pulsing seem to be ideally suited to creating long, branching discharges that are considerably longer than would be otherwise expected by output voltage considerations alone. High voltage discharges create filamentary multi-branched discharges which are purplish blue in colour. High energy discharges create thicker discharges with fewer branches, are pale and luminous, almost white, and are much longer than low energy discharges, because of increased ionisation. There will be a strong smell of ozone and nitrogen oxides in the area. The important factors for maximum discharge length appear to be voltage, energy, and still air of low to moderate humidity. However, even more than 100 years later after the first use of Tesla coils, there are many aspects of Tesla coil discharges and the energy transfer process that are still not completely understood.

Wireless transmission and reception

The Tesla coil can also be used for wireless transmission. In addition to the positioning of the elevated terminal well above the top turn of the helical resonator, another difference from the sparking Tesla coil is the primary break rate. The optimized Tesla coil transmitter is a continuous wave oscillator with a break rate equaling the operating frequency. The combination of a helical resonator with an elevated terminal is also used for wireless reception. The Tesla coil receiver is intended for receiving the non-radiating electromagnetic field energy produced by the Tesla coil transmitter. The Tesla coil receiver is also adaptable for exploiting the ubiquitous vertical voltage gradient in the Earth's atmosphere. Tesla built and used various devices for detecting electromagnetic field energy. His early wireless apparatus operated on the basis of Hertzian waves or ordinary radio waves, electromagnetic waves that propagate in space without involvement of a conducting guiding surface. During his work at Colorado Springs, Tesla believed he had established electrical resonance of the entire Earth using the Tesla coil transmitter at his "Experimental Station."

Tesla stated one of the requirements of the World Wireless System was the construction of resonant receivers. The related concepts and methods are part of his wireless transmission system (US1119732 — Apparatus for Transmitting Electrical Energy — 1902 January 18). Tesla made a proposal that there needed to be many more than thirty transmission-reception stations worldwide. In one form of receiving circuit the two input terminals are connected each to a mechanical pulse-width modulation device adapted to reverse polarity at predetermined intervals of time and charge a capacitor. This form of Tesla system receiver has means for commutating the current impulses in the charging circuit so as to render them suitable for charging the storage device, a device for closing the receiving-circuit, and means for causing the receiver to be operated by the energy accumulated.



Tesla coil in one experiment of many conducted in Colorado Springs. This is a grounded tuned coil in resonance with a nearby transmitter; Light is glowing near the bottom.

A Tesla coil used as a receiver is referred to as a *Tesla receiving transformer*. The Tesla coil receiver acts as a step-down transformer with high current output. The parameters of a Tesla coil transmitter are identically applicable to it being a receiver (*e.g.*., an antenna circuit), due to reciprocity. Impedance, generally though, is not applied in an obvious way; for electrical impedance, the impedance at the load (*e.g.*., where the power is consumed) is most critical and, for a Tesla coil receiver, this is at the point of utilization (such as at an induction motor) rather than at the receiving node. Complex impedance of an antenna is related to the electrical length of the antenna at the wavelength in use. Commonly, impedance is adjusted at the load with a tuner or a matching networks composed of inductors and capacitors.

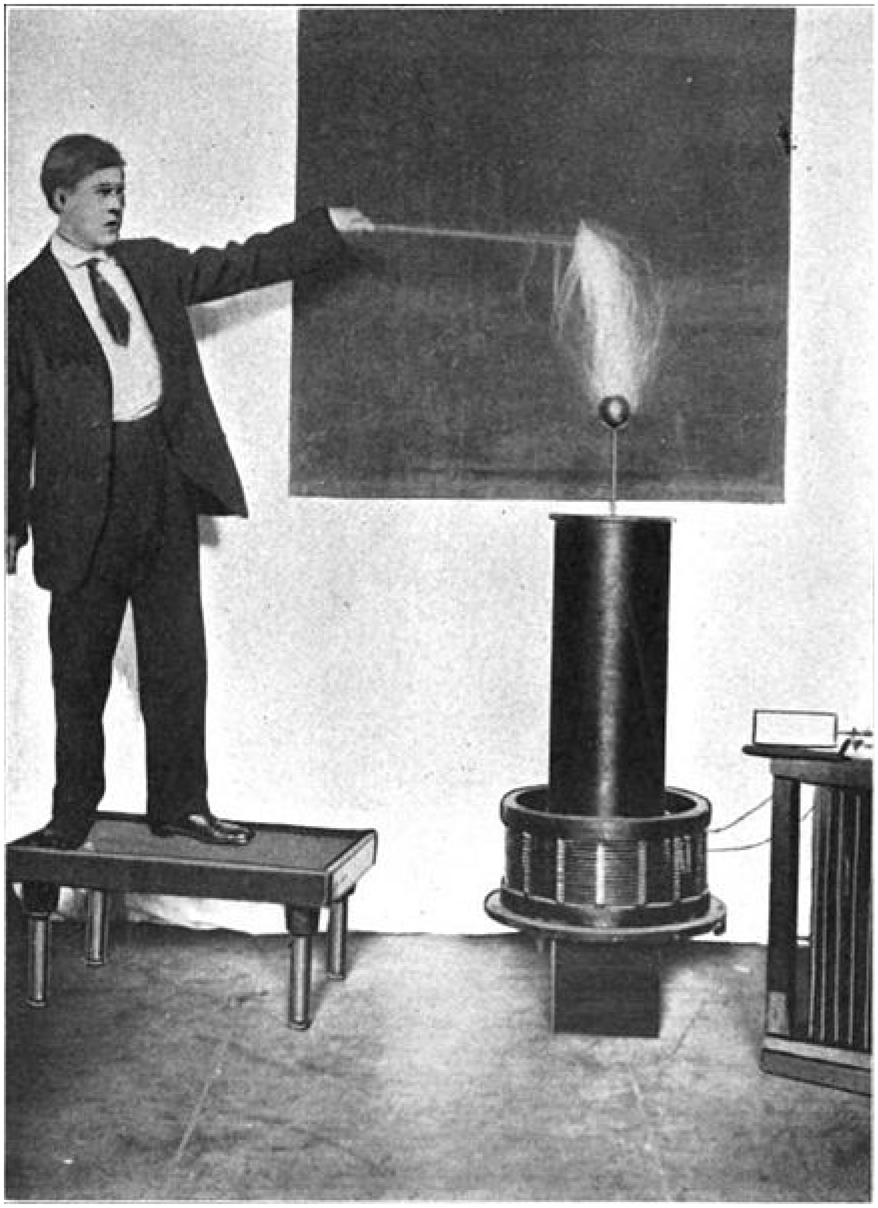
A Tesla coil can receive electromagnetic impulses from atmospheric electricity and radiant energy, besides normal wireless transmissions. Radiant energy throws off with great velocity minute particles which are strongly electrified and other rays falling on the insulated-conductor connected to a condenser (i.e., a capacitor) can cause the condenser to indefinitely charge electrically. The helical resonator can be "shock excited" due to radiant energy disturbances not only at the fundamental wave at one-quarter wave-length but also is excited at its harmonics. Hertzian methods can be used to excite the Tesla coil receiver with limitations that result in great disadvantages for utilization, though. The methods of ground conduction and the various induction methods can also be used to excite the Tesla coil receiver, but are again at a disadvantages for utilization. The charging-circuit can be adapted to be energized by the action of various other disturbances and effects at a distance. Arbitrary and intermittent oscillations that are propagated via conduction to the receiving resonator will charge the receiver's capacitor and utilize the potential energy to greater effect. Various radiations can be used to charge and discharge conductors, with the radiations considered electromagnetic vibrations of various wavelengths and ionizing potential. The Tesla receiver utilizes the effects or disturbances to charge a storage device with energy from an external source (natural or man-made) and controls the charging of said device by the actions of the effects or disturbances (during succeeding intervals of time determined by means of such effects and disturbances corresponding in succession and duration of the effects and disturbances). The stored energy can also be used to operate the receiving device. The accumulated energy can, for example, operate a transformer by discharging through a primary circuit at predetermined times which, from the secondary currents, operate the receiving device.

While Tesla coils can be used for these purposes, much of the public and media attention is directed away from transmission-reception applications of the Tesla coil since electrical spark discharges are fascinating to many people. Regardless of this fact, Tesla did suggest that this variation of the Tesla coil could utilize the phantom loop effect to form a circuit to induct energy from the Earth's magnetic field and other radiant energy sources (including, but not limited to, electrostatics). With regard to Tesla's statements on the harnessing of natural phenomena to obtain electric power, he stated:

Ere many generations pass, our machinery will be driven by a power obtainable at any point of the universe. — "Experiments with Alternate Currents of High Potential and High Frequency" (February 1892)

Tesla stated that the output power from these devices, attained from Hertzian methods of charging, was low, but alternative charging means are available. Tesla receivers, operated correctly, act as a step-down transformer with high current output. There are, to date, no commercial power generation entities or businesses that have utilized this technology to full effect. The power levels achieved by Tesla coil receivers have, thus far, been a fraction of the output power of the transmitters.

High frequency electrical safety



Student conducting Tesla coil streamers through his body, 1909

The 'skin effect'

The dangers of contact with high frequency electrical current are sometimes perceived as being less than at lower frequencies, because the subject usually doesn't feel pain or a 'shock'. This is often erroneously attributed to skin effect, a phenomenon that tends to inhibit alternating current from flowing inside conducting media. It was thought that in the body, Tesla currents travelled close to the skin surface, making them safer than lower frequency electric currents. In fact, in the early 1900s a major use of Tesla coils was to apply high frequency current directly to the body in electrotherapy.

Although skin effect limits Tesla currents to the outer fraction of an inch in metal conductors, the 'skin depth' of human flesh at typical Tesla coil frequencies is still of the order of 60 inches (150 cm) or more. This means that high frequency currents will still preferentially flow through deeper, better conducting, portions of an experimenter's body such as the circulatory and nervous systems. The reason for the lack of pain is that a human being's nervous system does not sense the flow of potentially dangerous electrical currents above 15–20 kHz; essentially, in order for nerves to be activated, a significant number of ions must cross their membrane before the current (and hence voltage) reverses. Since the body no longer provides a warning 'shock', novices may touch the output streamers of small Tesla coils without feeling painful shocks. However, there is anecdotal evidence among Tesla coil experimenters that temporary tissue damage may still occur and be observed as muscle pain, joint pain, or tingling for hours or even days afterwards. This is believed to be caused by the damaging effects of internal current flow, and is especially common with continuous wave (CW), solid state or vacuum tube type Tesla coils. Some transformers can provide alternating current with such high frequencies that the skin depth becomes small enough for the voltage to be safe. Skin depth is inversely proportional to the root of the frequency, putting these frequencies in the megahertz range.

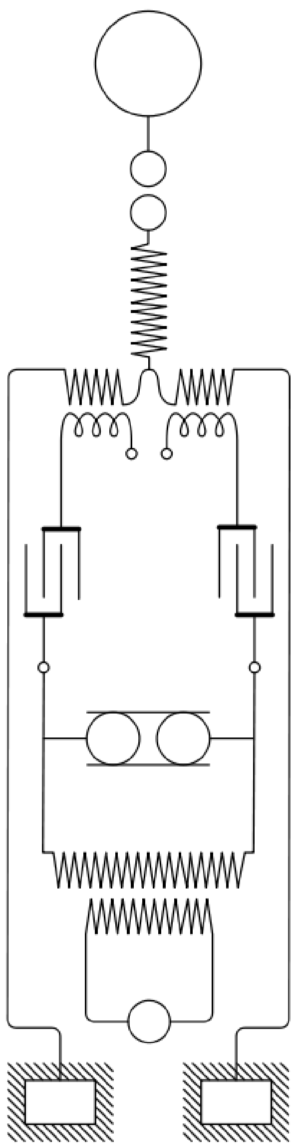
Large Tesla coils and magnifiers can deliver dangerous levels of high frequency current, and they can also develop significantly higher voltages (often 250,000–500,000 volts, or more). Because of the higher voltages, large systems can deliver higher energy, potentially lethal, repetitive high voltage capacitor discharges from their top terminals. Doubling the output voltage quadruples the electrostatic energy stored in a given top terminal capacitance. If an unwary experimenter accidentally places himself in path of the high voltage capacitor discharge to ground, the low current electric shock can cause involuntary spasms of major muscle groups and may induce life-threatening ventricular fibrillation and cardiac arrest. Even lower power vacuum tube or solid state Tesla coils can deliver RF currents that are capable of causing temporary internal tissue, nerve, or joint damage through Joule heating. In addition, an RF arc can carbonize flesh, causing a painful and dangerous bone-deep RF burn that may take months to heal. Because of these risks, knowledgeable experimenters avoid contact with streamers from all but the smallest systems. Professionals usually use other means of protection such as a Faraday cage or a chain mail suit to prevent dangerous currents from entering their body.

The most serious dangers associated with Tesla coil operation are associated with the primary circuit. It is the primary circuit that is capable of delivering a sufficient current at a significant voltage to stop the heart of a careless experimenter. Because these components are not the source of the trademark visual or auditory coil effects, they may easily be overlooked as the chief source of hazard. Should a high frequency arc strike the exposed primary coil while, at the same time, another arc has also been allowed to strike to a person, the ionized gas of the two arcs forms a circuit that may conduct lethal, low-frequency current from the primary into the person.

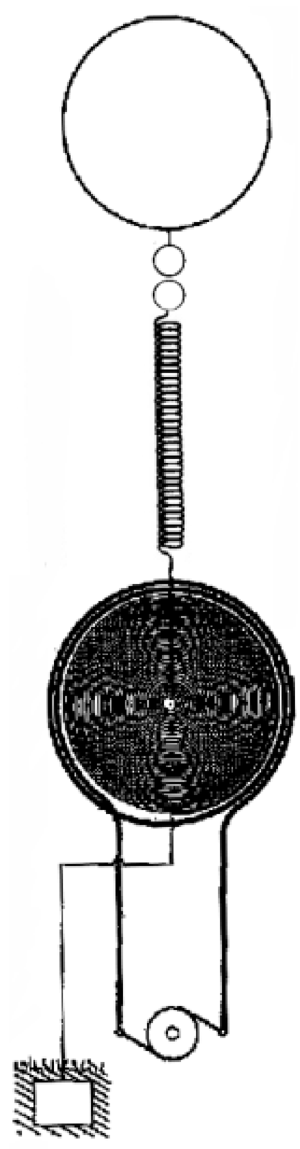
Further, great care should be taken when working on the primary section of a coil even when it has been disconnected from its power source for some time. The tank capacitors can remain charged for days with enough energy to deliver a fatal shock. Proper designs should always include 'bleeder resistors' to bleed off stored charge from the capacitors. In addition, a safety shorting operation should be performed on each capacitor before any internal work is performed.

Instances and devices

Magnifier Configurations



Classically driven configuration.



Later-type driven configuration. Pancake may be horizontal; lead to resonator is kept clear of it.

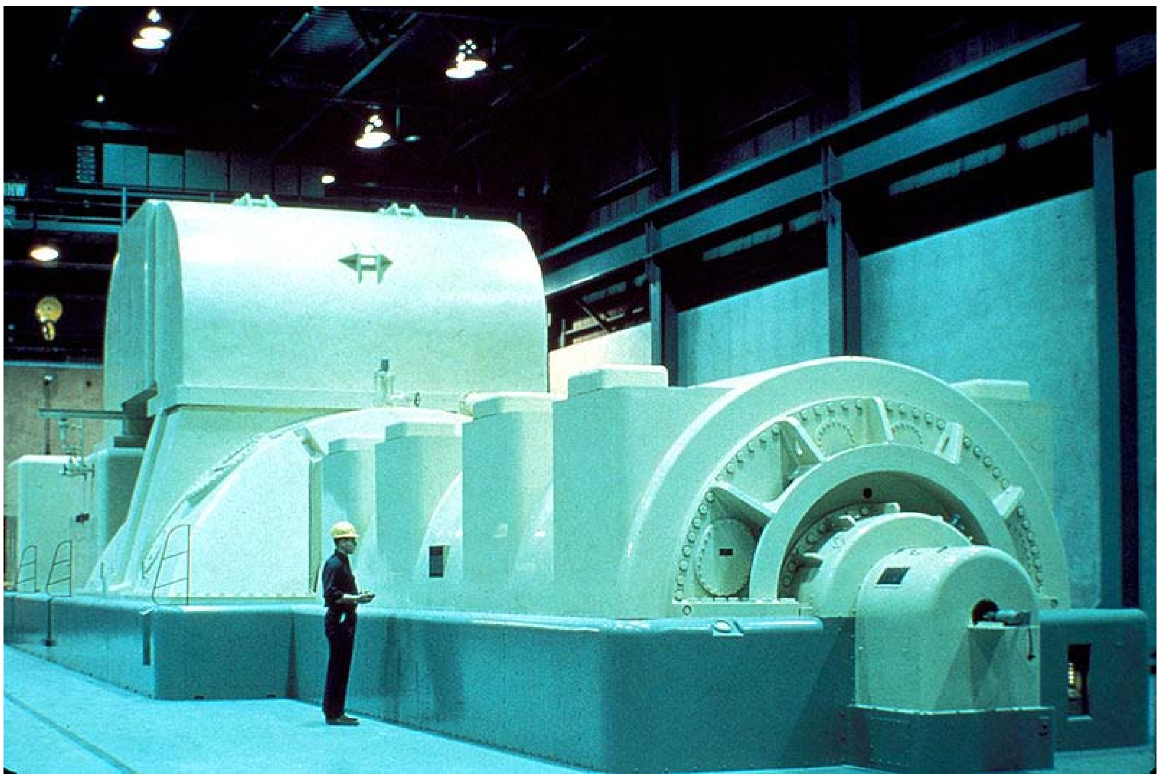
Tesla's Colorado Springs laboratory possessed one of the largest Tesla coils ever built, known as the "Magnifying Transmitter". The Magnifying Transmitter is somewhat different from classic 2-coil Tesla coils. A Magnifier uses a 2-coil 'driver' to excite the base of a third coil ('resonator') that is located some distance from the driver. The operating principles of both systems are similar. The world's largest currently existing 2-coil Tesla coil is a 130,000-watt unit, part of a 38-foot-tall (12 m) sculpture. It is owned by Alan Gibbs and currently resides in a private sculpture park at Kakanui Point near Auckland, New Zealand.

The Tesla coil is an early predecessor (along with the induction coil) of a more modern device called a flyback transformer, which provides the voltage needed to power the cathode ray tube used in some televisions and computer monitors. The disruptive discharge coil remains in common use as the *ignition coil* or *spark coil* in the ignition system of an internal combustion engine. These two devices do not use resonance to accumulate energy, however, which is the distinguishing feature of a Tesla coil. They do use inductive "kick", the forced, abrupt decay of the magnetic field, such that a voltage is provided by the coil at its primary terminals that is much greater than the voltage that was applied to establish the magnetic field, and it is this higher voltage that is then multiplied by the transformer turns ratio. Thus, they do store energy, and a Tesla resonator stores energy. A modern, low power variant of the Tesla coil is also used to power plasma globe sculptures and similar devices.

Scientists working with a glass vacuum line (e.g. chemists working with volatile substances in the gas phase, inside a system of glass tubes, taps and bulbs) test for the presence of tiny pin-holes in the apparatus (especially a newly blown piece of glassware) using a Tesla coil. When the system is evacuated and the discharging end of the coil moved over the glass, the discharge travels through any pin-hole immediately below it and thus illuminates the hole, indicating points that need to be annealed or re-blown before they can be used in an experiment.

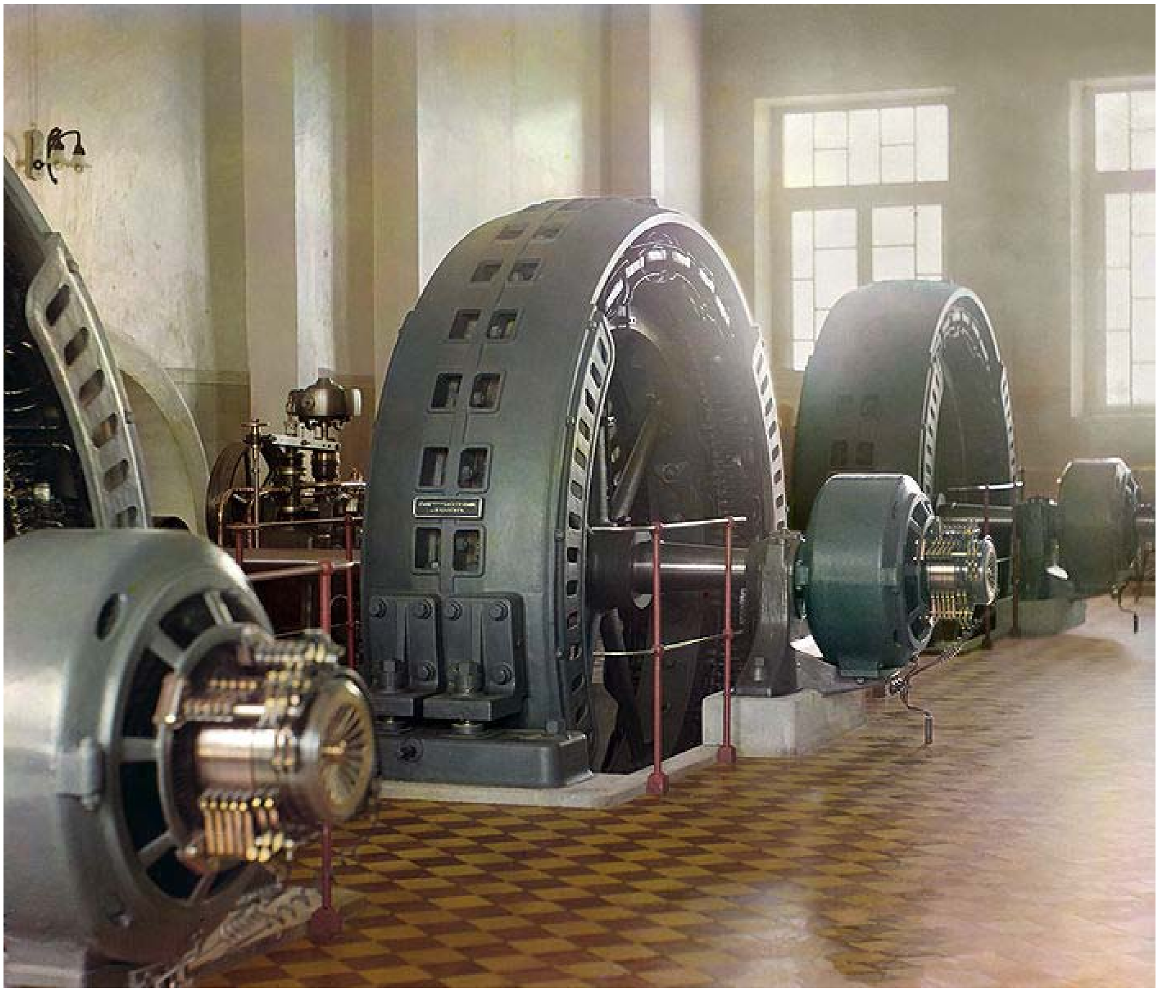
Chapter-8

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

Early Ganz 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:

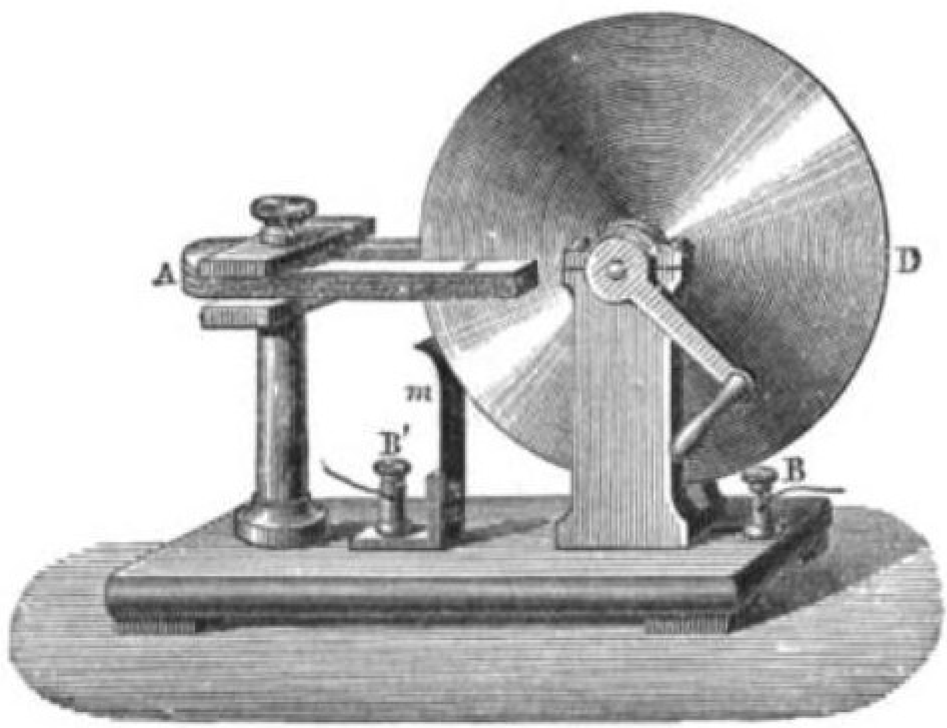
- Electrostatic induction
- The triboelectric effect, where the contact between two insulators leaves them charged.

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



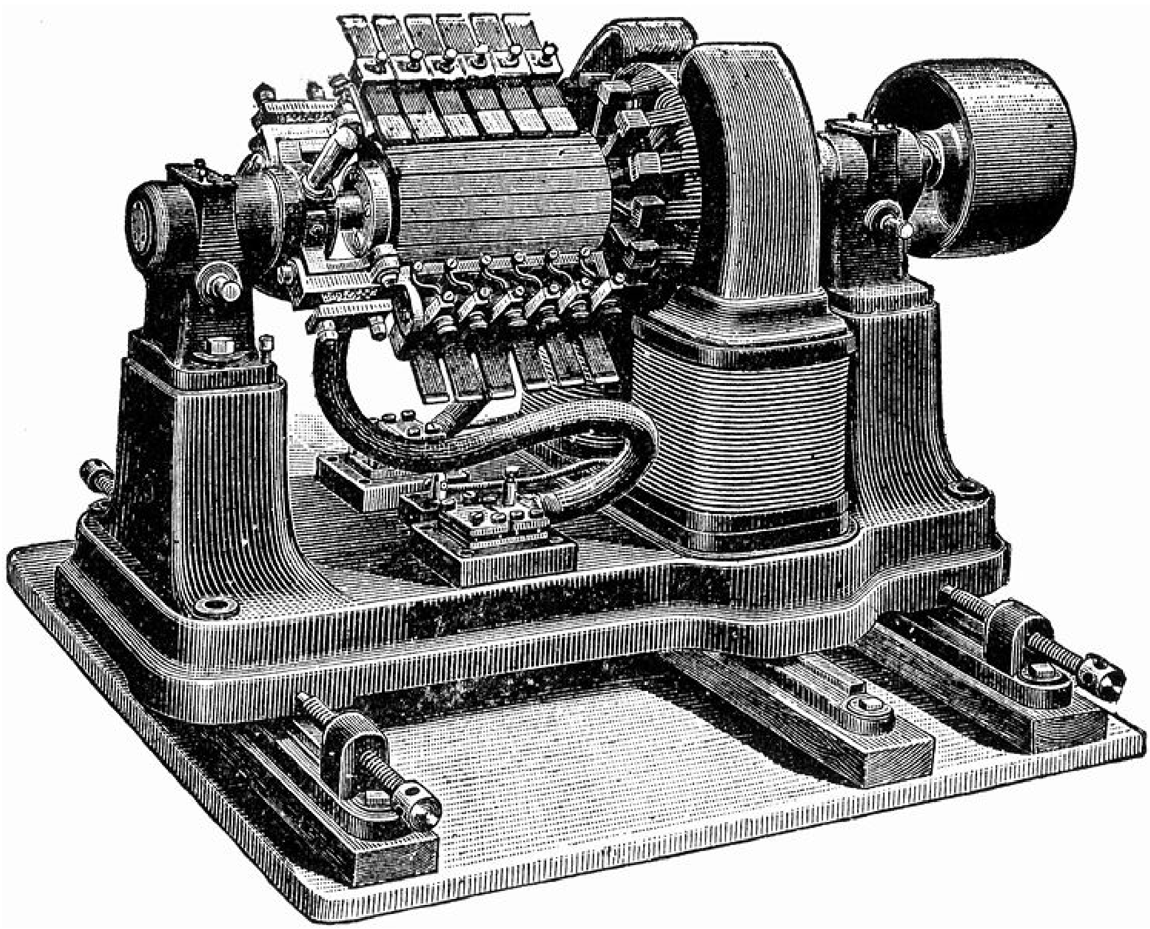
Faraday disk, the first electric generator. The horseshoe-shaped magnet *(A)* created a magnetic field through the disk *(D)*. When the disk was turned this induced an electric current radially outward from the center toward the rim. The current flowed out through the sliding spring contact *m*, through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

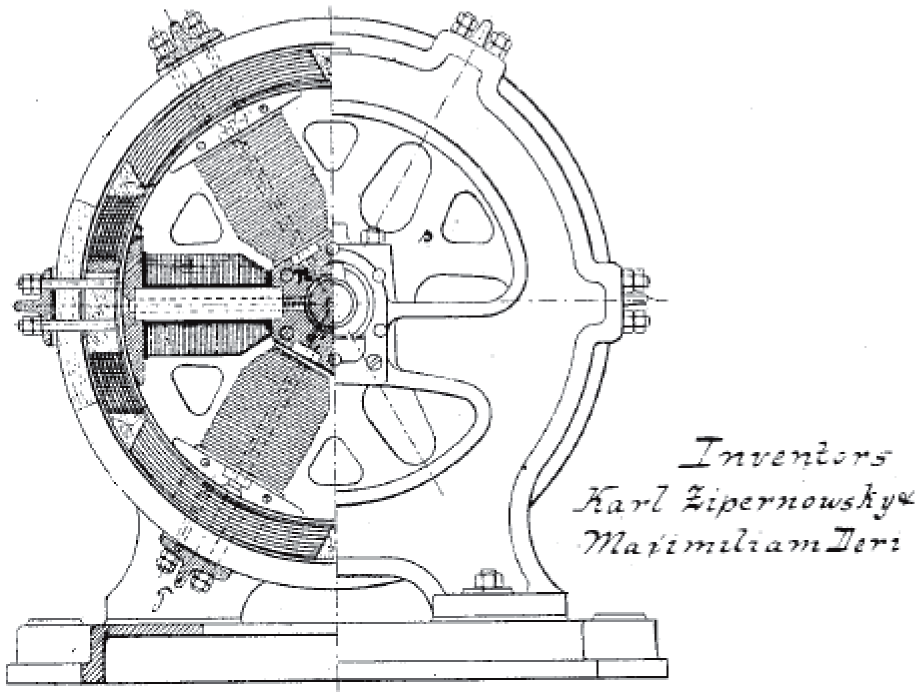
This design was inefficient due to self-cancelling counterflows of current in regions not under the influence of the magnetic field. While current was induced directly underneath the magnet, the current would circulate backwards in regions outside the influence of the magnetic field. This counterflow 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:

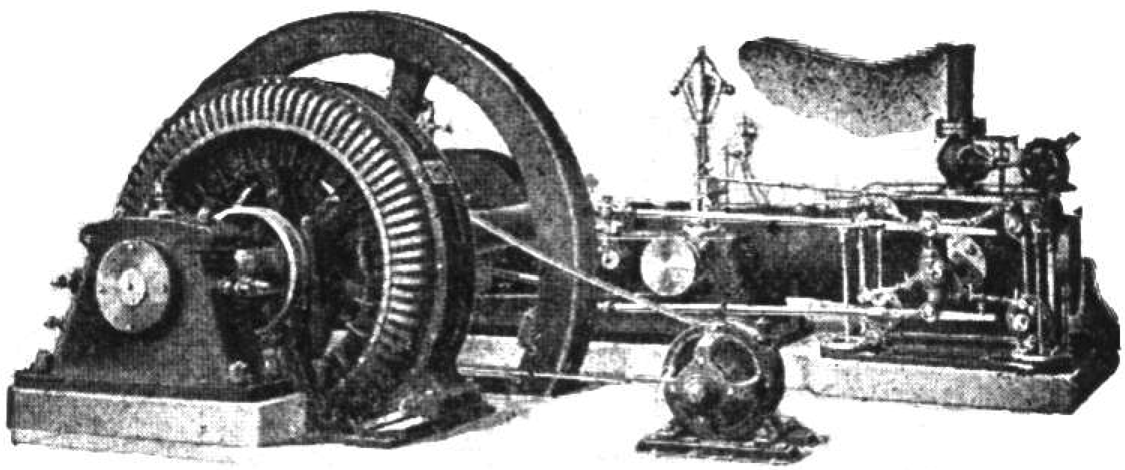
- Rotor: The rotating part of an electrical machine
- Stator: The stationary part of an electrical machine

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



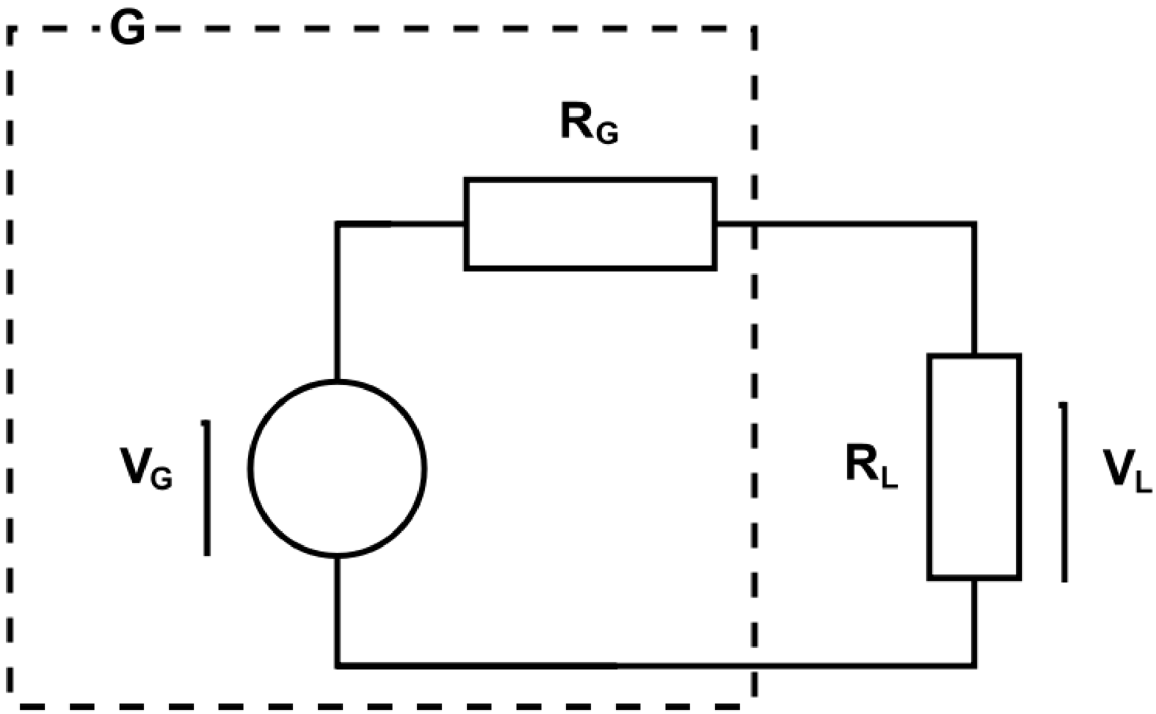
A small early 1900s 75 KVA direct-driven power station AC alternator, with a separate belt-driven exciter generator.

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. Portable radio receivers with a crank are made to reduce battery purchase requirements.

Linear electric generator

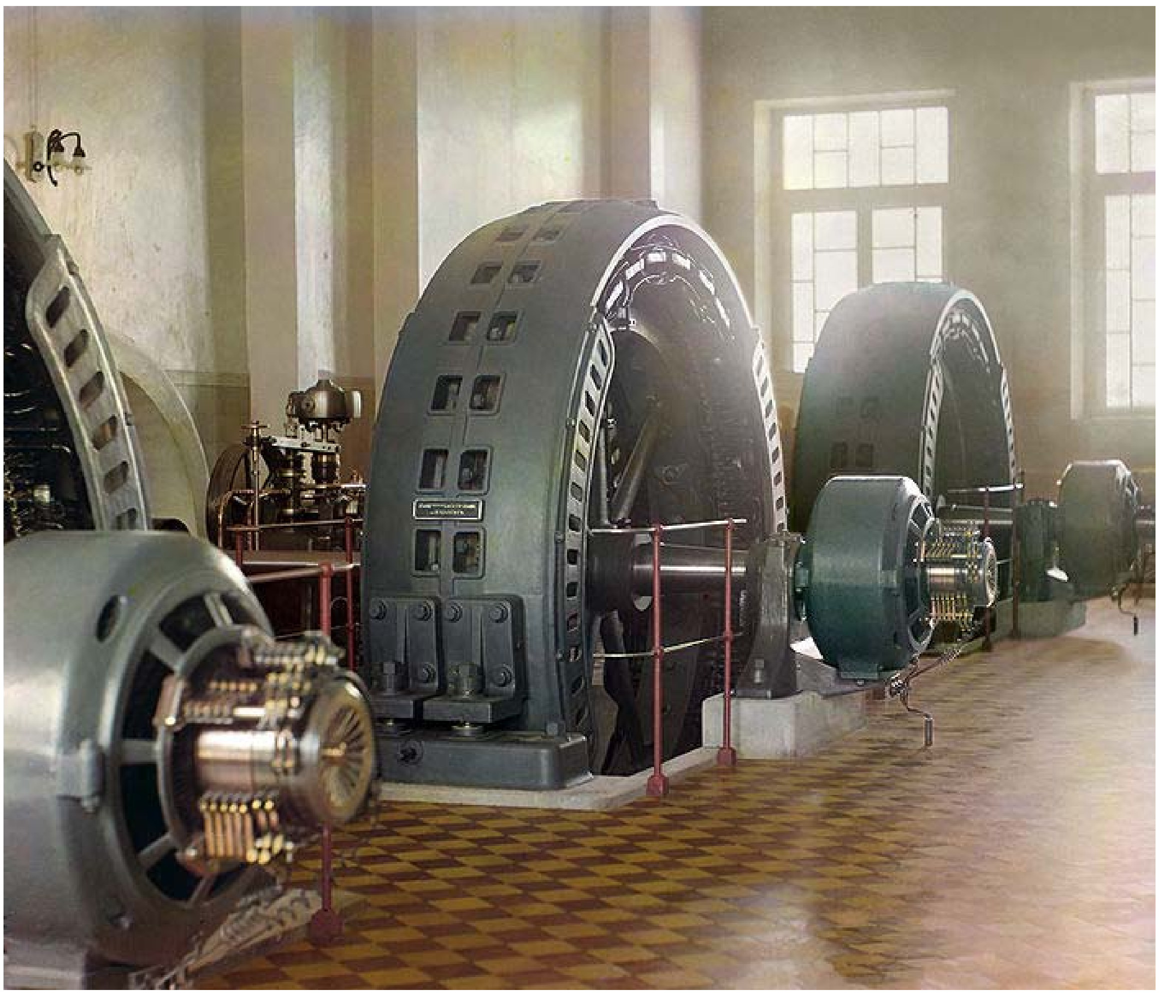
In the simplest form of linear electric generator, a sliding magnet moves back and forth through a solenoid - a spool of copper wire. An alternating current is induced in the loops of wire by Faraday's law of induction each time the magnet slides through. This type of generator is used in the Faraday 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-9

Alternator



Early 20th-century alternator made in Budapest, Hungary, in the power generating hall of a hydroelectric station (photograph by Prokudin-Gorsky, 1905–1915).

An **alternator** is an electromechanical device that converts mechanical energy to electrical energy in the form of alternating current.

Most alternators use a rotating magnetic field but linear alternators are occasionally used. In principle, any AC electrical generator can be called an alternator, but usually the word refers to small rotating machines driven by automotive and other internal combustion engines. Alternators in power stations driven by steam turbines are called turbo-alternators.

History

Alternating current generating systems were known in simple forms from the discovery of the magnetic induction of electric current. The early machines were developed by pioneers such as Michael Faraday and Hippolyte Pixii.

Faraday developed the "rotating rectangle", whose operation was *heteropolar* - each active conductor passed successively through regions where the magnetic field was in opposite directions. The first public demonstration of a more robust "alternator system" took place in 1886. Large two-phase alternating current generators were built by a British electrician, J.E.H. Gordon, in 1882. Lord Kelvin and Sebastian Ferranti also developed early alternators, producing frequencies between 100 and 300 Hz. In 1891, Nikola Tesla patented a practical "high-frequency" alternator (which operated around 15 kHz).. After 1891, polyphase alternators were introduced to supply currents of multiple differing phases. Later alternators were designed for varying alternating-current frequencies between sixteen and about one hundred hertz, for use with arc lighting, incandescent lighting and electric motors.

Principle of operation

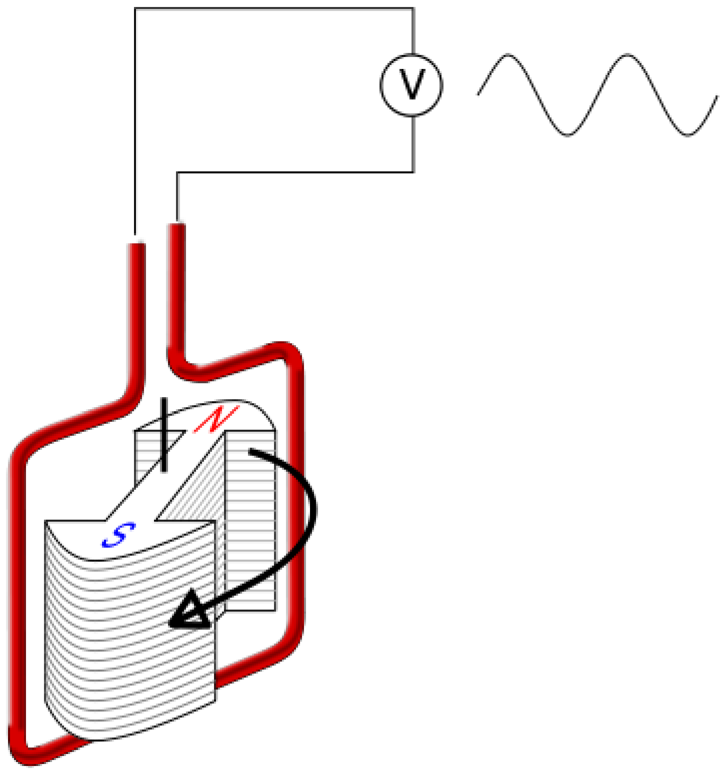


Diagram of a simple alternator with a rotating magnetic core (rotor) and stationary wire (stator) also showing the current induced in the stator by the rotating magnetic field of the rotor.

Alternators generate electricity using the same principle as DC generators, namely, when the magnetic field around a conductor changes, a current is induced in the conductor. Typically, a rotating magnet, called the rotor turns within a stationary set of conductors wound in coils on an iron core, called the stator. The field cuts across the conductors, generating an induced EMF(Electro-Magnetic Field), as the mechanical input causes the rotor to turn.

The rotating magnetic field induces an AC voltage in the stator windings. Often there are three sets of stator windings, physically offset so that the rotating magnetic field produces a three phase current, displaced by one-third of a period with respect to each other.

The rotors magnetic field may be produced by induction (as in a "brush-less" alternator), by permanent magnets (as in very small machines), or by a rotor winding energized with direct current through slip rings and brushes. The rotors magnetic field may even be provided by stationary field winding, with moving poles in the rotor. Automotive alternators invariably use a rotor winding, which allows control of the alternators generated voltage by varying the current in the rotor field winding. Permanent magnet machines avoid the loss due to magnetizing current in the rotor, but are restricted in size, owing to the cost of the magnet material. Since the permanent magnet field is constant, the terminal voltage varies directly with the speed of the generator. Brushless AC generators are usually larger machines than those used in automotive applications.

An automatic voltage control device controls the field current to keep output voltage constant. If the output voltage from the stationary armature coils drops due to an increase in demand, more current is fed into the rotating field coils through the Automatic Voltage Regulator or AVR. This increases the magnetic field around the field coils which induces a greater voltage in the armature coils. Thus, the output voltage is brought back up to its original value.

Alternators in central power stations use may also control the field current to regulate reactive power and to help stabilize the power system against the effects of momentary faults.

Synchronous speeds

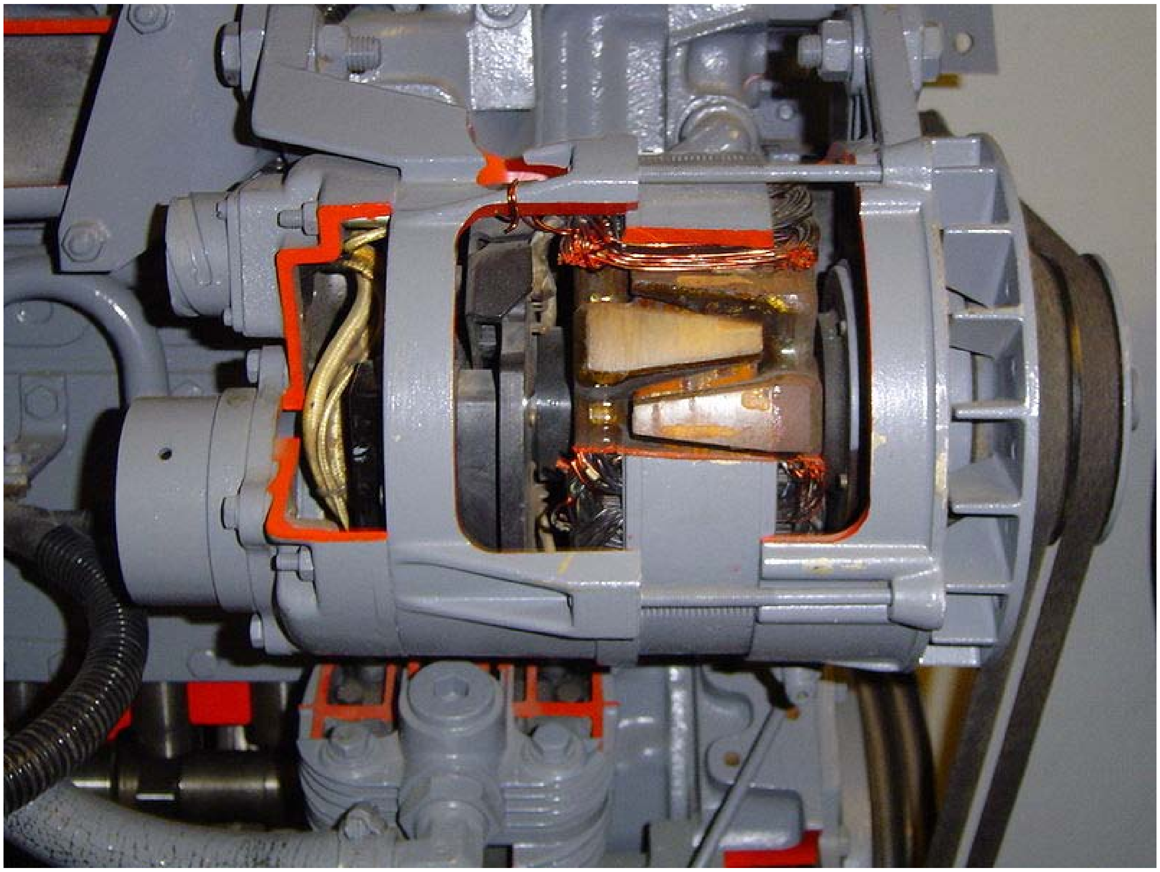
The output frequency of an alternator depends on the number of poles and the rotational speed. The speed corresponding to a particular frequency is called the *synchronous speed* for that frequency. This table gives some examples:

Poles	**RPM at 50 Hz**	**RPM at 60 Hz**
2	3,000	3,600
4	1,500	1,800
6	1,000	1,200
8	750	900
10	600	720
12	500	600
14	428.6	514.3
16	375	450
18	333.3	400
20	300	360

More generally, one cycle of alternating current is produced each time a pair of field poles passes over a point on the stationary winding. The relation between speed and frequency is $N = 120f / P$, where f is the frequency in Hz (cycles per second). P is the number of poles (2,4,6...) and N is the rotational speed in revolutions per minute (RPM). Very old descriptions of alternating current systems sometimes give the frequency in terms of alternations per minute, counting each half-cycle as one *alternation*; so 12,000 alternations per minute corresponds to 100 Hz.

Automotive alternators

Alternator mounted in the lower right front of an automobile engine with a serpentine belt pulley



Cut-away of an alternator, showing the claw-pole construction; two of the wedge-shaped field poles, alternating N and S, are visible in the centre and the stationary armature winding is visible at the top and bottom of the opening. The belt and pulley at the right hand end drives the alternator.

Alternators are used in modern automobiles to charge the battery and to power a car's electric system when its engine is running. Alternators have the great advantage over direct-current generators of not using a commutator, which makes them simpler, lighter, less costly, and more rugged than a DC generator, and the slip rings allow for greatly extended brush life. The stronger construction of automotive alternators allows them to use a smaller pulley so as to turn faster than the engine, improving output when the engine is idling. The availability of low-cost solid-state diodes from 1960 onward allowed car manufacturers to substitute alternators for DC generators (major American manufacturers had made the transition to alternators by 1962, for example). Automotive alternators use a set of rectifiers (diode bridge) to convert AC to DC. To provide direct current with low ripple, automotive alternators have a three-phase winding. In addition, the pole-pieces of the rotor are shaped (claw-pole) so as to produce a voltage waveform closer to a square wave that, when rectified by the diodes, produces even less ripple than the rectification of three-phase sinusoidal voltages.

Typical passenger vehicle and light truck alternators use Lundell or claw-pole field construction, where the field north and south poles are all energized by a single winding, with the poles looking rather like fingers of two hands interlocked with each other. Larger vehicles may have salient-pole alternators similar to larger machines. The automotive alternator is usually belt driven at 2-3 times the engine crankshaft speed. Automotive alternators are not restricted to a certain RPM because the alternating current is rectified to direct current and need not be any constant frequency.

Modern automotive alternators have a voltage regulator built into them. The voltage regulator operates by modulating the small field current in order to produce a constant voltage at the stator output. The field current is much smaller than the output current of the alternator; for example, a 70 A alternator may need only 2 A of field current. The field current is supplied to the rotor windings by slip rings and brushes. The low current and relatively smooth slip rings ensure greater reliability and longer life than that obtained by a DC generator with its commutator and higher current being passed through its brushes.

Efficiency of automotive alternators is limited by fan cooling loss, bearing loss, iron loss, copper loss, and the voltage drop in the diode bridges; at part load, efficiency is between 50-62% depending on the size of alternator, and varies with alternator speed. In comparison, very small high-performance permanent magnet alternators, such as those used for bicycle lighting systems, achieve an efficiency around 60%. Larger permanent magnet alternators can achieve much higher efficiency. By contrast, the large AC generators used in power stations run at carefully controlled speeds and have no constraints on size or weight. Consequently, they have much higher efficiencies, on the order of 98% from shaft to AC output power.

The field windings are initially supplied via the ignition switch and charge warning light, which is why the light is on when the ignition is on but the engine is not running. Once the engine is running and the alternator is generating, a diode feeds the field current from the alternator main output, thus equalizing the voltage across the warning light which goes off. The wire supplying the field current is often referred to as the "exciter" wire. The drawback of this arrangement is that if the warning light fails or the "exciter" wire is disconnected, no excitation current reaches the alternator field windings and so the alternator, due to low residual magnetism in the rotor, will not generate any power. However, some alternators will self-excite when the engine is revved to a certain speed. Also, some warning light circuits are equipped with a resistor in parallel with the warning light that will permit excitation current to flow even if the warning light fails. The driver should check that the warning light is on when the engine is stopped; otherwise, there might not be any indication of a failure of the alternator drive belt which normally also drives the cooling water pump.

Very large automotive alternators used on buses, heavy equipment or emergency vehicles may produce 300 amperes. Very old automobiles with minimal lighting and electronic devices may have only a 30 A alternator. Typical passenger car and light truck alternators are rated around 50-70 A, though higher ratings are becoming more common, especially as there is more load on the vehicle's electrical system with, for example, the introduction of air conditioning and electric power steering systems. Semi-trucks usually have alternators around 140 amperes. Very large automotive alternators may be water-cooled or oil-cooled.

Many alternator voltage regulators are today linked to the vehicle's onboard computer system and, in recent years, other factors including air temperature (obtained from the intake air temperature sensor or battery temperature sensor in many cases) and engine load are considered in adjusting the battery charging voltage supplied by the alternator.

Marine alternators

Marine alternators used in yachts are similar to automotive alternators, with appropriate adaptations to the salt-water environment. Marine alternators are designed to be explosion proof so that brush sparking will not ignite explosive gas mixtures in an engine room environment. They may be 12 or 24 volt depending on the type of system installed. Larger marine diesels may have two or more alternators to cope with the heavy electrical demand of a modern yacht. On single alternator circuits, the power is split between the engine starting battery and the domestic or house battery (or batteries) by use of a split-charge diode (battery isolator) or a mechanical switch. Because the alternator only produces power when running, engine control panels are typically fed directly from the alternator by means of an auxiliary terminal. Other typical connections are for charge control circuits.

Brushless alternators

A brushless alternator is composed of two alternators built end-to-end on one shaft. Smaller brushless alternators may look like one unit but the two parts are readily identifiable on the large versions. The larger of the two sections is the main alternator and the smaller one is the exciter. The exciter has stationary field coils and a rotating armature (power coils). The main alternator uses the opposite configuration with a rotating field and stationary armature. A bridge rectifier, called the rotating rectifier assembly, is mounted on a plate attached to the rotor. Neither brushes nor slip rings are used, which reduces the number of wearing parts. The main alternator has a rotating field as described above and a stationary armature (power generation windings).

Varying the amount of current through the stationary exciter field coils varies the 3-phase output from the exciter. This output is rectified by a rotating rectifier assembly, mounted on the rotor, and the resultant DC supplies the rotating field of the main alternator and hence alternator output. The result of all this is that a small DC exciter current indirectly controls the output of the main alternator.

Hybrid automobiles

Hybrid automobiles replace the separate alternator and starter motor with a combined motor/generator that performs both functions, cranking the internal combustion engine when starting, providing additional mechanical power for accelerating, and charging a large storage battery when the vehicle is running at constant speed. These rotating machines have considerably more powerful electronic devices for their control than the automotive alternator described above.

Radio alternators

High frequency alternators of the variable-reluctance type were applied commercially to radio transmission in the low-frequency radio bands. These were used for transmission of Morse code and, experimentally, for transmission of voice and music.

Chapter-10

Electrostatic Generator

A Van de Graaff generator, for class room demonstrations.

An **electrostatic generator**, or **electrostatic machine**, is a mechanical device that produces *static electricity*, or electricity at high voltage and low continuous current. The knowledge of static electricity dates back to the earliest civilizations, but for millennia it remained merely an interesting and mystifying phenomenon, without a theory to explain its behavior and often confused with magnetism. By the end of the 17th Century, researchers had developed practical means of generating electricity by friction, but the development of electrostatic machines did not begin in earnest until the 18th century, when they became fundamental instruments in the studies about the new science of electricity. Electrostatic generators operate by using manual (or other) power to transform mechanical work into electric energy. They develop electrostatic charges of opposite signs rendered to two conductors, using only electric forces. They work by using moving plates, drums, or belts to carry electric charge to a high potential electrode. The charge is generated by one of two methods: either the triboelectric effect (friction) or electrostatic induction.

Description

Electrostatic machines are typically used in science classrooms to safely demonstrate electrical forces and high voltage phenomena. The elevated potential differences achieved have been also used for a variety of practical applications, such as operating X-ray tubes, medical applications, sterilization of food, and nuclear physics experiments. Electrostatic generators such as the Van de Graaff generator, and variations as the Pelletron, also find use in physics research.

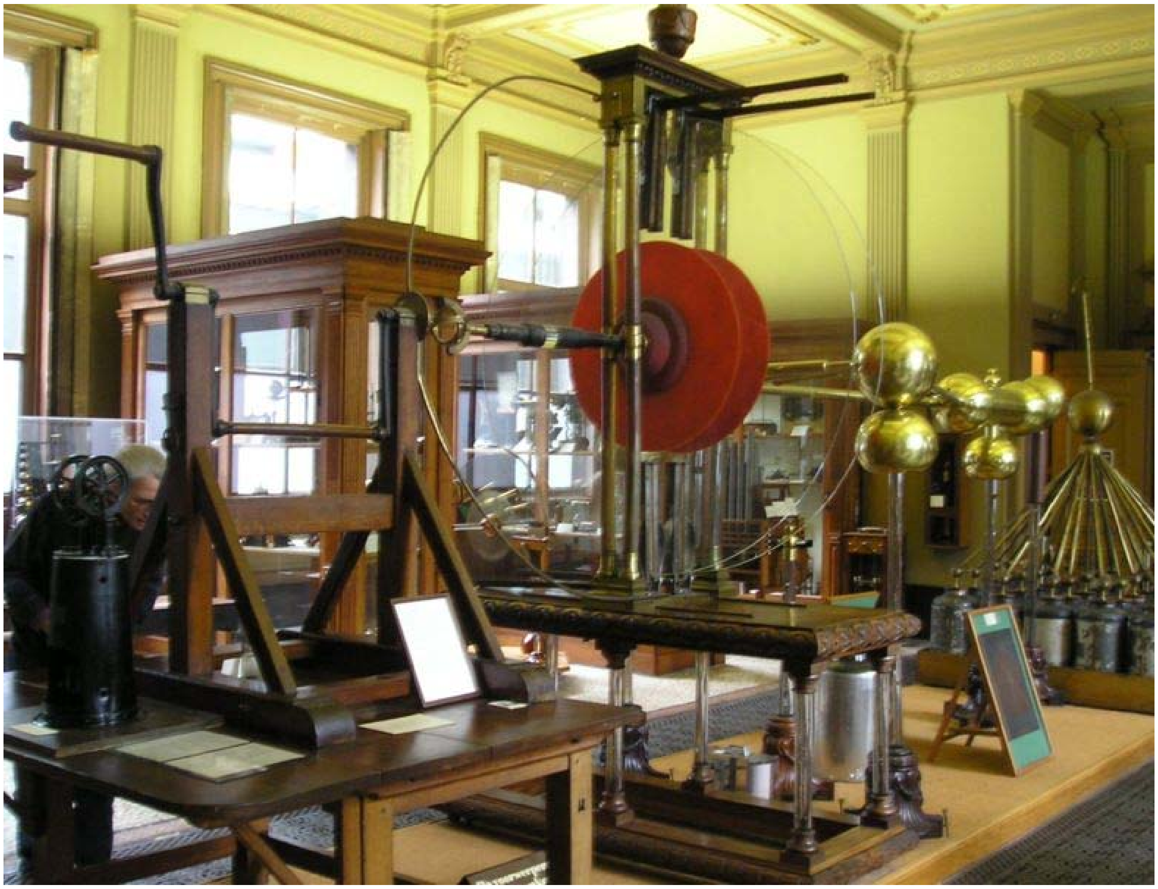
Electrostatic generators can be divided into two categories depending on how the charge is generated:

- Friction machines use the triboelectric effect (electricity generated by contact or friction)
- Influence machines use electrostatic induction

Friction machines

History

Typical friction machine using a glass globe, common in the 18th century



Martinus van Marum's Electrostatic generator at Teylers Museum

The first electrostatic generators are called *friction machines* because of the friction in the generation process. A primitive form of frictional electrical machine was invented around 1663 by Otto von Guericke, using a sulphur globe that could be rotated and rubbed by hand. It may not actually have been rotated during use, but inspired many later machines that used rotating globes. Isaac Newton suggested the use of a glass globe instead of a sulphur one.(Optics, 8th Query) Francis Hauksbee improved the basic design.

Generators were further advanced when G. M. Bose of Wittenberg added a collecting conductor (an insulated tube or cylinder supported on silk strings). In 1746, Watson's machine had a large wheel turning several glass globes with a sword and a gun barrel suspended from silk cords for its prime conductors. J. H. Winkler, professor of physics at Leipzig, substituted a leather cushion for the hand. Andreas Gordon of Erfurt, a Scottish Benedictine monk, used a glass cylinder in place of a sphere. Jesse Ramsden, in 1768, constructed a widely used version of a plate electrical generator. By 1784, the van Marum machine could produce voltage with either polarity. Martin van Marum constructed a large electrostatic machine of high quality for his experiments (currently on display at the Teylers Museum in the Netherlands).

The electric machine was subsequently improved by Francis Hauksbee, Litzendorf, and by Prof. Georg Matthias Bose, about 1750. Litzendorf substituted a glass ball for the sulphur ball of Guericke. Boze was the first to employ the "prime conductor" in such machines, this consisting of an iron rod held in the hand of a person whose body was insulated by standing on a block of resin. Ingenhousz, during 1746, invented electric machines made of plate glass. Experiments with the electric machine were largely aided by the discovery of the property of a glass plate, when coated on both sides with tinfoil, of accumulating a charge of electricity when connected with a source of electromotive force. The electric machine was soon further improved by Andrew Gordon, a Scotsman, Professor at Erfurt, who substituted a glass cylinder in place of a glass globe; and by Giessing of Leipzig who added a "rubber" consisting of a cushion of woollen material. The collector, consisting of a series of metal points, was added to the machine by Benjamin Wilson about 1746, and in 1762, John Canton of England (also the inventor of the first pith-ball electroscope) improved the efficiency of electric machines by sprinkling an amalgam of tin over the surface of the rubber.

In 1785, N. Rouland constructed a silk belted machine which rubbed two grounded hare fur covered tubes. Edward Nairne developed an electrostatic generator for medical purposes in 1787 which had the ability to generate either positive or negative electricity, the first named being collected from the prime conductor carrying the collecting points and the second from another prime conductor carrying the friction pad. The Winter machine possessed higher efficiency than earlier friction machines. In the 1830s, Georg Ohm possessed a machine similar to the van Marum machine for his research (which is now at the Deutsches Museum, Munich, Germany). In 1840, the Woodward machine was developed from improving the Ramsden machine (placing the prime conductor above the disk(s)). Also in 1840, the Armstrong hydroelectric machine was developed and used steam as a charge carrier.

Friction operation

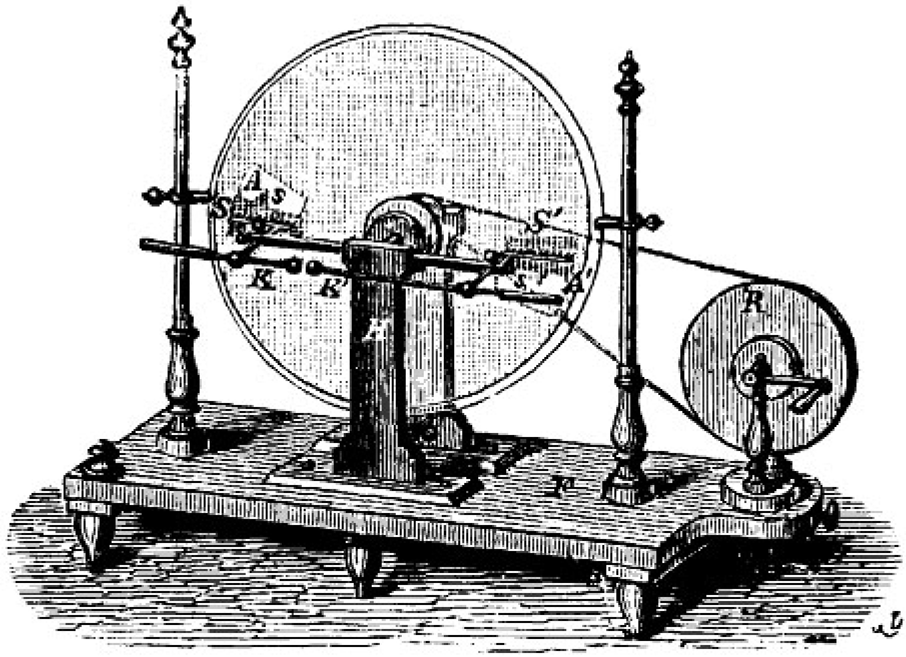
The presence of surface charge imbalance means that the objects will exhibit attractive or repulsive forces. This surface charge imbalance, which leads to static electricity, can be generated by touching two differing surfaces together and then separating them due to the phenomena of contact electrification and the triboelectric effect. Rubbing two non-conductive objects generates a great amount of static electricity. This is not just the result of friction; two non-conductive surfaces can become charged by just being placed one on top of the other. Since most surfaces have a rough texture, it takes longer to achieve charging through contact than through rubbing. Rubbing objects together increases amount of adhesive contact between the two surfaces. Usually insulators, e.g., substances that do not conduct electricity, are good at both generating, and holding, a surface charge. Some examples of these substances are rubber, plastic, glass, and pith. Conductive objects in contact generate charge imbalance too, but retain the charges only if insulated. The charge that is transferred during contact electrification is stored on the surface of each object. Note that the presence of electric current does not detract from the electrostatic forces nor from the sparking, from the corona discharge, or other phenomena. Both phenomena can exist simultaneously in the same system.

Influence machines

History

Frictional machines were, in time, gradually superseded by the second class of instrument mentioned above, namely, *influence machines*. These operate by electrostatic induction and convert mechanical work into electrostatic energy by the aid of a small initial charge which is continually being replenished and reinforced. The first suggestion of an influence machine appears to have grown out of the invention of Volta's *electrophorus*. The electrophorus is a single-plate capacitor used to produce imbalances of electric charge via the process of electrostatic induction. The next step was when Abraham Bennet, the inventor of the gold leaf electroscope, described a "*doubler of electricity*" (Phil. Trans., 1787), as a device similar to the electrophorus, but that could amplify a small charge by means of repeated manual operations with three insulated plates, in order to make it observable in an electroscope. Erasmus Darwin, W. Wilson, G. C. Bohnenberger, and (later, 1841) J. C. E. Péclet developed various modifications of Bennet's device. In 1788, William Nicholson proposed his rotating doubler, which can be considered as the first rotating influence machine. His instrument was described as "an instrument which by turning a winch produces the two states of electricity without friction or communication with the earth". (Phil. Trans., 1788, p. 403) Nicholson later described a "spinning condenser" apparatus, as a better instrument for measurements.

Others, including T. Cavallo (who developed the "Cavallo multiplier", a charge multiplier using simple addition, in 1795), John Read, Charles Bernard Desormes, and Jean Nicolas Pierre Hachette, developed further various forms of rotating doublers. In 1798, The German scientist and preacher Gottlieb Christoph Bohnenberger, described the Bohnenberger machine, along with several other doublers of Bennet and Nicholson types in a book. The most interesting of these were described in the "Annalen der Physik" (1801). Giuseppe Belli, in 1831, developed a simple symmetrical doubler which consisted of two curved metal plates between which revolved a pair of plates carried on an insulating stem. It was the first symmetrical influence machine, with identical structures for both terminals. This apparatus was reinvented several times, by C. F. Varley, that patented a high power version in 1860, by Lord Kelvin (the "replenisher") 1868, and by A. D. Moore (the "dirod"), more recently. Lord Kelvin also devised a combined influence machine and electromagnetic machine, commonly called a mouse mill, for electrifying the ink in connection with his siphon recorder, and a water-drop electrostatic generator (1867), which he called the "*water-dropping condenser*".



Holtz's influence machine.

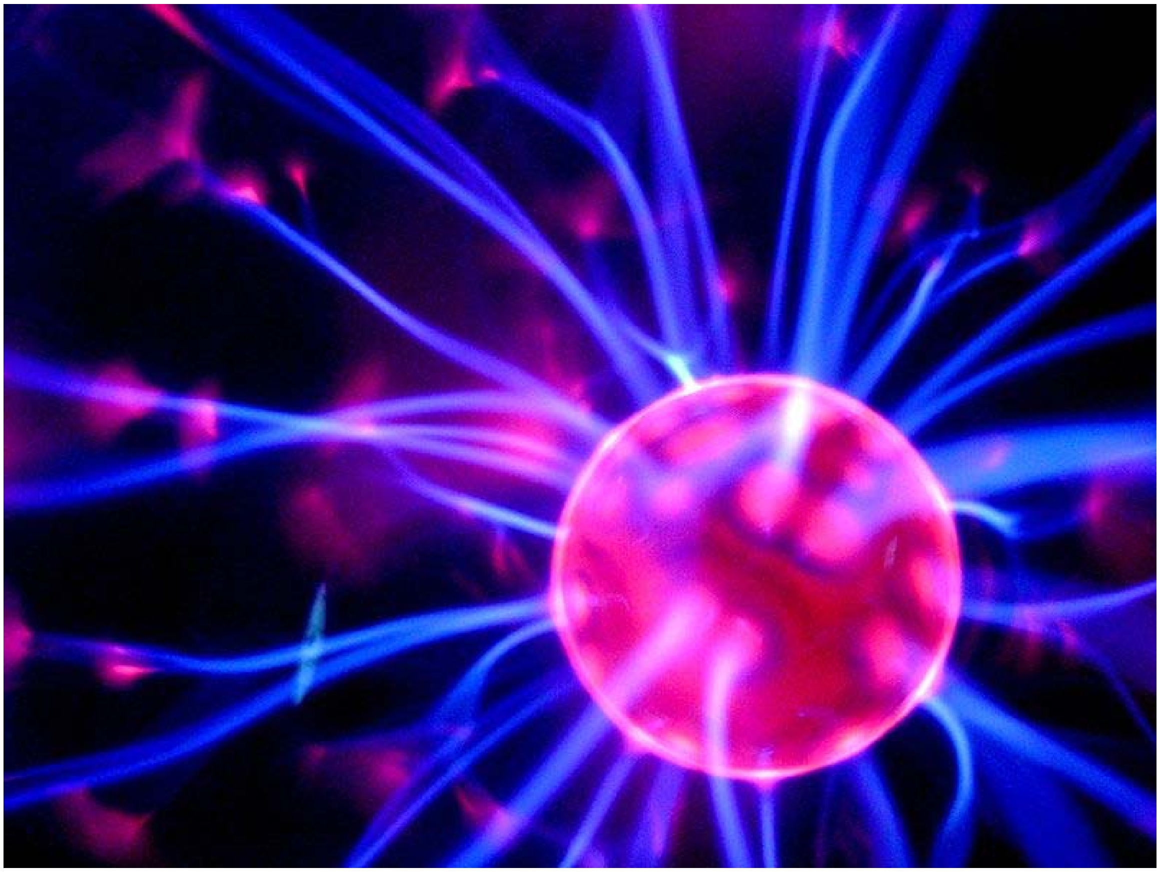
Between 1864 and 1880, W. T. B. Holtz constructed and described a large number of influence machines which were considered the most advanced developments of the time. In one form, the Holtz machine consisted of a glass disk mounted on a horizontal axis which could be made to rotate at a considerable speed by a multiplying gear, interacting with induction plates mounted in a fixed disk close to it. In 1865, August J. I. Toepler developed an influence machine that consisted of two disks fixed on the same shaft and rotating in the same direction. In 1868, the Schwedoff machine had a curious structure to increase the output current. Also in 1868, several mixed friction-influence machine were developed, including the Kundt machine and the Carré machine. In 1866, the Piche machine (or Bertsch machine) was developed. In 1869, H. Julius Smith received the American patent for a portable and airtight device that was designed to ignite powder. Also in 1869, sectorless machines in Germany were investigated by Poggendorff.

The action and efficiency of influence machines were further investigated by F. Rossetti, A. Righi, and F. W. G. Kohlrausch. E. E. N. Mascart, A. Roiti, and E. Bouchotte also examined the efficiency and current producing power of influence machines. In 1871, sectorless machines were investigated by Musaeus. In 1872, Righi's electrometer was developed and was one of the first antecedents of the Van de Graaff generator. In 1873, Leyser developed the Leyser machine, a variation of the Holtz machine. In 1880, Robert Voss (a Berlin instrument maker) devised a form of machine in which he claimed that the principles of Toepler and Holtz were combined. The same structure become also known as the *Toepler-Holtz* machine. In 1878, the British inventor James Wimshurst started his studies about electrostatic generators, improving the Holtz machine, in a powerful version with multiple disks. The classical *Wimshurst machine*, that become the most popular form of influence machine, was reported to the scientific community by 1883, although previous machines with very similar structures were previously described by Holtz and Musaeus. In 1885, one of the largest-ever Wimshurst machines was built in England (it is now at the Chicago Museum of Science and Industry). In 1887, Weinhold modified the Leyser machine with a system of vertical metal bar inductors with wooden cylinders close to the disk for avoiding polarity reversals. M. L. Lebiez described the Lebiez machine, that was essentially a simplified Voss machine (*L'Électricien*, April 1895, pp. 225–227). In 1894, Bonetti designed a machine with the structure of the Wimshurst machine, but without metal sectors in the disks. This machine is significantly more powerful than the sectored version, but it must usually be started with an externally-applied charge.

In 1898, the Pidgeon machine was developed with a unique setup by W. R. Pidgeon. On October 28 of that year, Pidgeon presented this machine to the Physical Society after several years of investigation into influence machines (beginning at the start of the decade). The device was later reported in the *Philosophical Magazine* (Dec. 1898, pg. 564) and the *Electrical Review* (Vol. XLV, pg. 748). A Pidgeon machine possesses fixed inductors arranged in a manner that increases the electrical induction effect (and its electrical output is at least double that of typical machines of this type [except when it is overtaxed]). The essential features of the Pidgeon machine are, one, the combination of the rotating support and the fixed support for inducing charge, and, two, the improved insulation of all parts of the machine (but more especially of the generator's carriers). Pidgeon machines are a combination of a Wimshurst Machine and Voss Machine, with special features adapted to reduce the amount of charge leakage. Pidgeon machines excite themselves more readily than the best of these types of machines. In addition, Pidgeon investigated higher current "triplex" section machines (or "double machines with a single central disk") with enclosed sectors (and went on to receive British Patent 22517 (1899) for this type of machine).

Multiple disk machines and "triplex" electrostatic machines (generators with three disks) were also developed extensively around the turn of the century. In 1900, F. Tudsbury discovered that enclosing a generator in a metallic chamber containing compressed air, or better, carbon dioxide, the insulating properties of compressed gases enabled a greatly improved effect to be obtained owing to the increase in the breakdown voltage of the compressed gas, and reduction of the leakage across the plates and insulating supports. In 1903, Alfred Wehrsen patented an ebonite rotating disk possessing embedded sectors with button contacts at the disk surface. In 1907, Heinrich Wommelsdorf reported a variation of the Holtz machine using this disk and inductors embedded in celluloid plates (DE154175; "Wehrsen machine"). Wommelsdorf also developed several high-performance electrostatic generators, of which the best known were his "Condenser machines" (1920). These were single disk machines, using disks with embedded sectors that were accessed at the edges.

Modern electrostatic generators



An example of a common modern device using high voltage (a "plasma globe", that does not use static electricity)

Electrostatic generators had a fundamental role in the investigations about the structure of matter, starting at the end of the 19th century. By the 1920s, it was evident that machines able to produce greater voltage were needed. The *Van de Graaff generator* was developed, starting in 1929, at MIT. The first model was demonstrated in October 1929. The basic idea was to use an insulating belt to transport electric charge to the interior of an insulated hollow terminal, where it could be discharged regardless of the potential already present on the terminal, that does not produce any electric field in its interior. The idea was not new, but the implementation using an electronic power supply to charge the belt was a fundamental innovation that made the old machines obsolete. The first machine used a silk ribbon bought at a five and dime store as the charge transport belt. In 1931 a version able to produce 1,000,000 volts was described in a patent disclosure. Nikola Tesla wrote a Scientific American article, "*Possibilities of Electro-Static Generators*" in 1934 concerning the Van de Graaff generator (pp. 132–134 and 163-165). Tesla stated, "*I believe that when new types* [of Van de Graaff generators] *are developed and sufficiently improved a great future will be assured to them*". High-power machines were soon developed, working on pressurized containers to allow greater charge concentration on the surfaces without ionization. Variations of the Van de Graaff generator were also developed for Physics research, as the Pelletron, that uses a chain with alternating insulating and conducting links for charge transport. Simplified Van de Graaff generators are commonly seen in demonstrations about static electricity, due to its high-voltage capability, producing the curious effect of making the hair of people touching the terminal, standing over an insulating support, stand up.

Between 1945 and 1960, the French researcher Noël Felici developed a series of high-power electrostatic generators, based on electronic excitation and using cylinders rotating at high speed and hydrogen in pressurized containers.

Fringe science and devices

These generators have been used, sometimes inappropriately and with some controversy, to support various fringe science investigations. In 1911, George Samuel Piggott received a patent for a compact double machine enclosed within a pressurized box for his experiments concerning radiotelegraphy and "antigravity". Much later (in the 1960s), a machine known as "Testatika" was built by German engineer, Paul Suisse Bauman, and promoted by a Swiss community, the Methernithans. Testatika is an electromagnetic generator based on the 1898 Pidgeon electrostatic machine, said to produce "free energy" available directly from the environment.

Chapter-11

Gramme Machine

A Gramme machine or Gramme magneto.

A **Gramme machine**, **Gramme ring**, **Gramme magneto**, or **Gramme dynamo** is an electrical generator which produces direct current, named for its Belgian inventor, Zénobe Gramme, and was built as either a dynamo or a magneto. It was the first generator to produce power on a commercial scale for industry. Inspired by a machine invented by Antonio Pacinotti in 1860, Gramme was the developer of a new induced rotor in form of a wire-wrapped ring (**Gramme ring**) and demonstrated this apparatus to the Academy of Sciences in Paris in 1871.

Description

Gramme machine

The Gramme machine used a ring armature, i.e., a series of thirty armature coils, wound around a revolving ring of soft iron. The coils are connected in series, and the junction between each pair is connected to a commutator on which two brushes run. The permanent magnets magnetize the soft iron ring, producing a magnetic field which rotates around through the coils in order as the armature turns. This induces a voltage in two of the coils on opposite sides of the armature, which is picked off by the brushes.

Earlier electromagnetic machines passed a magnet near the poles of one or two electromagnets, creating brief spikes or pulses of DC resulting in a transient output of low average power, rather than a constant output of high average power.

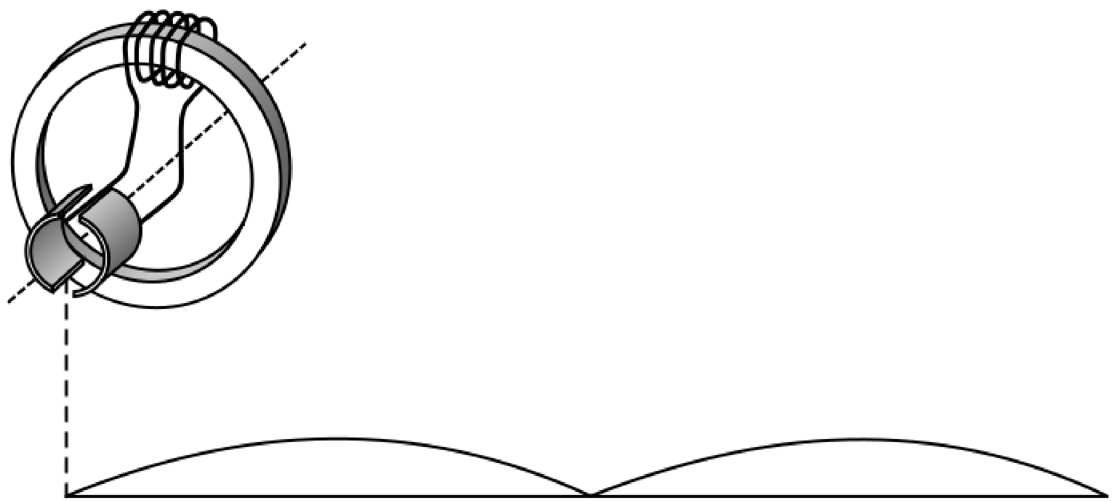
With enough coils, the resulting voltage waveform is practically constant, thus producing a near direct current supply. This type of machine needs only electromagnets producing the magnetic field to become a modern generator..

Invention of modern electric motor

During a demonstration at an industrial exposition in Vienna in 1873, Gramme accidentally discovered that this device, if supplied with a constant-voltage power supply, will act as an electric motor. Gramme's partner, Hippolyte Fontaine, carelessly connected the terminals of a Gramme machine to another dynamo which was producing electricity, and its shaft began to spin. The Gramme machine was the first powerful electric motor useful as more than a toy or laboratory curiosity. Today the design forms the basis of nearly all DC electric motors. Gramme's use of multiple commutator contacts with multiple overlapped coils, and his innovation of using a ring armature, was an improvement on earlier dynamos and helped usher in development of large-scale electrical devices.

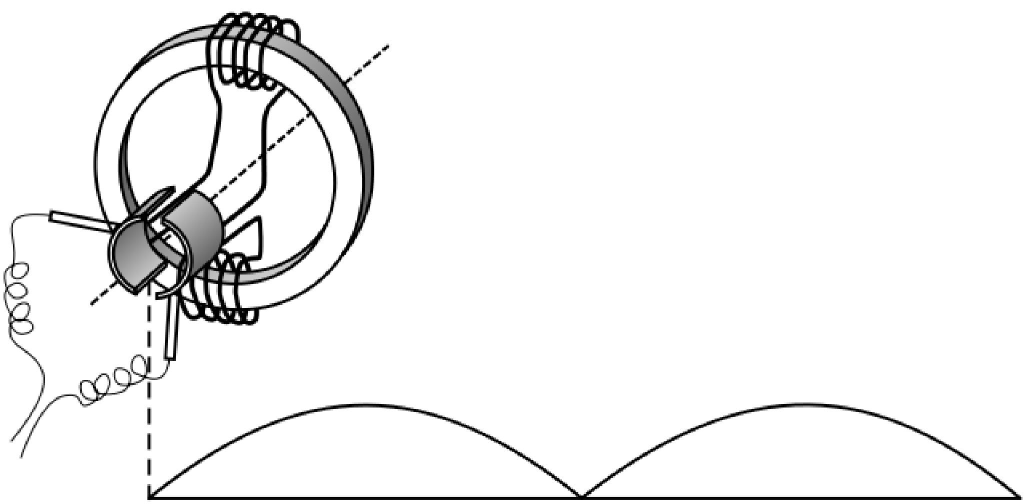
Earlier designs of electric motors were notoriously inefficient because they had large, or very large, air gaps throughout much of the rotation of their rotors. Long air gaps create weak forces, resulting in low torque. A device called the St. Louis motor (still available from scientific supply houses), although not intended to, clearly demonstrates this great inefficiency, and seriously misleads students as to how real motors work. These early inefficient designs apparently were based on observing how magnets attracted ferromagnetic materials (such as iron and steel) from some distance away. It took a number of decades in the 19th century for electrical engineers to learn the importance of small air gaps. The Gramme ring, however, has a comparatively small air gap, which enhances its efficiency. (In the illustration, the large hoop-like piece is probably the permanent magnet; the Gramme ring is rather hard to see.)

Principle of Operation



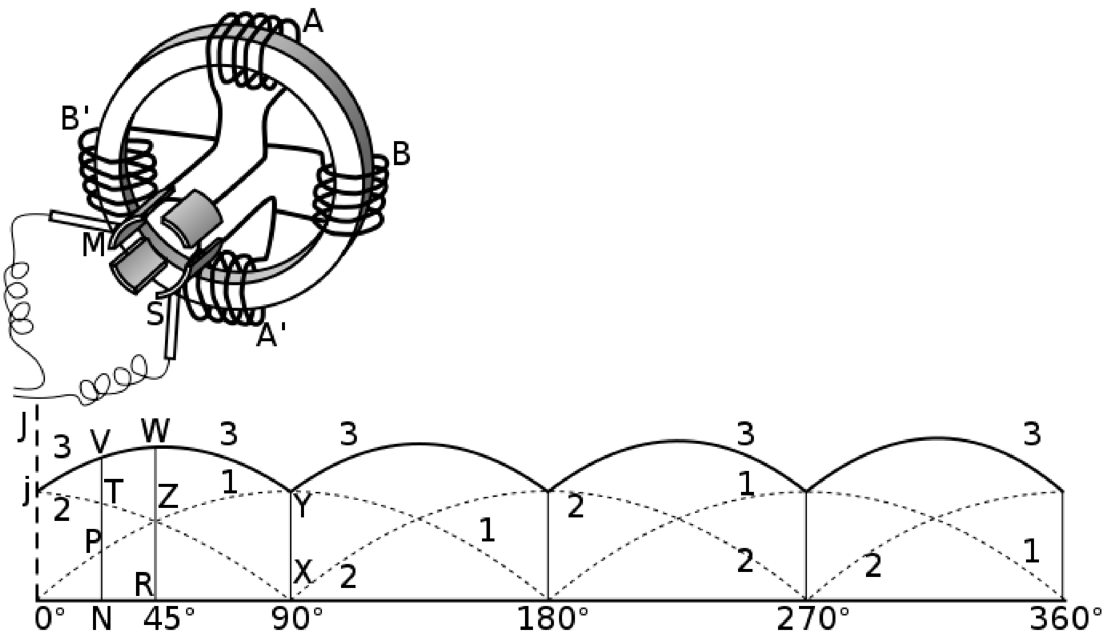
One-pole, one-coil Gramme ring.

This illustration shows a simplified one-pole, one-coil Gramme ring and a graph of the current produced as the ring spins one revolution. While no actual device uses this exact design, this diagram is a building block to better understand the next illustrations.



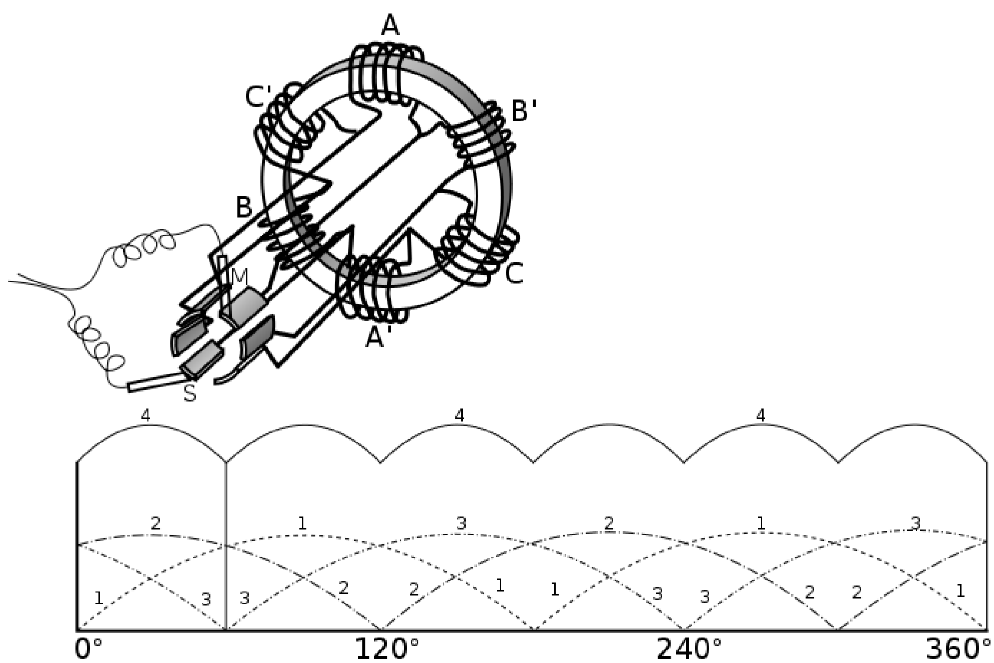
One-pole, two-coil Gramme ring.

A one-pole, two-coil Gramme ring. The second coil on the opposite side of the ring is wired in parallel with the first. Because the bottom coil is oriented opposite of the top coil, but both are immersed in the same magnetic field, the current forms a ring across the brush terminals.



Two-pole, four-coil Gramme ring.

A two-pole, four-coil Gramme ring. The coils of A and A' sum together, as do the coils of B and B', producing two pulses of power 90° out of phase with each other. When coils A and A' are at maximum output, coils B and B' are at zero output.



Three-pole, six-coil Gramme ring.

A three-pole, six-coil Gramme ring, and a graph of the combined three poles, each 120° out of phase from the other and summing together.

Modern Form of the Gramme Ring

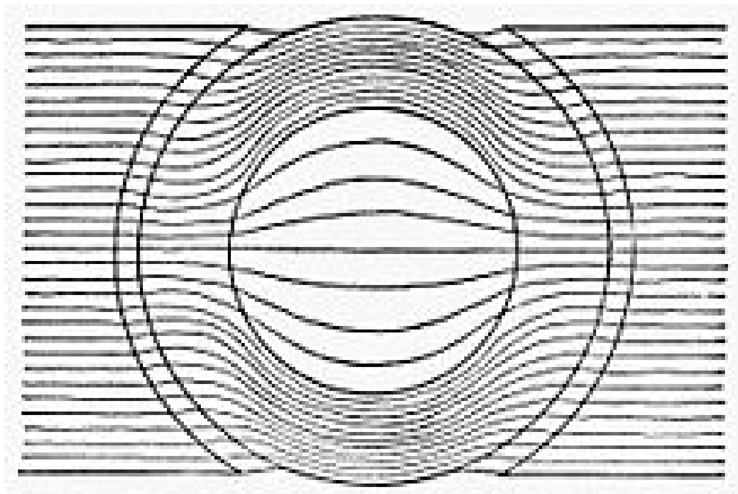
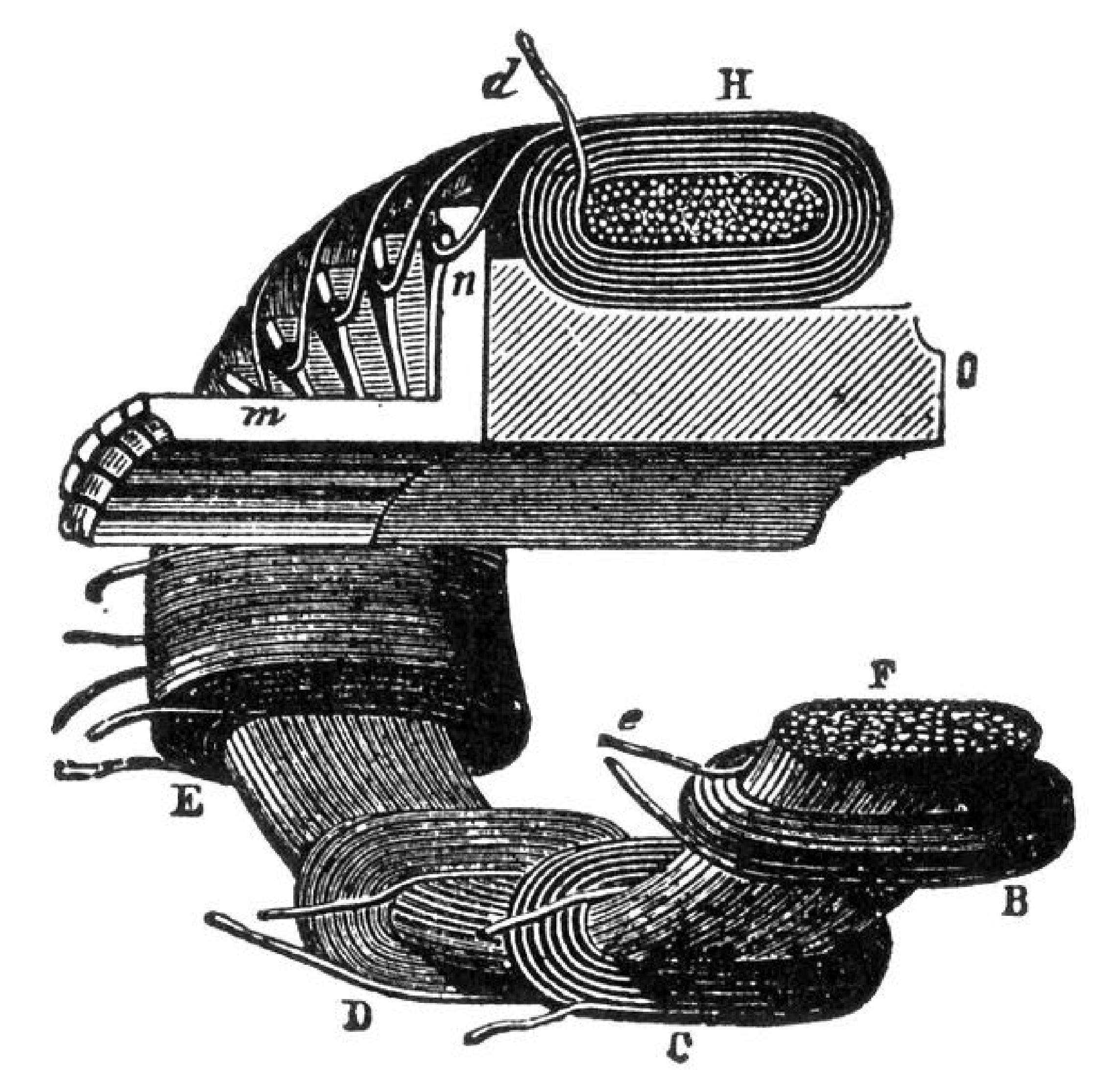


Diagram of magnetic lines through a Gramme ring, showing the very few magnetic lines of force crossing the center gap.

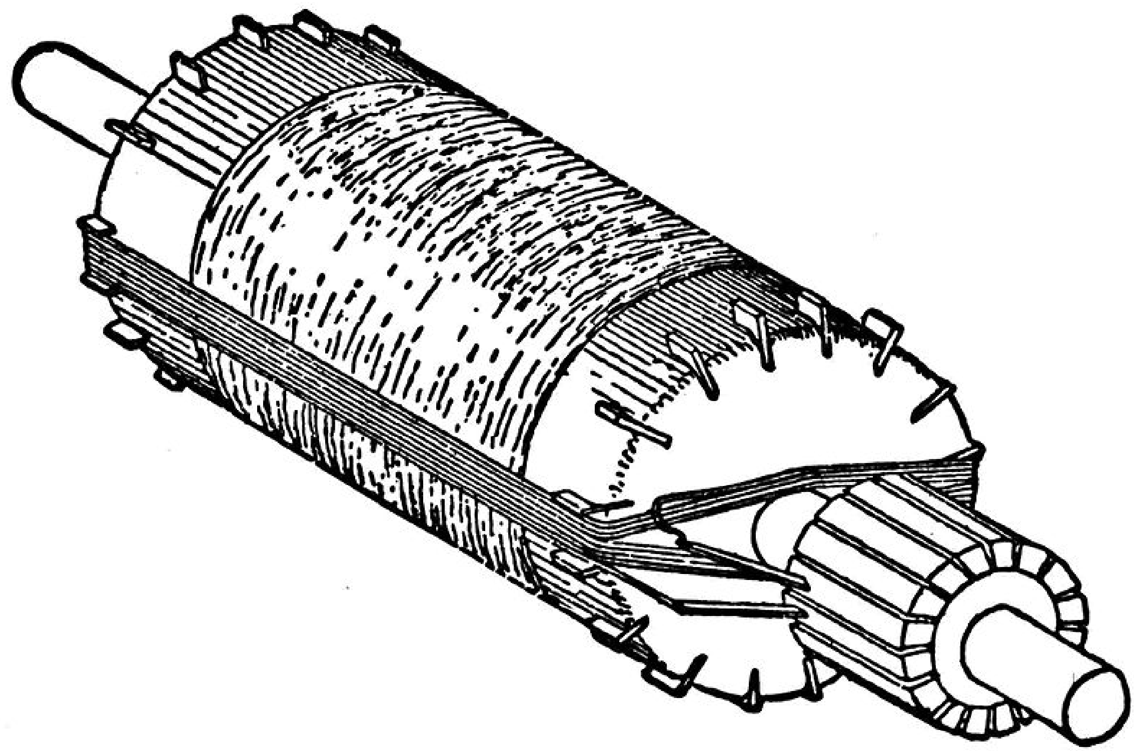
While the Gramme ring permitted a more steady power output, it suffered from a technical design inefficiency due to how magnetic lines of force pass through a ring armature. The field lines tend to concentrate within and follow the surface metal of the ring to the other side, with relatively few lines of force penetrating into the interior of the ring.



Early form of the Gramme ring armature with coils penetrating the interior of the ring.

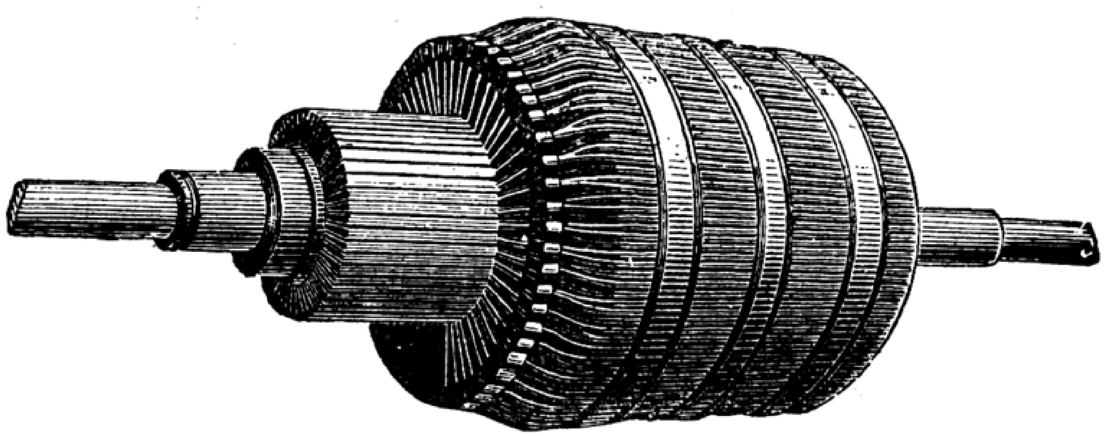
Consequently the interior windings of each small coil are minimally effective at producing power because they cut very few lines of force compared with the windings on the exterior of the ring. The interior windings are effectively *dead wire* and only add resistance to the circuit, lowering efficiency.

Initial attempts to insert a stationary field coil within the center of the ring to help the lines penetrate into the center proved too complex to engineer.



Example of a single winding around the exterior of a drum core with no wires penetrating the interior.

Eventually it was found to be more efficient to wrap a single loop of wire across the exterior of the ring and simply not have any part of the loop pass through the interior. This also reduces construction complexity since one large winding spanning the width of the ring is able to take the place of two smaller windings on opposite sides of the ring. All modern armatures use this externally-wrapped design, although the windings do not extend fully across the diameter; they are more akin to chords of a circle, in geometrical terms. Neighboring windings overlap, as can be seen in almost any modern motor or generator rotor that has a commutator. In addition, windings are placed into slots with a rounded shape (as seen from the end of the rotor). At the surface of the rotor, the slots are only as wide as needed to permit the insulated wire to pass through them while winding the coils.



Modern design of the Gramme ring, wrapped only around the exterior of the core.

While the hollow ring could now be replaced with a solid cylindrical core or *drum*, the ring still proves to be a more efficient design, because in a solid core the field lines concentrate in a thin surface region and minimally penetrate the center. For very a large power-generation armature several feet in diameter, using a hollow ring armature requires far less metal and is lighter than a solid core drum armature. The hollow center of the ring also provides a path for ventilation and cooling in high power applications.

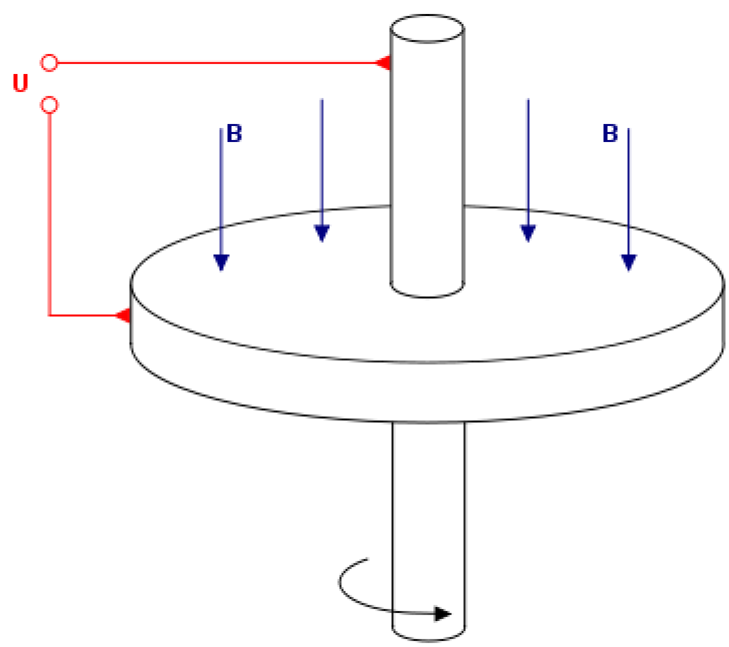
In small armatures a solid drum is often used simply for ease of construction, since the core can be easily formed from a stack of stamped metal disks keyed to lock into a slot on the shaft.

Chapter-12

Homopolar Generator

A **homopolar generator** is a DC electrical generator comprising an electrically conductive disc rotating in a plane perpendicular to a uniform static magnetic field. A potential difference is created between the center of the disc and the rim, the electrical polarity depending on the direction of rotation and the orientation of the field. It is also known as a **unipolar generator**, **acyclic generator**, **disk dynamo**, or **Faraday disc**. The voltage is typically low, on the order of a few volts in the case of small demonstration models, but large research generators can produce hundreds of volts, and some systems have multiple generators in series to produce an even larger voltage. They are unusual in that they can source tremendous electric current, some more than a million amperes, because the homopolar generator can be made to have very low internal resistance.

The Faraday disc



Faraday disc

The homopolar generator was developed first by Michael Faraday during his experiments in 1831. It is frequently called the **Faraday disc** in his honor. It was the beginning of modern dynamos — that is, electrical generators which operate using a magnetic field. It was very inefficient and was not used as a practical power source, but it showed the possibility of generating electric power using magnetism, and led the way for commutated direct current dynamos and then alternating current alternators.

The Faraday disc was primarily inefficient due to counterflows of current. While current flow 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 radially from axis to edge, and eliminate areas where counterflow could occur.

Homopolar generator development

The remains of the ANU 500 MJ generator

Long after the original Faraday disc had been abandoned as a practical generator, a modified version combining the magnet and disc in a single rotating part (the *rotor*) was developed. Sometimes the name *homopolar generator* is reserved for this configuration.

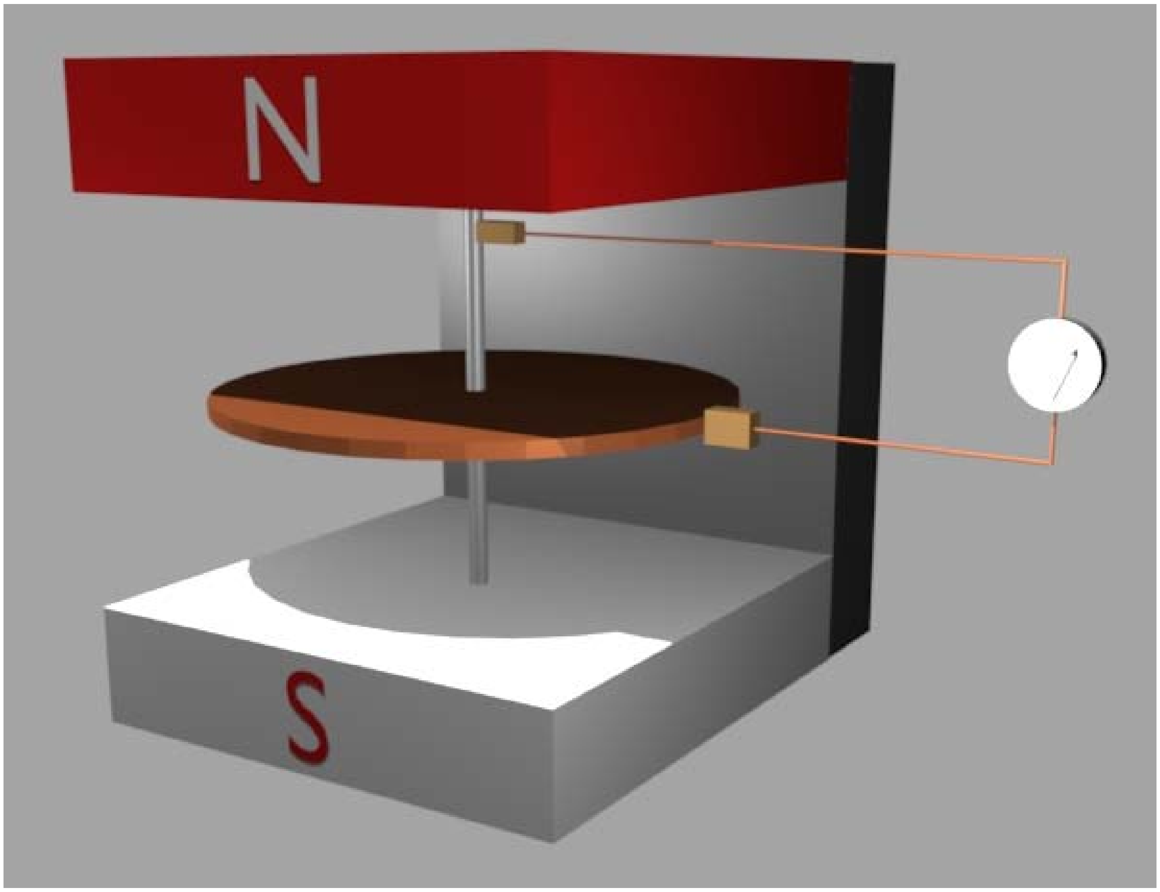
One of the earliest patents on the general type of homopolar generators was attained by A. F. Delafield, U.S. Patent 278,516. Other early patents for homopolar generators were awarded to S. Z. De Ferranti and C. Batchelor separately. Nikola Tesla was interested in the Faraday disc and conducted work with homopolar generators. He eventually patented an improved version of the device and his US patent ("Dynamo Electric Machine") describes an arrangement of two parallel discs with separate, parallel shafts, joined like pulleys by a metallic belt. Each disc had a field that was the opposite of the other, so that the flow of current was from the one shaft to the disc edge, across the belt to the other disc edge and to the second shaft. This would have greatly reduced the frictional losses caused by sliding contacts by allowing both electrical pickups to interface with the shafts of the two disks rather than at the shaft and a high-speed rim. Later, patents were awarded to C. P. Steinmetz and E. Thomson for their work with homopolar generators. The **Forbes dynamo**, developed by the Scottish electrical engineer George Forbes, was in widespread use during the beginning of the 20th century. Much of the development done in homopolar generators was patented by J. E. Noeggerath and R. Eickemeyer.

Homopolar generators underwent a renaissance in the 1950s as a source of pulsed power storage. These devices used heavy disks as a form of flywheel to store mechanical energy that could be quickly dumped into an experimental apparatus. An early example of this sort of device was built by Sir Mark Oliphant at the Research School of Physical Sciences and Engineering, Australian National University. It stored up to 500 megajoules of energy and was used as an extremely high-current source for synchrotron experimentation from 1962 until it was disassembled in 1986. Oliphant's construction was capable of supplying currents of up to 2 megaamperes (MA).

Similar devices of even larger size are designed and built by Parker Kinetic Designs (formerly OIME Research & Development) of Austin. They have produced devices for a variety of roles, from powering railguns to linear motors (for space launches) to a variety of weapons designs. Industrial designs of 10 MJ were introduced for a variety of roles, including electrical welding.

Description and operation

Disk-type generator



Basic Faraday disc generator

This device consists of a conducting flywheel rotating in a magnetic field with one electrical contact near the axis and the other near the periphery. It has been used for generating very high currents at low voltages in applications such as welding, electrolysis and railgun research. In pulsed energy applications, the angular momentum of the rotor is used to store energy over a long period and then release it in a short time.

In contrast to other types of generators, the output voltage never changes polarity. The charge separation results from the Lorentz force on the free charges in the disk. The motion is azimuthal and the field is axial, so the electromotive force is radial. The electrical contacts are usually made through a "brush" or slip ring, which results in large losses at the low voltages generated. Some of these losses can be reduced by using mercury or other easily liquified metal or alloy (gallium, NaK) as the "brush", to provide essentially uninterrupted electrical contact.

If the magnetic field is provided by a permanent magnet, the generator works regardless of whether the magnet is fixed to the stator or rotates with the disc. Before the discovery of the electron and the Lorentz force law, the phenomenon was inexplicable and was known as the Faraday paradox.

Drum-type generator

A drum-type HPG has a magnetic field (B) that radiates radially from the center of the drum and induces voltage (V) down the length of the drum. A conducting drum spun from above in the field of a "speaker" type of magnet that has one pole in the center of the drum and the other pole surrounding the drum could use conducting ball bearings at the top and bottom of the drum to pick up the generated current.

Astrophysical unipolar inductors

Unipolar inductors occur in astrophysics where a conductor rotates through a magnetic field, for example, the movement of the highly conductive plasma in a cosmic body's ionosphere through its magnetic field. In their book, *Cosmical Electrodynamics*, Hannes Alfvén and Carl-Gunne Fälthammar write:

"Since cosmical clouds of ionized gas are generally magnetized, their motion produces induced electric fields [..] For example the motion of the magnetized interplanetary plasma produces electric fields that are essential for the production of aurora and magnetic storms" [..]
".. the rotation of a conductor in a magnetic field produces an electric field in the system at rest. This phenomenon is well known from laboratory experiments and is usually called 'homopolar ' or 'unipolar' induction.

Unipolar inductors have been associated with the aurorae on Uranus, binary stars, black holes, galaxies, the Jupiter Io system, the Moon, the Solar Wind, sunspots, and in the Venusian magnetic tail.

Physics

Like all dynamos, the Faraday disc converts kinetic energy to electrical energy. This machine can be analysed using Faraday's own law of electromagnetic induction. This law (in its modern form) states that an electric current is induced in a closed electrical circuit when the magnetic flux enclosed by the circuit changes (in either magnitude or direction). For the Faraday disk it is necessary, however, to consider that the circuit(s) consist of each radial "spoke" of the disk connected to the rim and center and then through the external circuit.

The Lorentz force law is more easily used to explain the machine's behaviour. This law, discovered thirty years after Faraday's death, states that the force on an electron is proportional to the cross product of its velocity and the magnetic flux vector. In geometrical terms, this means that the force is at right-angles to both the velocity (azimuthal) and the magnetic flux (axial), which is therefore in a radial direction. The radial movement of the electrons in the disc produces a charge separation between the center of the disc and its rim, and if the circuit is completed an electric current will be produced.

Chapter-13

Induction Generator

An **induction generator** or **asynchronous generator** is a type of AC electrical generator that uses the principles of induction motors to produce power. Induction generators operate by mechanically turning their rotor in generator mode, giving negative slip. In most cases, a regular AC asynchronous motor is used as a generator, without any internal modifications.

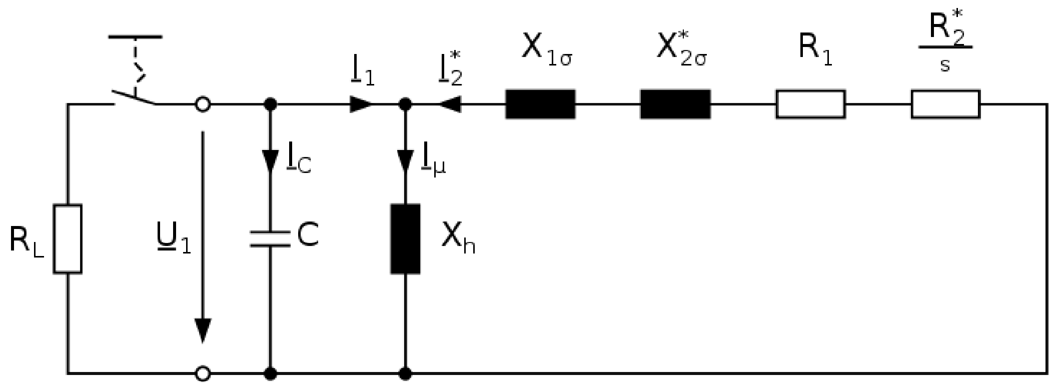
Principle of operation

Induction generators and motors produce electrical power when their shaft is rotated faster than the *synchronous frequency*. For a typical four-pole motor (two pairs of poles on stator) operating on a 60 Hz electrical grid, synchronous speed is 1800 rotations per minute. Similar four-pole motor operating on a 50 Hz grid will have synchronous speed equal to 1500 rpm.

In normal motor operation, stator flux rotation is faster than the rotor rotation. This is causing stator flux to induce rotor currents, which create rotor flux with magnetic polarity opposite to stator. In this way, rotor is dragged along behind stator flux, by value equal to slip.

In generator operation, certain prime mover (turbine, engine) is driving the rotor above the synchronous speed. Stator flux still induces currents in the rotor, but since the opposing rotor flux is now cutting the stator coils, active current is produced in stator coils, and motor is now operating as a generator, and sending power back to the electrical grid.

Excitation



Equivalent circuit of induction generator

Note that a source of excitation current for magnetizing flux (reactive power) for stator is still required, to induce rotor current.

Induction generators are not, in general, self-exciting, meaning they require an electrical supply, at least initially, to produce the rotating magnetic flux (although in practice an induction generator will often self start due to residual magnetism.) The electrical supply can be supplied from the electrical grid or, once it starts producing power, from the generator itself. The rotating magnetic flux from the stator induces currents in the rotor, which also produces a magnetic field. If the rotor turns slower than the rate of the rotating flux, the machine acts like an induction motor. If the rotor is turned faster, it acts like a generator, producing power at the synchronous frequency.

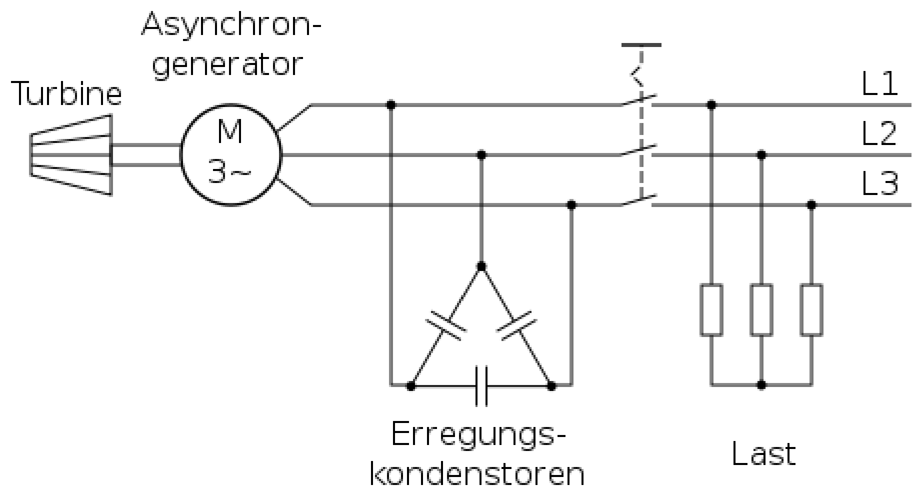
Active power

Active power delivered to the line is proportional to slip above the synchronous speed. Full rated power of the generator is reached at very small slip values (motor dependent, typically 3%). At synchronous speed of 1800 rpm, generator will produce no power. When the driving speed is increased to 1860 rpm, full output power is produced. If the prime mover is unable to produce enough power to fully drive the generator, speed will remain somewhere between 1800 and 1860 rpm range.

Required capacitance

Capacitor bank must supply reactive power to the motor when used in stand-alone mode. Reactive power supplied should be equal or greater than the reactive power that machine normally draws when operating as a motor. Terminal voltage will increase with capacitance, but is limited by iron saturation.

Grid and stand-alone connections



Typical connections when used as a standalone generator

In induction generators the magnetizing flux is established by a capacitor bank connected to the machine in case of stand alone system and in case of grid connection it draws magnetizing current from the grid.

For a grid connected system, frequency and voltage at the machine will be dictated by the electric grid, since it is very small compared to the whole system.

For stand-alone systems, frequency and voltage are complex function of machine parameters, capacitance used for excitation, and load value and type.

Use of induction generators

Induction generators are often used in wind turbines and some micro hydro installations due to their ability to produce useful power at varying rotor speeds. Induction generators are mechanically and electrically simpler than other generator types. They are also more rugged, requiring no brushes or commutators.

Induction generators are particularly suitable and usually used for wind generating stations as in this case speed is always a variable factor, and the generator is easy on the gearbox.

Example application

We must use 10 hp, 1760 r/min, 440 V, 3 phase induction motor as an asynchronous generator. Full-load current of the motor is 10 A and full-load power factor is 0.8.

Required capacitance per phase if capacitors are connected in delta:

Apparent power $S = \sqrt{3}\, E\, I = 1.73 * 440 * 10 = 7612$ VA
Active power $P = S \cos\theta = 7612 * 0.8 = 6090$ W
Reactive power $Q = \sqrt{S^2 - P^2} = 4567$ VAR

For machine to run as an asynchronous generator, capacitor bank must supply minimum 4567 / 3 phases = 1523 VAR per phase. Voltage per capacitor is 440 V because capacitors are connected in delta.

Capacitive current $I_c = Q/E = 1523/440 = 3.46$ A
Capacitive reactance per phase $X_c = E/I = 127\ \Omega$

Minimum capacitance per phase:

$C = 1 / (2*\pi*f*X_c) = 1 / (2 * 3.141 * 60 * 127) = 21$ microfarads.

If load also absorbs reactive power, capacitor bank must be increased in size to compensate.

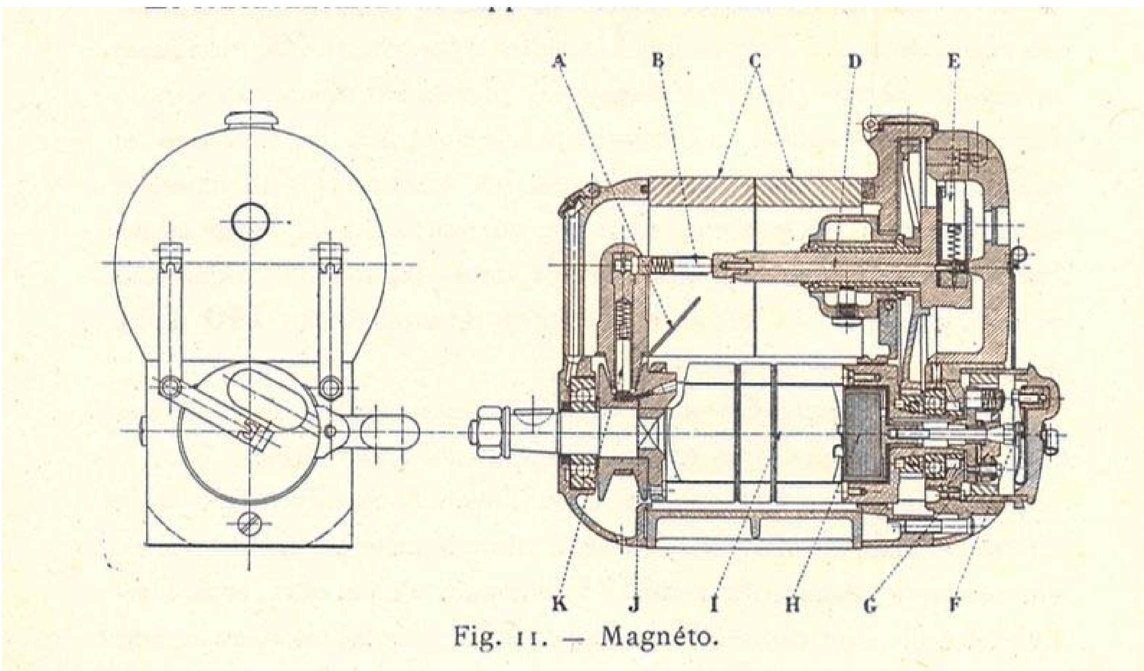
Prime mover speed should be used to generate frequency of 60 Hz:

Typically, slip should be similar to full-load value when machine is running as motor, but negative (generator operation):

Slip = 1800 - 1760 = 40 rpm
Required prime mover speed N = 1800 + Slip = 1840 rpm.

Chapter-14

Magneto



Renault 190HP magneto

A **magneto** is an electrical generator that uses permanent magnets to produce alternating current. Hand-cranked magneto generators were used to provide ringing current in early telephone systems. Magnetos adapted to produce pulses of high voltage are used in the ignition systems of some gasoline-powered internal combustion engines to provide power to the spark plugs. The magneto is now confined mainly to engines where there is no available electrical supply, for example in lawnmowers and chainsaws. It is also universally used in aviation piston engines even though an electrical supply is usually available. This is because a magneto ignition system is more reliable than a battery-coil system. People discussing magnetos and coils used in early internal-combustion engines generally used the term "tension" instead of the more modern term "voltage."

History

Production of electric current from a moving magnetic field was demonstrated by Faraday in 1831. The first machines to produce electric current from magnetism used permanent magnets; the dynamo machine, which used an electromagnet to produce the magnetic field, was developed later. The machine build by Hippolyte Pixii in 1832 used a rotating permanent magnet to induce alternating voltage in two fixed coils.

The first person to develop the idea of a high-tension magneto was Andre Boudeville, but his design omitted a condenser (capacitor); Frederick Richard Simms in partnership with Robert Bosch were the first to develop a practical high-tension magneto.

Magneto ignition was introduced on the 1899 Daimler Phönix. This was followed by Benz, Mors, Turcat-Mery, and Nesseldorf, and soon was used on most cars up until about 1918 in both low voltage (voltage for secondary coils to fire the spark plugs) and high voltage magnetos (to fire the spark plug directly, similar to coil ignitions, introduced by Bosch in 1903).

The magneto also had a medical use for treatment of mental illness in the beginnings of electromedicine. In 1850, Duchenne, a French doctor, developed and manufactured a magneto with a variable outer voltage and frequency, through varying revolutions by hand or varying the inductance of the two coils, putting out or putting in both ferromagnetic cores.

One popular and common use of magnetos of today is for powering lights on bicycles. A small magneto is mounted on the wheel of the bicycle and generates power as the wheel turns.

Operation

In the type known as a *shuttle magneto*, the engine rotates a coil of wire between the poles of a magnet. In the *inductor magneto*, the magnet is rotated and the coil remains stationary.

On each revolution, a cam opens the contact breaker one or more times, interrupting the current, which causes the electromagnetic field in the primary coil to collapse. As the field collapses there is a voltage induced (as described by Faraday's Law) across the primary coil. As the points open, point spacing is such that the voltage across the primary coil would arc across the points. A capacitor is placed across the points which absorbs the energy stored in the primary coil. The capacitor and the coil together form a resonant circuit which allows the energy to oscillate from the capacitor to the coil and back again. Due to the inevitable losses in the system, this oscillation decays fairly rapidly.

A second coil, with many more turns than the primary, is wound on the same iron core to form an electrical transformer. The ratio of turns in the secondary winding to the number of turns in the primary winding, is called the *turns ratio*. Voltage across the primary coil results in a proportional voltage being induced across the secondary winding of the coil. The turns ratio between the primary and secondary coil is selected so that the voltage across the secondary reaches a very high value, enough to arc across the gap of the spark plug.

In a modern installation, the magneto only has a single low tension winding which is connected to an external ignition coil which not only has a low tension winding, but also a secondary winding of many thousands of turns to deliver the high voltage required for the spark plug(s). Such a system is known as an "energy transfer" ignition system. Initially this was done because it was easier to provide good insulation for the secondary winding of an external coil than it was in a coil buried in the construction of the magneto (early magnetos had the coil assembly externally to the rotating parts to make them easier to insulate - at the expense of efficiency). In more modern times, insulation materials have improved to the point where constructing self contained magnetos is relatively easy, but energy transfer systems are still used where the ultimate in reliability is required such as in aviation engines.

Aviation

Because it requires no battery or other source of energy, the magneto is a compact and reliable self-contained ignition system, which is why it remains in use in many general aviation applications.

Magneto-equipped aircraft engines are typically *dual-plugged*; each cylinder has two spark plugs, with each plug having a separate magneto system. This practice began at the beginning of World War I in 1914. Dual plugs provide better engine performance and also redundancy if a magneto fails. Two sparks provide two flame fronts within the cylinder. The two flame fronts decrease the time needed for the fuel charge to burn, and therefore burn most of the fuel at a lower temperature and pressure. As the pressure within a cylinder increases, the temperature rises and the fuel mixture far from the original flame front can ignite by itself, producing an unsynchronized flame front elsewhere in the cylinder. This leads to a rapid rise in cylinder pressure that produces engine knock. Higher octane fuel increases the time required for autoignition at a given temperature and pressure, reducing knock, but by burning the fuel charge faster, two flame fronts can decrease an engine's octane requirement. As the size of the combustion chamber determines the time to burn the fuel charge, this was especially important for the large bore size of most aircraft engines around World War II.

Automobile

Some aviation engines as well as some older luxury cars have had dual-plugged systems with one set of plugs fired by a magneto, and the other set wired to a coil, dynamo, and battery circuit. This was done to improve engine efficiency without sacrificing reliability. Magnetos were once considered a more reliable ignition source, but have the disadvantage of having fixed timing. This means that the timing must be a compromise setting, which is neither the best for low RPM nor the best for high RPM. On the other hand, battery ignition systems have almost always had a timing advance system which can set the timing to the best setting for the speed the engine is turning, improving power output and fuel efficiency. As the reliability of battery ignition systems improved, the magneto fell out of favor for general automotive use, but may still be found in sport or racing engines.

Telephone

1896 Telephone, hand crank for magneto on right (Sweden)

Many early manual telephones had a hand cranked "magneto" generator to produce a (relatively) high voltage alternating signal to ring the bells of other telephones on the same (party) line and to alert the operator. These were usually on long rural lines served by small manual exchanges, which were not "common battery". The telephone instrument was "local battery", containing two large "No. 6" carbon-zinc dry cells.

Chapter-15

Radioisotope Thermoelectric Generator

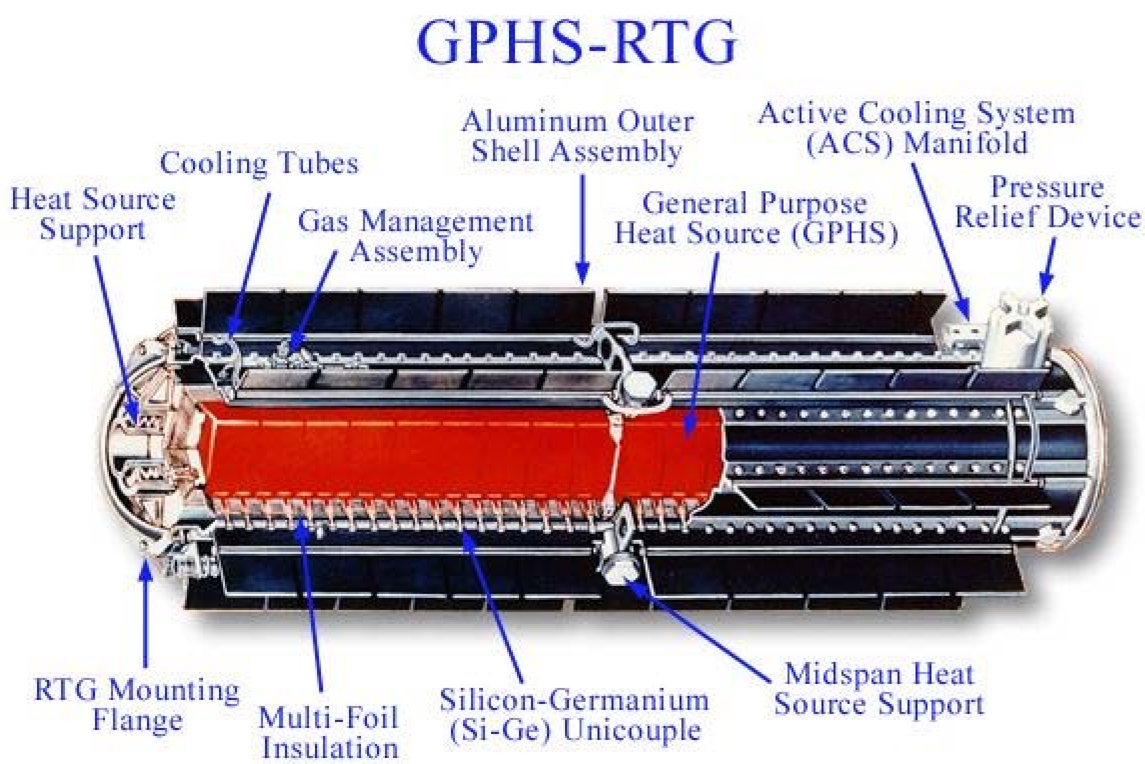


Diagram of an RTG used on the Cassini probe

A **radioisotope thermoelectric generator** (**RTG**, **RITEG**) is a nuclear reactor technology electrical generator that obtains its power from radioactive decay. In such a device, the heat released by the decay of a suitable radioactive material is converted into electricity by the Seebeck effect using an array of thermocouples.

RTGs can be considered as a type of battery and have been used as power sources in satellites, space probes and unmanned remote facilities, such as a series of lighthouses built by the former Soviet Union inside the Arctic Circle. RTGs are usually the most desirable power source for robotic or unmaintained situations needing a few hundred watts or less of power for durations too long for fuel cells, batteries, or generators to provide economically, and in places where solar cells are not viable. Safe use of RTGs requires containment of the radioisotopes long after the productive life of the unit.

History

A pellet of $^{238}PuO_2$ to be used in an RTG for either the Cassini or Galileo mission. The initial output is 62 watts and the pellet glows because of the heat generated by the radioactive decay (primarily α). Photo is taken after insulating the pellet under a graphite blanket for minutes and removing the blanket.

The first RTG launched in space by the United States was SNAP 3 in 1961 aboard the Navy Transit 4A spacecraft. One of the first terrestrial uses of RTGs was in 1966 by the US Navy at the uninhabited Fairway Rock Island in Alaska, where it remained in use until its removal in 1995.

A common application of RTGs is as power sources on spacecraft. Systems for Nuclear Auxiliary Power (SNAP) units were used especially for probes that travel far enough from the Sun that solar panels are no longer viable. As such they are used with Pioneer 10, Pioneer 11, Voyager 1, Voyager 2, Galileo, Ulysses, Cassini and New Horizons. In addition, RTGs were used to power the two Viking landers and for the scientific experiments left on the Moon by the crews of Apollo 12 through 17 (SNAP 27s). Because Apollo 13 was aborted, its RTG now rests in the South Pacific ocean, in the vicinity of the Tonga Trench. RTGs were also used for the Nimbus, Transit and LES satellites. By comparison, only a few space vehicles have been launched using full-fledged nuclear reactors: the Soviet RORSAT series and the American SNAP-10A.

In addition to spacecraft, the Soviet Union constructed many unmanned lighthouses and navigation beacons powered by RTGs. Powered by Strontium 90 (^{90}Sr), they are very reliable and provide a steady source of power. Critics argue that they could cause environmental and security problems, as leakage or theft of the radioactive material could pass unnoticed for years (or possibly forever: some of these lighthouses cannot be found because of poor record keeping). In one instance, the radioactive compartments were opened by a thief. In another case, three woodcutters in Georgia came across one of the units and slept close to it as a heat source during a cold night. Two of the three were later hospitalized with severe radiation burns. The unit was eventually recovered and isolated.

There are approximately 1,000 such RTGs in Russia. All of them have long exhausted their 10-year engineered life spans. They are likely no longer functional, and may be in need of dismantling. Some of them have become the prey of metal hunters, who strip the RTGs' metal casings, regardless of the risk of radioactive contamination.

The United States Air Force uses RTGs to power remote sensing stations for *Top-ROCC* and *Save-Igloo* radar systems predominantly located in Alaska.

In the past, small "plutonium cells" (very small ^{238}Pu-powered RTGs) were used in implanted heart pacemakers to ensure a very long "battery life". As of 2004 about 90 were still in use. When the wearer dies and if the generator is not removed before cremation, the device will be subject to great heat. The plutonium dioxide is a stable solid which is normally sintered in air at a temperature much higher than that used in the cremation of human remains, and so is unlikely to be dispersed.

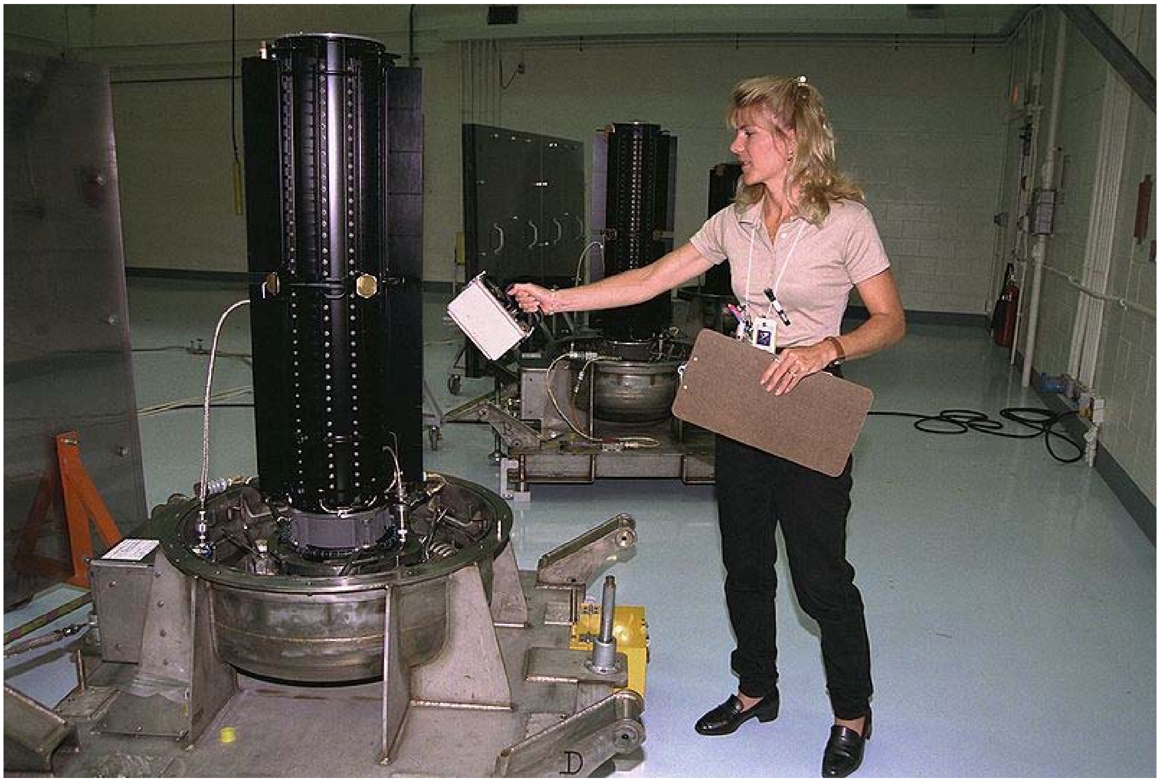
Although not strictly RTGs, similar units called radioisotope heater units are also used by various spacecraft including the Russian Lunokhod moon rover (using a Polonium 210 heat generator), and the Mars Exploration Rovers, Galileo and Cassini. These devices use small samples of radioactive material to produce heat directly, instead of electricity.

Design

The design of an RTG is simple by the standards of nuclear technology: the main component is a sturdy container of a radioactive material (the fuel). Thermocouples are placed in the walls of the container, with the outer end of each thermocouple connected to a heat sink. Radioactive decay of the fuel produces heat which flows through the thermocouples to the heat sink, generating electricity in the process.

A thermocouple is a thermoelectric device that converts thermal energy directly into electrical energy using the Seebeck effect. It is made of two kinds of metal (or semiconductors) that can both conduct electricity. They are connected to each other in a closed loop. If the two junctions are at different temperatures, an electric current will flow in the loop.

Fuels



Inspection of Cassini spacecraft RTGs before launch

New Horizons in assembly hall

Criteria

The radioactive material used in RTGs must have several characteristics:

- It should produce high energy radiation. Energy release per decay is proportional to power production per mole. Alpha decays in general release about 10 times as much energy as the beta decay of strontium-90 or caesium-137.
- Radiation must be of a type easily absorbed and transferred into thermal radiation, preferably alpha radiation. Beta radiation can give off considerable amounts of gamma/X-ray radiation through bremsstrahlung secondary radiation production, thus requiring heavy shielding. Isotopes must not produce significant amounts of gamma, neutron radiation or penetrating radiation in general through other decay modes or decay chain products.
- The half-life must be long enough that it will release energy at a relatively continuous rate for a reasonable amount of time. The amount of energy released per time (power) of a given quantity is inversely proportional to half-life. Twice the half-life will result in half the power per mole. Typical half-lives for radioisotopes used in RTGs are therefore several decades, although isotopes with shorter half-lives could be used for specialized applications.

- For spaceflight use, the fuel must produce a large amount of power per mass and volume (density). Density and weight are not as important for terrestrial use, unless there are size restrictions.
  The decay energy can be calculated if the energy of radioactive radiation or the mass loss before and after radioactive decay is known.

Selection of isotopes

The first two criteria limit the number of possible fuels to fewer than 30 atomic isotopes within the entire table of nuclides. Plutonium-238, curium-244 and strontium-90 are the most often cited candidate isotopes, but other isotopes such as polonium-210, promethium-147, caesium-137, cerium-144, ruthenium-106, cobalt-60, curium-242 and thulium isotopes have also been studied.

^{238}Pu, ^{90}Sr

Plutonium-238 has the lowest shielding requirements and longest half-life. Only three candidate isotopes meet the last criterion (not all are listed above) and need less than 25 mm of lead shielding to keep radiation. ^{238}Pu (the best of these three) needs less than 2.5 mm, and in many cases no shielding is needed in a ^{238}Pu RTG, as the casing itself is adequate.

^{238}Pu has become the most widely used fuel for RTGs, in the form of plutonium(IV) oxide (PuO_2). ^{238}Pu has a half-life of 87.7 years, reasonable power density and exceptionally low gamma and neutron radiation levels. Some Russian terrestrial RTGs have used strontium-90; this isotope has a shorter half-life, much lower power density and produces gamma radiation, but is cheaper.

^{210}Po

Some prototype RTGs, first built in 1958 by USA Atomic Energy Commission, have used polonium-210. This isotope provides phenomenal power density due to its high radioactive activity, but has limited use because of its very short half-life of 138 days, again due to its high activity. A kilogram of pure ^{210}Po in the form of a cube would be about 48 mm (about 2 inches) on a side and emit about 140kW. The heat of melting is about 60kJ/kg, the heat of evaporation about 10 times larger. If there is no efficient cooling, the self heating power is sufficient for melting then partly vaporizing itself.

^{242}Cm, ^{244}Cm, ^{241}Am

Curium-242 and curium-244 have also been studied as well, but require heavy shielding from gamma and neutron radiation produced from spontaneous fission.

Americium-241 is a potential candidate isotope with a longer half-life than ^{238}Pu: ^{241}Am has a half-life of 432 years and could hypothetically power a device for centuries. However, the power density of ^{241}Am is only 1/4 that of ^{238}Pu, and ^{241}Am produces more penetrating radiation through decay chain products than ^{238}Pu and needs about 18 mm worth of lead shielding. Even so, its shielding requirements in an RTG are the second lowest of all possible isotopes: only ^{238}Pu requires less. With a current global shortage of ^{238}Pu, a closer look is being given to ^{241}Am.

Life span

Soviet RTGs in dilapidated and vandalized condition, powered by Strontium-90 ^{90}Sr.

Most RTGs use ^{238}Pu which decays with a half-life of 87.7 years. RTGs using this material will therefore diminish in power output by 0.787% of their capacity per year. 23 years after production, such an RTG will have decreased in power by 16.6%, i.e. providing 83.4% of its initial output. Thus, with a starting capacity of 470 W, after 23 years it would have a capacity of 392 W. However, the bi-metallic thermocouples used to convert thermal energy into electrical energy degrade as well; at the beginning of 2001, the power generated by the Voyager RTGs had dropped to 315 W for Voyager 1 and to 319 W for Voyager 2. Therefore in early 2001, the thermocouples were working at about 80% of their original capacity.

This life span was of particular importance during the Galileo mission. Originally intended to launch in 1986, it was delayed by the Space Shuttle Challenger accident. Due to this unforeseen event the probe had to sit in storage for 4 years before launching in 1989. Subsequently, its RTGs had decayed somewhat, necessitating replanning the power budget for the mission.

Efficiency

RTGs use thermoelectric couples or "thermocouples" to convert heat from the radioactive material into electricity. Thermocouples, though very reliable and long-lasting, are very inefficient; efficiencies above 10% have never been achieved and most RTGs have efficiencies between 3–7%. Thermoelectric materials in space missions to date have included silicon germanium alloys, lead telluride and tellurides of antimony, germanium and silver (TAGS). Studies have been done on improving efficiency by using other technologies to generate electricity from heat. Achieving higher efficiency would mean less radioactive fuel is needed to produce the same amount of power, and therefore a lighter overall weight for the generator. This is a critically important factor in spaceflight launch cost considerations.

A thermionic converter – an energy conversion device which relies on the principle of thermionic emission—can achieve efficiencies between 10–20%, but requires higher temperatures than those at which standard RTGs run. Some prototype ^{210}Po RTGs have used thermionics, and potentially other extremely radioactive isotopes could also provide power by this means, but short half-lives make these infeasible. Several space-bound nuclear reactors have used thermionics, but nuclear reactors are usually too heavy to use on most space probes.

Thermophotovoltaic cells work by the same principles as a photovoltaic cell, except that they convert infrared light emitted by a hot surface rather than visible light into electricity. Thermophotovoltaic cells have an efficiency slightly higher than thermocouples and can be overlaid on top of thermocouples, potentially doubling efficiency. Systems with radioisotope generators simulated by electric heaters have demonstrated efficiencies of 20%, but have not been tested with actual radioisotopes. Some theoretical thermophotovoltaic cell designs have efficiencies up to 30%, but these have yet to be built or confirmed. Thermophotovoltaic cells and silicon thermocouples degrade faster than thermocouples, especially in the presence of ionizing radiation.

Dynamic generators can provide power at more than 4 times the conversion efficiency of RTGs. NASA and DOE have been developing a next-generation radioisotope-fueled power source called the Stirling Radioisotope Generator (SRG) that uses free-piston Stirling engines coupled to linear alternators to convert heat to electricity. SRG prototypes demonstrated an average efficiency of 23%. Greater efficiency can be achieved by increasing the temperature ratio between the hot and cold ends of the generator. The use of non-contacting moving parts, non-degrading flexural bearings, and a lubrication-free and hermetically sealed environment have, in test units, demonstrated no appreciable degradation over years of operation. Experimental results demonstrate that an SRG could continue running for decades without maintenance. Vibration can be eliminated as a concern by implementation of dynamic balancing or use of dual-opposed piston movement. Potential applications of a Stirling radioisotope power system include exploration and science missions to deep-space, Mars, and the Moon.

Safety

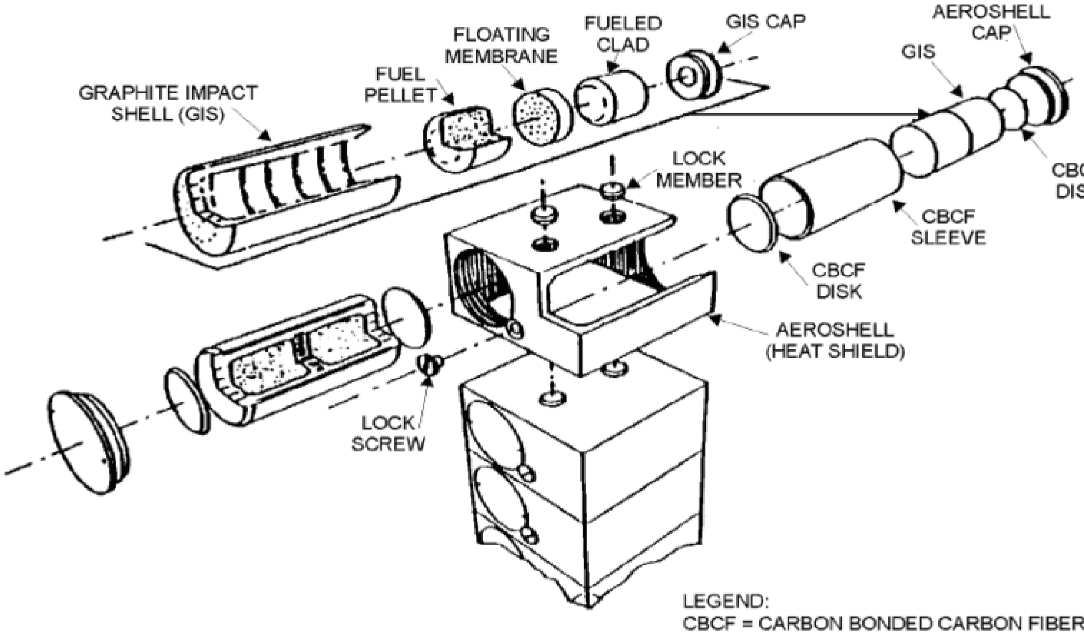


FIGURE 2-6. DIAGRAM OF GENERAL PURPOSE HEAT SOURCE MODULE

Diagram of a stack of general purpose heat source modules as used in RTGs

Radioactive contamination

RTGs may pose a risk of radioactive contamination: if the container holding the fuel leaks, the radioactive material may contaminate the environment.

For spacecraft, the main concern is that if an accident were to occur during launch or a subsequent passage of a spacecraft close to Earth, harmful material could be released into the atmosphere; and their use in spacecraft and elsewhere has attracted controversy.

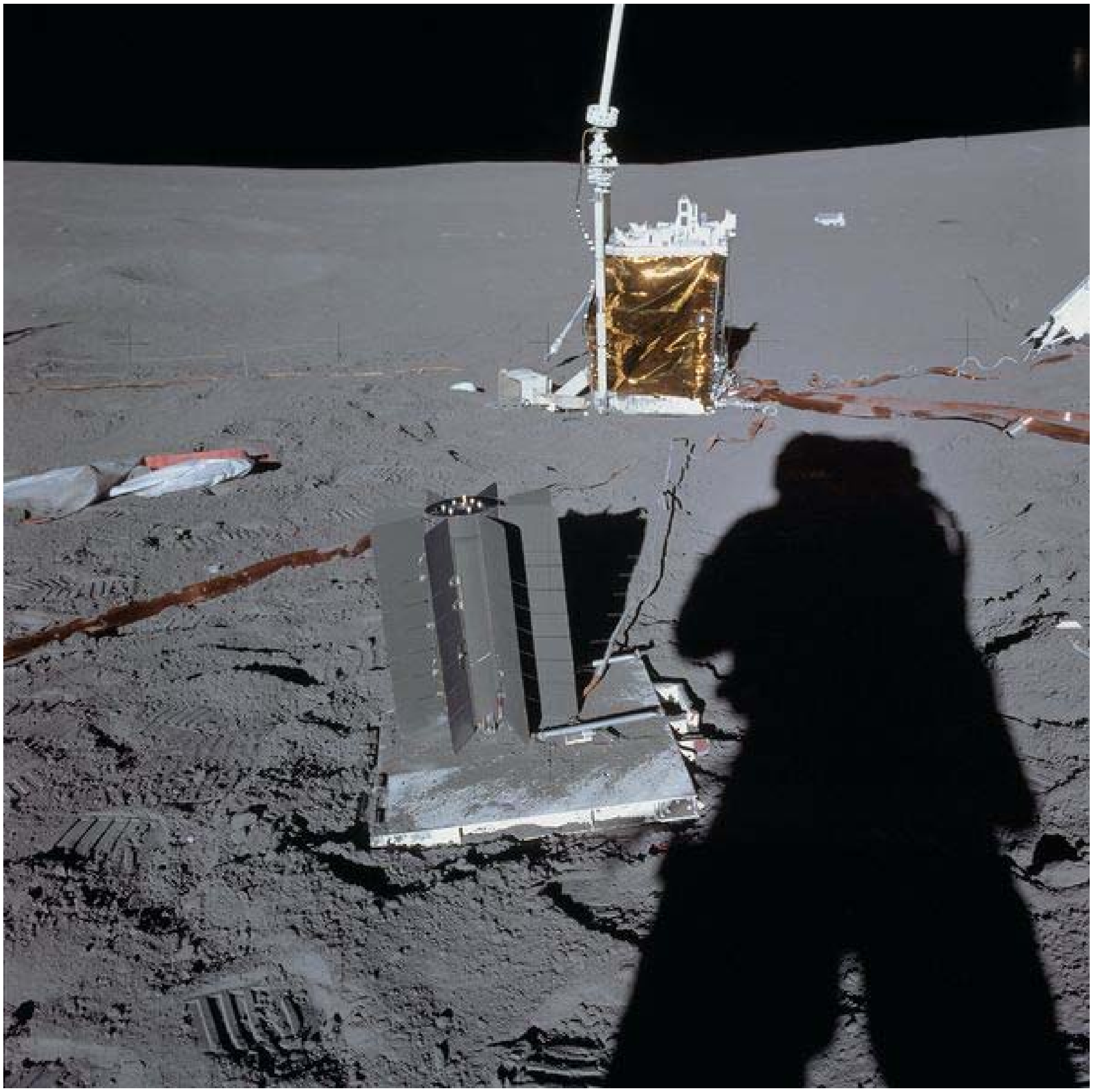
However, this event is not considered likely with current RTG cask designs. For instance, the environmental impact study for the Cassini-Huygens probe launched in 1997 estimated the probability of contamination accidents at various stages in the mission. The probability of an accident occurring which caused radioactive release from one or more of its 3 RTGs (or from its 129 radioisotope heater units) during the first 3.5 minutes following launch was estimated at 1 in 1,400; the chances of a release later in the ascent into orbit were 1 in 476; after that the likelihood of an accidental release fell off sharply to less than 1 in a million. If an accident which had the potential to cause contamination occurred during the launch phases (such as the spacecraft failing to reach orbit), the probability of contamination actually being caused by the RTGs was estimated at about 1 in 10. In any event, the launch was successful and Cassini-Huygens reached Saturn.

The plutonium 238 used in these RTGs has a half-life of 87.74 years, in contrast to the 24,110 year half-life of plutonium 239 used in nuclear weapons and reactors. A consequence of the shorter half life is that plutonium 238 is about 275 times more radioactive than plutonium 239 (i.e. 17.3 Ci/g compared to 0.063 Ci/g). For instance, 3.6 kg of plutonium 238 undergoes the same number of radioactive decays per second as 1 tonne of plutonium 239. Since the morbidity of the two isotopes in terms of absorbed radioactivity is almost exactly the same, plutonium 238 is around 275 times more toxic by weight than plutonium 239.

The alpha radiation emitted by either isotope will not penetrate the skin, but it can irradiate internal organs if plutonium is inhaled or ingested. Particularly at risk is the skeleton, the surface of which is likely to absorb the isotope, and the liver, where the isotope will collect and become concentrated.

There have been at least six known accidents involving RTG-powered spacecraft:

1. the first one was a launch failure on 21 April 1964 in which the U.S. Transit-5BN-3 navigation satellite failed to achieve orbit and burnt up on re-entry north of Madagascar. The 17,000 Ci (630 TBq) plutonium metal fuel in its SNAP-9a RTG was injected into the atmosphere over the Southern Hemisphere where it burnt up, and traces of plutonium 238 were detected in the area a few months later.
2. the second was the Nimbus B-1 weather satellite whose launch vehicle was deliberately destroyed shortly after launch on 21 May 1968 because of erratic trajectory. Launched from the Vandenberg Air Force Base, its SNAP-19 RTG containing relatively inert plutonium dioxide was recovered intact from the seabed in the Santa Barbara Channel five months later and no environmental contamination was detected.
3. two more were failures of Soviet Cosmos missions containing RTG-powered lunar rovers in 1969, both of which released radioactivity as they burnt up.
4. there were also five failures involving Soviet or Russian spacecraft which were carrying nuclear reactors rather than RTGs between 1973 and 1993.



A SNAP-27 RTG deployed by the astronauts of Apollo 14 identical to the one lost in the reentry of Apollo 13

5. the failure of the Apollo 13 mission in April 1970 meant that the Lunar Module reentered the atmosphere carrying an RTG and burnt up over Fiji. It carried a SNAP-27 RTG containing 44,500 curies (1,650 TBq) of plutonium dioxide which survived reentry into the Earth's atmosphere intact, as it was designed to do, the trajectory being arranged so that it would plunge into 6–9 kilometers of water in the Tonga trench in the Pacific Ocean. The absence of plutonium 238 contamination in atmospheric and seawater sampling confirmed the assumption that the cask is intact on the seabed. The cask is expected to contain the fuel for at least 10 half-lives (i.e. 870 years). The US Department of Energy has conducted seawater tests and determined that the graphite casing, which was designed to withstand reentry, is stable and no release of plutonium should occur. Subsequent

investigations have found no increase in the natural background radiation in the area. The Apollo 13 accident represents an extreme scenario due to the high re-entry velocities of the craft returning from cislunar space. This accident has served to validate the design of later-generation RTGs as highly safe.

To minimize the risk of the radioactive material being released, the fuel is stored in individual modular units with their own heat shielding. They are surrounded by a layer of iridium metal and encased in high-strength graphite blocks. These two materials are corrosion- and heat-resistant. Surrounding the graphite blocks is an aeroshell, designed to protect the entire assembly against the heat of reentering the Earth's atmosphere. The plutonium fuel is also stored in a ceramic form that is heat-resistant, minimising the risk of vaporization and aerosolization. The ceramic is also highly insoluble.

The most recent accident involving a spacecraft RTG was the failure of the Russian Mars 96 probe launch on 16 November 1996. The two RTGs onboard carried in total 200 g of plutonium and are assumed to have survived reentry (as they were designed to do). They are thought to now lie somewhere in a northeast-southwest running oval 320 km long by 80 km wide which is centred 32 km east of Iquique, Chile.

Many Beta-M RTGs produced by the Soviet Union to power lighthouses and beacons have become orphaned sources of radiation. Several of these units have been illegally dismantled for scrap metal resulting in the complete exposure of the Sr-90 source, fallen into the ocean, or have defective shielding due to poor design or physical damage. The US Department of Defense cooperative threat reduction program has expressed concern that material from the Beta-M RTGs can be used by terrorists to construct a dirty bomb.

NASA claims 28 U.S. space missions have safely flown radioisotope energy sources since 1961.

Nuclear fission

RTGs and nuclear power reactors use very different nuclear reactions. Nuclear power reactors use controlled nuclear fission. When an atom of U-235 or Pu-239 fuel fissions, neutrons are released that trigger additional fissions in a chain reaction at a rate that can be controlled with neutron absorbers. This is an advantage in that power can be varied with demand or shut off entirely for maintenance. It is also a disadvantage in that care is needed to avoid uncontrolled operation at dangerously high power levels.

Chain reactions do not occur in RTGs, so heat is produced at a fully predictable and steadily decreasing rate that depends only on the amount of fuel isotope and its half-life. An accidental power excursion is impossible. On the other hand, heat generation cannot be varied with demand or shut off when not needed. Auxiliary power supplies (such as rechargeable batteries) may be needed to meet peak demand, and adequate cooling must be provided at all times including the prelaunch and early flight phases of a space mission.

There are no nuclear proliferation risks associated with plutonium-238. The same properties, primarily its high specific power, that make it a desirable RTG fuel make it useless in nuclear weapons. Pu-238 is fissionable, not fissile. It will occasionally spontaneously fission instead of undergoing alpha decay or it can be induced to fission with an external source of fast neutrons produced by various fusion reactions, but it cannot sustain the chain-reaction needed in a nuclear weapon fission primary. Because of its relatively high spontaneous fission rate compared with that of the fissile bomb fuel isotope Pu-239, its presence even as a contaminant would degrade performance by increasing the likelihood of a fizzle, a low yield caused by premature initiation of the chain reaction before optimum conditions have been reached. Any significant amounts of Pu-238 would also generate heat that would have to be continually dissipated until the bomb was used.

Pu-238 could in principle be used as the tertiary stage to boost the yield of a fission-fusion-fission (thermonuclear) weapon, but there is no reason to use it in this way. Natural or even depleted uranium will also fission with fast fusion neutrons, is far more readily available, and generates essentially no heat in storage.

Pu-238 could conceivably be used in a radiological or dirty bomb to exploit the significant public fear of plutonium.

RTG for interstellar probes

RTG have been proposed for use on realistic interstellar precursor missions and interstellar probes. An example of this is the Innovative Interstellar Explorer (2003–current) proposal from NASA. A RTG using Am-241 was proposed for this type of mission in 2002. This could support mission extensions up to 1000 years on the interstellar probe, because the power output would be more stable in the long-term than plutonium. Other isotopes for RTG were also examined in the study, looking at traits such as watt/gram, half-life, and decay products. An interstellar probe proposal from 1999 suggested using three advanced radioisotope power source (ARPS).

The RTG electricity can be used for powering scientific instruments and communication to Earth on the probes. One mission proposed using the electricity to power ion engines, calling this method radioisotope electric propulsion (REP).

Models

Space

MHW = Multi-Hundred Watt

Name & Model	Used On (# of RTGs per User)	Maximum output		Radio-isotope	Max fuel used (kg)	Mass (kg)
		Electrical (W)	Heat (W)			
ASRG*	in prototype phase, Discovery Program	~140 (2x70)	~500	^{238}Pu	~1	~34
MMRTG	in prototype phase, MSL	~110	~2000	^{238}Pu	~4	<45
GPHS-RTG	Cassini (3), New Horizons (1), Galileo (2), Ulysses (1)	300	4400	^{238}Pu	7.8	55.9–57.8
MHW-RTG	LES-8/9, Voyager 1 (3), Voyager 2 (3)	160	2400	^{238}Pu	~4.5	37.7
SNAP-3B	Transit-4A (1)	2.7	52.5	^{238}Pu	?	2.1
SNAP-9A	Transit 5BN1/2 (1)	25	525	^{238}Pu	~1	12.3
SNAP-19	Nimbus-3 (2), Pioneer 10 (4), Pioneer 11 (4)	40.3	525	^{238}Pu	~1	13.6
modified SNAP-19	Viking 1 (2), Viking 2 (2)	42.7	525	^{238}Pu	~1	15.2
SNAP-27	Apollo 12–17 ALSEP (1)	73	1480	^{238}Pu	3.8	20

- The ASRG is in fact not an RTG; it is a stirling power device that runs on radioisotope

Terrestrial

Name & Model	Used On (# of RTGs per User)	Maximum output		Radioisotope	Max fuel used (kg)	Mass (kg)
		Electrical (W)	Heat (W)			
Beta-M	Obsolete Soviet unmanned lighthouses & beacons	10	230	^{90}Sr	0.26	560
Efir-MA		30	720	?	?	1250
IEU-1		80	2200	?	?	2500
IEU-2		14	580	?	?	600
Gong		18	315	?	?	600
Gorn		60	1100	^{90}Sr	?	1050
IEU-2M		20	690	?	?	600

IEU-1M	120 (180)	2200 (3300)	?	?	2(3) × 1050
Sentinel 25	9–20		$SrTiO_J$	0.54	907–1814
Sentinel 100F	53		Sr_2Ti0_4	1.77	1234

Chapter-16

Van De Graaff Generator

Van de Graaff-Generator

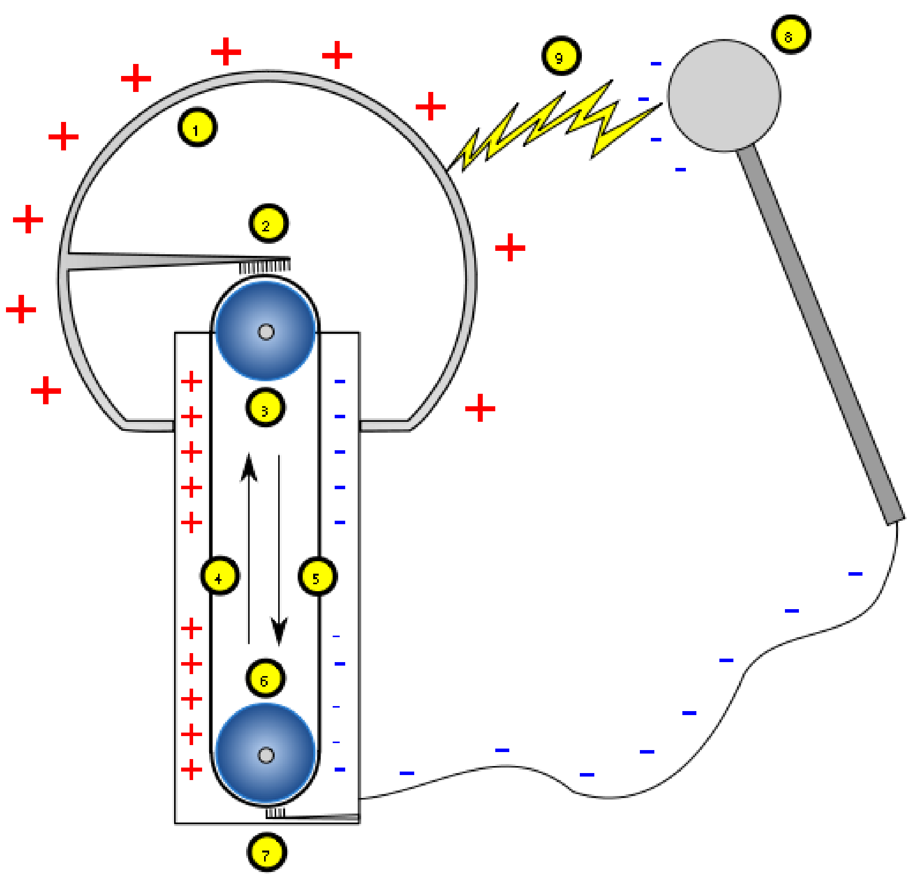
Van de Graaff-Generator.

Uses	Accelerating electrons to sterilize food and process materials, accelerating protons for nuclear physics experiments,

	driving X-Ray tubes, etc.
Inventor	Robert J. Van de Graaff
Related items	Van de Graaff, linear particle accelerator

A **Van de Graaff generator** is an electrostatic generator which uses a moving belt to accumulate very high electrostatically stable voltages on a hollow metal globe on the top of the stand. Invented in 1929 by American physicist Robert J. Van de Graaff, the potential differences achieved in modern Van de Graaff generators can reach 5 megavolts. The Van de Graaff generator can be thought of as a constant-current source connected in parallel with a capacitor and a very large electrical resistance.

Description



Schematic view of a classical Van de Graaff-generator.
1) hollow metal sphere
2) upper electrode
3) upper roller (metal)

4) side of the belt with positive charges
5) opposite side of the belt with negative charges
6) lower roller (for example an acrylic glass)
7) lower electrode (ground)
8) spherical device with negative charges, used to discharge the main sphere
9) spark produced by the difference of potentials

A simple Van de Graaff-generator consists of a belt of silk, or a similar flexible dielectric material, running over two metal pulleys, one of which is surrounded by a hollow metal sphere. Two electrodes, (2) and (7), in the form of comb-shaped rows of sharp metal points, are positioned respectively near to the bottom of the lower pulley and inside the sphere, over the upper pulley. Comb (2) is connected to the sphere, and comb (7) to the ground. A high DC potential (with respect to earth) is applied to roller (6); a positive potential in this example.

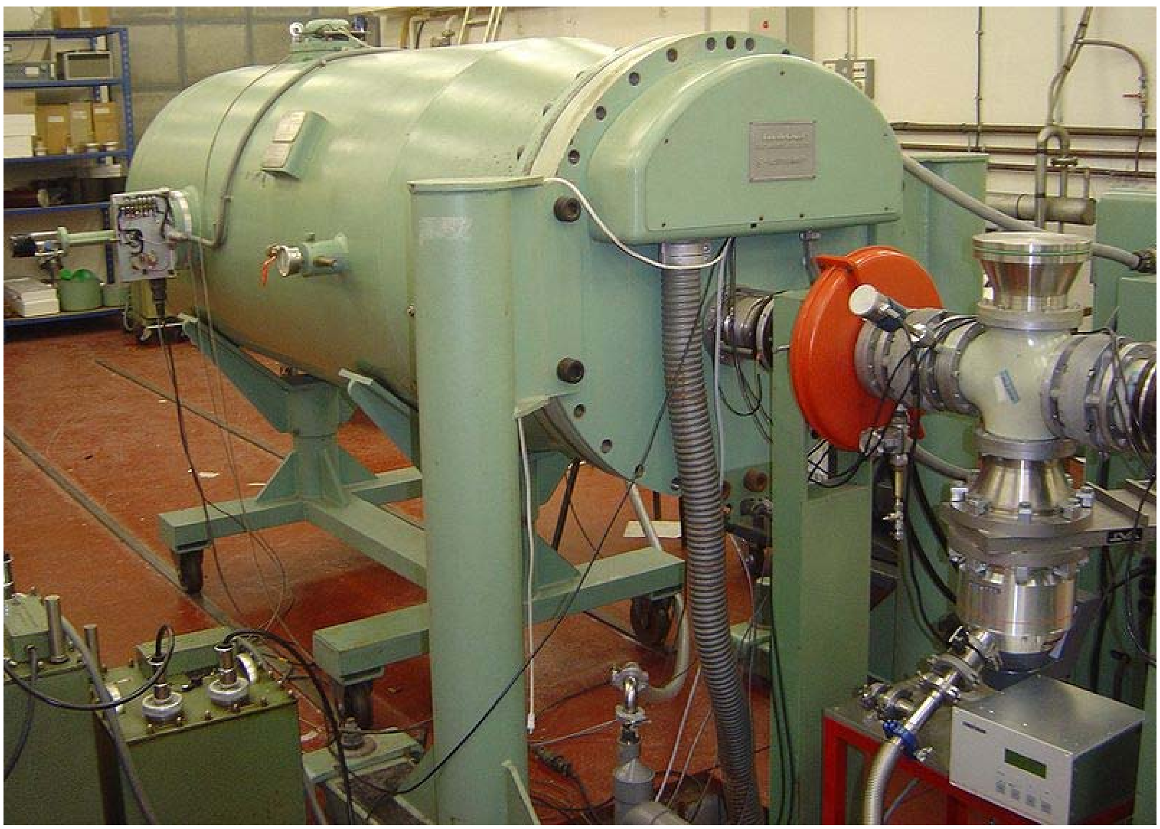
As the belt passes in front of the lower comb, it receives negative charge that escapes from its points due to the influence of the electric field around the lower pulley, that ionizes the air at the points. As the belt touches the upper roller (3), it transfers some electrons, leaving the roller with a negative charge (if it is insulated from the terminal), which added to the negative charge in the belt generates enough electric field to ionize the air at the points of the upper comb. Electrons then leak from the belt to the upper comb and to the terminal, leaving the belt positively charged as it returns down and the terminal negatively charged. The sphere shields the upper roller and comb from the electric field generated by charges that accumulate at the outer surface of it, causing the discharge and change of polarity of the belt at the upper roller to occur practically as if the terminal were grounded. As the belt continues to move, a constant *charging current* travels via the belt, and the sphere continues to accumulate negative charge until the rate that charge is being lost (through leakage and corona discharges) equals the charging current. The larger the sphere and the farther it is from ground, the higher will be its final potential.

Another method for building Van de Graaff generators is to use the triboelectric effect. The friction between the belt and the rollers, one of them now made of insulating material, or both made with insulating materials at different positions on the triboelectric scale, one above and other below the material of the belt, charges the rollers with opposite polarities. The strong e-field from the rollers then induces a corona discharge at the tips of the pointed comb electrodes. The electrodes then "spray" a charge onto the belt which is opposite in polarity to the charge on the rollers. The remaining operation is otherwise the same as the voltage-injecting version above. This type of generator is easier to build for science fair or homemade projects, since it doesn't require a potentially dangerous high voltage source. The trade-off is that it cannot build up as high a voltage as the other type, that cannot also be easily regulated, and operation may become difficult under humid conditions (which can severely reduce triboelectric effects).

A Van de Graaff generator terminal doesn't need to be sphere shaped in order to work, and in fact the optimum shape is a sphere with an inward curve around the hole where the belt enters. The fact that electrically charged conductors of any shape have no e-field inside makes it possible to keep adding charges continuously. A rounded terminal minimizes the electric field around it, allowing greater potentials to be achieved without ionization of the surrounding air, or other dielectric gas. Outside the sphere the e-field quickly becomes very strong and applying charges from the outside would soon be prevented by the field.

Since a Van de Graaff generator can supply the same small current at almost any level of electrical potential, it is an example of a nearly ideal current source. The maximum achievable potential is approximately equal to the sphere's radius multiplied by the e-field where corona discharges begin to form within the surrounding gas. For example, a polished spherical electrode 30 cm in diameter immersed in air at STP (which has a breakdown voltage of about 30 kV/cm) could be expected to develop a maximum voltage of about 450 kV.

History



A Van de Graaff generator integrated with a particle accelerator. The generator produces the high fields (in the megavolt range) that accelerate the particles.

Van de Graaff generator of the first Hungarian linear particle accelerator. It achieved 700 kV in 1951 and 1000 kV in 1952. (Constructor: Simonyi Károly; Sopron, 1951.)

The fundamental idea for the friction machine as high-voltage supply, using electrostatic influence to charge rotating disk or belt can be traced back to the 17th century or even before (cf. Friction machines History)

The Van de Graaff generator was developed, starting in 1929, by physicist Robert J. Van de Graaff at Princeton University. The first model was demonstrated in October 1929. The first machine used a silk ribbon bought at a five-and-dime store as the charge transport belt. In 1931 a version able to produce 1,000,000 volts was described in a patent disclosure. This version had two 60 cm diameter charge accumulation spheres mounted on borosilicate glass columns 180 cm high; the apparatus cost only $90 in 1931.

Van de Graaff applied for a patent in December 1931, which was assigned to MIT in exchange for a share of net income. The patent was later granted.

In 1933 Van de Graaff built a 40-foot (12 m) model at MIT's Round Hill facility, the use of which was donated by Colonel Edward H. R. Green.

A more recent development is the **tandem Van de Graaff accelerator**, containing one or more Van de Graaff generators, in which negatively charged ions are accelerated through one potential difference before being stripped of two or more electrons, inside a high voltage terminal, and accelerated again.

One of Van de Graaff's accelerators used two charged domes of sufficient size that each of the domes had laboratories inside - one to provide the source of the accelerated beam, and the other to analyze the actual experiment. The power for the equipment inside the domes came from generators that ran off the belt, and several sessions came to a rather gruesome end when a pigeon would try to fly between the two domes, causing them to discharge. (The accelerator was set up in an airplane hangar.)

By the 1970s, up to 14 million volts could be achieved at the terminal of a tandem that used a tank of high pressure sulfur hexafluoride (SF_6) gas to prevent sparking by trapping electrons. This allowed the generation of heavy ion beams of several tens of megaelectronvolts, sufficient to study light ion direct nuclear reactions. The highest potential sustained by a Van de Graaff accelerator is 25.5 MV, achieved by the tandem at the Holifield Radioactive Ion Beam Facility at Oak Ridge National Laboratory.

A further development is the pelletron, where the rubber or fabric belt is replaced by a chain of short conductive rods connected by insulating links, and the air-ionizing electrodes are replaced by a grounded roller and inductive charging electrode. The chain can be operated at much higher velocity than a belt, and both the voltage and currents attainable are much higher than with a conventional Van de Graaff generator. The 14 UD Heavy Ion Accelerator at The Australian National University houses a 15 million volt pelletron. Its chains are more than 20 meters long and can travel faster than 50 km/hr.

The Nuclear Structure Facility (NSF) at Daresbury Laboratory was proposed in the 1970s, commissioned in 1981 and opened for experiments in 1983. It consisted of a tandem Van de Graaff generator operating routinely at 20 MV, housed in a distinctive building 70 metres high. During its lifetime it accelerated 80 different ion beams for experimental use, ranging from protons to uranium. A particular feature was the ability to accelerate rare isotopic and radioactive beams. Perhaps the most important discovery made on the NSF was that of super-deformed nuclei. These nuclei, when formed from the fusion of lighter elements, rotate very rapidly. The pattern of gamma-rays emitted as they slow down provided detailed information about the inner structure of the nucleus. Following financial cutbacks, the NSF closed in 1993.

A Van de Graaff generator on display at the Maker Faire, San Mateo, 2008.

Van de Graaff generators on display

The largest air-insulated Van de Graaff generator in the world, built by Dr. Van de Graaff in the 1930s, is now on permanent display at Boston's Museum of Science. With two conjoined 4.5 meter (15 foot) aluminium spheres standing on columns 22 feet (6.7 m) tall, this generator can often reach 2 MV (2 million volt). Shows using the Van de Graaff generator and several Tesla coils are conducted two to three times a day. Many science museums, such as the American Museum of Science and Energy, have small-scale Van de Graaff generators on display, and exploit their static-producing qualities to create "lightning" or make people's hair stand up.

Comparison with other high voltage generators

Other classical electrostatic machines like a Wimshurst Machine or a Bonetti machine can easily produce more current than a Van de Graaff generator for experiments with electrostatics, and have positive and negative output. The less insulated structures, however, result in smaller voltages.

Chapter-17

Doubly-Fed Electric Machine

Doubly-fed electric machines are electric motors or electric generators that have windings on both stationary and rotating parts, where both windings transfer significant power between shaft and electrical system. Doubly-fed machines are useful in applications that require varying speed of the machine's shaft for a fixed power system frequency.

Classification

Electric machines are either *Singly-Fed* with one winding set that actively participates in the energy conversion process or *Doubly-Fed* with two active winding sets. The wound-rotor induction machine and the field-excited synchronous machine are singly-fed machines because only one winding set actively participates in the energy conversion process.

Examples of operational doubly-fed electric machines are the conventional wound-rotor doubly-fed electric machine with a multiphase slip-ring assembly, the brushless wound-rotor doubly-fed electric machine, and the brushless doubly-fed induction electric machines.

Features of doubly fed machines

The ***wound rotor*** **doubly fed electric machine** is the only electric machine that operates with rated torque to twice synchronous speed for a given frequency of excitation (i.e., 7200 rpm @ 60 Hz and one pole-pair versus 3600 rpm for singly-fed electric machines). Higher speed with a given frequency of excitation is a metric for lower cost, higher efficiency, and higher power density. In concept, any electric machine can be converted to a wound-rotor doubly-fed electric motor or generator by changing the rotor assembly to a multiphase wound rotor assembly of equal stator winding set rating. If the rotor winding set can transfer active or *working* power to the electrical system, the conversion result is a wound-rotor doubly-fed electric motor or generator with twice the speed and power as the original singly-fed electric machine. The resulting dual-ported transformer circuit topology allows very high torque current without core saturation, all by electronically controlling half or less of the total motor power for full variable speed control.

In practice, the classical wound-rotor doubly-fed "induction" electric motor or generator system has known issues of instability, high maintenance and inefficiency of an integral multiphase slip-ring assembly, and discontinuity about synchronous speed where induction ceases to exist. A practical wound-rotor doubly-fed electric machine system that does not rely exclusively on asynchronous (i.e., induction) principles while symmetrically motoring or generating over its entire speed range has never materialized from the electric machine establishment, despite years of research to find an evolutionary brushless, synchronous, and stable control technology. Consequently, the wound-rotor doubly-fed induction electric machine has been forced into antiquity, except in large installations where efficiency and cost are critical over a limited speed range, such as wind turbines. This may change with recent Brushless Wound-Rotor Doubly-Fed Electric Machine technology development.

As do all electromagnetic electric machines, doubly fed machines need torque current to produce torque. Because there are no permanent magnets with a persistent but limited flux density in the doubly fed machine, magnetizing current is also needed to produce magnetic flux. Magnetizing current and torque current are orthogonal vectors and do not add directly. Since the magnetizing current is much smaller than the torque current, it is only significant in the efficiency of the machine at very low torque. Furuthermore, magnetizing current of the wound rotor doubly fed electric machine can be shared between the stator and rotor windings for lowest I^2R loss. For example, if all magnetizing current is supplied by the rotor windings, the stator will only have torque current and so unity power factor. At synchronous speed the rotor current has to be DC, as in ordinary synchronous machines. If the shaft speed is above or below synchronous speed, the rotor current must be AC at the slip frequency. Reactive power is used in the rotor winding when it is used to magnetize the machine in non-synchronous operation.

Rotor current is also needed to produce torque in addition to magnetization. Thus active power is present in the rotor in addition to reactive power.

The frequency and the magnitude of the rotor voltage is proportional to the difference between the speed of the machine and the synchronous speed (the slip). At standstill, the frequency will be the same as the frequency in the stator; the voltage is determined by the ratio of the stator and rotor winding turns. Thus if the number of turns is equal, the rotor has the same voltage as the stator. The doubly-fed machine is a transformer at standstill. The transformer-like characteristics are also present when it is rotating, manifesting itself especially during transients in the grid.

Due to the voltage and current behavior described above the rotor will either require, or generate, active power depending on the speed and torque. If the machine is producing torque and operating as a motor, the rotor will generate power if the speed is below synchronous speed (subsynchronous operation). At standstill all power fed in the stator (excluding losses) is returned via the rotor. The magnitude of the active power depends on the torque of the motor. Thus if the motor has rated torque, rated power is circulating through the stator and rotor but like all electric machines of similar rating, efficiency is based on the circulating current and not the circulating power. Like all electric machines, the efficiency of the machine is not very good at low speeds because current is required to produce torque but little or no mechanical power is produced.

If the machine is operating as a motor at speeds over the synchronous speed (supersynchronous operation), the mechanical power is fed in both through the stator and rotor. As a consequence the efficiency is now better than with singly fed motors. For example, at maximum speed the doubly-fed electric machine with equal stator and rotor turns produces same torque at double speed (and thus twice the power) as a singly-fed electric machine. The losses, being roughly proportional to the torque, are quite the same. Thus efficiency, which is the power taken divided by the total power produced, is better than singly-fed electric machines. Naturally one has to take into account the loss of the power electronic control equipment. However, the frequency converter of the doubly fed machine has to control only 50% or less of the power of the machine, and thus has about half of the loss of the singly-fed machines' frequency converter that has to pass through 100 % of the power.

Since efficiency is the ratio between the output power (i.e., input power minus the loss) to the input power, the magnetic core efficiency of a wound rotor doubly fed machine, which has just two winding sets (i.e., dual armature winding sets) of loss but shows twice the power for a given frequency and voltage of operation, is comparable to the magnetic core efficiency of permanent magnet machines with just one winding set (i.e., single armature winding set) of loss but without magnetizing current. Coupled with the low power electronic controller, the wound-rotor doubly-fed electric machine system would be more efficient than permanent magnet machine systems without magnetizing current.

For operation as a generator a similar situation exists. At subsynchronous speeds the stator is generating the power but part of it has to be fed back to rotor. At supersynchronous speeds both the rotor and stator are producing power to the grid.

Thus the current rating of the rotor converter is defined by the maximum active current required by the torque production and the maximum reactive current required to magnetize the machine.

Doubly-fed electric machines outperform the others in supersynchronous speeds. They can operate at constant torque to twice synchronous speed if each active winding is rated at half the total power of the machine (i.e., contiguous operation between sub-synchronous through supersynchronous speed range).

It is important to note, however, that doubly fed machines do not produce more continuous rated torque per volume than singly fed machines. The bigger power rating is due to the higher speed attainable without weakening the magnetic flux. The short time maximum torque of a ***wound rotor*** **doubly fed electric machine** is, however, much higher than all other electric machines, including induction or permanent magnet machines, because increasing torque current does not directly increase air-gap flux, which leads to core saturation. In practice, increasing torque current is only limited by the temperature of the windings and the maximum current capability of the rotor frequency converter but for only the doubly-fed electric machine, the frequency converter is rated for half or less of the system power.

With one of the two armature winding sets (i.e., doubly fed) residing on the rotor and stator body, respectively, the rotor real estate of the wound-rotor doubly fed machine actively participates in the energy conversion process, which is different from all other electric machines, including permanent magnet synchronous machines. As a result, the magnetic core of the wound-rotor doubly fed electric machine shows highest power density.

Changing of the direction of the rotation requires the swap of two stator phases near zero speed if symmetrical speed range in both directions is required.

Further note, it is common to dimension the doubly fed machine to operate only at a narrow speed range around synchronous speed and thus further decrease the power rating (and cost) of the frequency converter in the rotor circuit.

Typical applications of doubly fed machines have been high power pumps and fans, hydro and wind generators, shaft generators for ships etc. where operating speed range has been quite narrow, less than ± 30 % of the synchronous speed and only small power is required in the subsynchronous range.

Due to the high rotor to stator winding turn ratio and the high voltage thus induced in the rotor at standstill, the starting of this kind of restricted operating speed range motor drive is usually done with rotor resistors in induction motor mode. When speed is in the operating speed range, the resistors are disconnected and the frequency converter is connected to the rotor. It is also possible to short circuit the stator and use the frequency converter in the induction motor control mode to accelerate the motor to the operating speed range. Generators, naturally, don't usually need any additional starting means because wind or water is used to accelerate the machine to the operating speed range.

Electronic control

The electronic controller, a **frequency converter**, conditions bi-directional (i.e., four quadrant), speed synchronized, and multiphase electrical power to at least one of the winding sets (generally, the rotor winding set). Using four quadrant control, which must be continuously stable throughout the speed range, a wound-rotor doubly-fed electric machine with two poles (i.e., one pole-pair) has a constant torque speed range of 7200 rpm when operating at 60 Hz. However, in high power applications two or three pole-pair machines with respectively lower maximum speeds are common.

The electronic controller is smaller, less expensive, more efficient, and more compact than electronic controllers of singly-fed electric machine because in the simplest configuration, only the power of the rotating (or moving) active winding set is controlled, which is less than half the total power output of the electric machine.

Due to the lack of damper windings used in synchronous machines, the wound-rotor doubly fed electric machines are susceptible to instability without stabilizing control because torque is a function of position. Pioneering work of Drs. Albertson, Long, Novotny, and Schmitz from the engineering department of the University of Wisconsin realized this must be overcome with instantaneous control. Like any synchronous machine, losing synchronism will result in alternating torque pulsation and other related consequences.

Doubly-fed electric machines require electronic control for practical operation and should be considered an electric machine *system* or more appropriately, an adjustable-speed drive.

Wound-rotor doubly-fed electric machine

Construction

Two multiphase winding sets with similar pole-pairs are placed on the rotor and stator bodies, respectively. The wound-rotor doubly-fed electric machine is the only electric machine with two independent active winding sets, the rotor and stator winding sets, occupying the same core volume as other electric machines. Since the rotor winding set actively participates in the energy conversion process with the stator winding set, utilization of the magnetic core real estate is optimized.

The doubly fed machine operation at unity stator power factor requires higher flux in the air-gap of the machine than when the machine is used as wound rotor induction machine. It is quite common that wound rotor machines not designed to doubly fed operation saturate heavily if doubly fed operation at rated stator voltage is attempted. Thus a special design for doubly fed operation is necessary.

A multiphase slip ring assembly (i.e., sliding electrical contacts) is traditionally used to transfer power to the rotating (moving) winding set and to allow independent control of the rotor winding set. The slip ring assembly requires maintenance and compromises system reliability, cost and efficiency. Attempts to avoid the slip ring assembly are constantly being researched with limited success.

Control

Although the multiphase slip ring assembly compromises core real estate, reliability, cost, and efficiency, it allows independent electronic control of the rotor (moving) winding set so both multiphase winding sets actively participate in the energy conversion process with the electronic controller controlling half (or less) of the power capacity of the electric machine for full control of the machine.

This is especially important when operating at synchronous speed, because then the rotor current will be DC current. Without slip rings the production of DC current in the rotor winding is only possible when the frequency converter is at least partly located in the rotor and rotating with it. This kind of rotor converter naturally requires its own winding system (preferably using high frequency in the 10 kHz range for compact size) for power transfer out of or into the rotor. This kind of arrangement, which is without the cost and loss of a multiphase slip-ring assembly, would show lower cost and higher efficiency, if the two electronic stages on the rotor and stator assembly, respectively, and the intermediate winding stages were similar to the two stages of electronics and the DC link stage of the conventional electronic controller. Furthermore, there are thermal and mechanical constraints (for example centrifugal forces) of the power electronic assembly in the rotor. However, electronics have been incorporated on the rotor for many years (i.e., high speed alternators with brushless field exciters) for the improved reliability. Furthermore, high frequency power transfer is used in many applications because of improvements in efficiency and cost over low frequency alternatives, such as the DC link chokes and capacitors in traditional electronic controllers.

Efficiency

Neglecting the slip ring assembly, the theoretical electrical loss of the wound-rotor doubly-fed machine in supersynchronous operation is comparable to the most efficient electric machine systems available (i.e., the synchronous electric machine with permanent magnet assembly) with similar operating metrics because the total current is split between the rotor and stator winding sets while the electrical loss of the winding set is proportional to the square product of the current flowing through the winding set. Further considering the electronic controller conditions less than 50% of the power of the machine, the wound-rotor doubly-fed electric motor or generator (without brushes and with stable control at any speed) theoretically shows nearly half the electrical loss (i.e., winding set loss) of other electric motor or generator systems of similar rating.

Power density

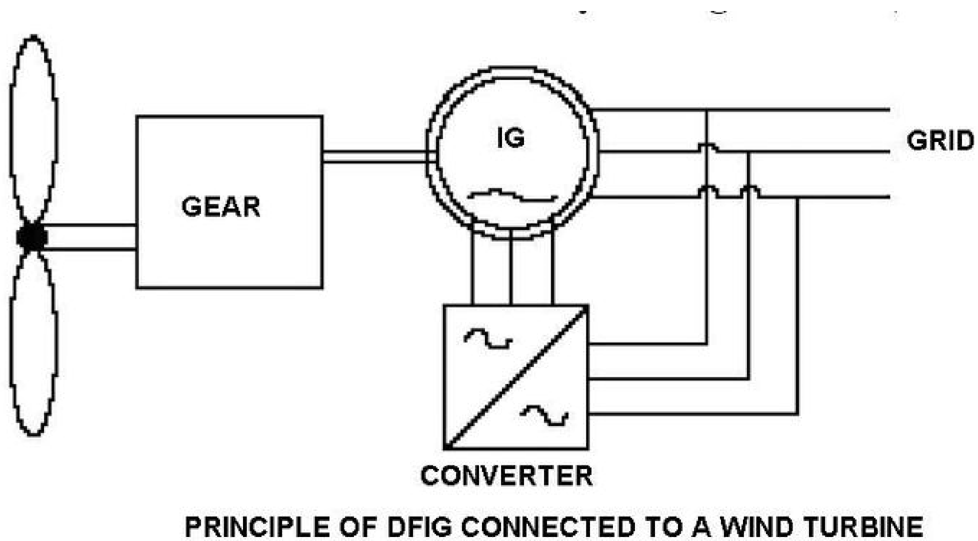
Neglecting the slip ring assembly and considering similar air-gap flux density, the physical size of the magnetic core of the wound-rotor doubly-fed electric machine is smaller than other electric machines because the two active winding sets are individually placed on the rotor and stator bodies, respectively, with virtually no real-estate penalty. In all other electric machines, the rotor assembly is passive real estate that does not actively contribute to power production. The potential of higher speed for a given frequency of excitation, alone, is an indication of higher power density potential. The continuous constant-torque speed range is up to 7200 rpm @ 60 Hz with 2 poles compared to 3600 rpm @ 60 Hz with 2 poles for other electric machines. In theory, the core volume is nearly half the physical size (i.e., winding set loss) of other electric motor or generator systems of similar rating.

Cost

Neglecting the slip ring assembly, the theoretical system cost is nearly 50% less than other machines of similar rating because the power rating of the electronic controller, which is the significant cost of any electric machine system, is 50% (or less) than other electric motor or generator systems of similar rating.

Double fed induction generator

DFIG is an abbreviation for Double Fed Induction Generator, a generating principle widely used in wind turbines. It is based on an induction generator with a multiphase wound rotor and a multiphase slip ring assembly with brushes for access to the rotor windings. It is possible to avoid the multiphase slip ring assembly, but there are problems with efficiency, cost and size. A better alternative is a brushless wound-rotor doubly-fed electric machine.



Principle of a Double Fed Induction Generator connected to a wind turbine

The principle of the DFIG is that rotor windings are connected to the grid via slip rings and back-to-back voltage source converter that controls both the rotor and the grid currents. Thus rotor frequency can freely differ from the grid frequency (50 or 60 Hz). By using the converter to control the rotor currents, it is possible to adjust the active and reactive power fed to the grid from the stator independently of the generator's turning speed. The control principle used is either the two-axis current vector control or direct torque control (DTC). DTC has turned out to have better stability than current vector control especially when high reactive currents are required from the generator.

The doubly-fed generator rotors are typically wound with 2 to 3 times the number of turns of the stator. This means that the rotor voltages will be higher and currents respectively lower. Thus in the typical ± 30 % operational speed range around the synchronous speed, the rated current of the converter is accordingly lower which leads to a lower cost of the converter. The drawback is that controlled operation outside the operational speed range is impossible because of the higher than rated rotor voltage. Further, the voltage transients due to the grid disturbances (three- and two-phase voltage dips, especially) will also be magnified. In order to prevent high rotor voltages - and high currents resulting from these voltages - from destroying the IGBTs and diodes of the converter, a protection circuit (called crowbar) is used.

The crowbar will short-circuit the rotor windings through a small resistance when excessive currents or voltages are detected. In order to be able to continue the operation as quickly as possible an active crowbar has to be used. The active crowbar can remove the rotor short in a controlled way and thus the rotor side converter can be started only after 20-60 ms from the start of the grid disturbance. Thus it is possible to generate reactive current to the grid during the rest of the voltage dip and in this way help the grid to recover from the fault.

As a summary, a doubly fed induction machine is a wound-rotor doubly-fed electric machine and has several advantages over a conventional induction machine in wind power applications. First, as the rotor circuit is controlled by a power electronics converter, the induction generator is able to both import and export reactive power. This has important consequences for power system stability and allows the machine to support the grid during severe voltage disturbances (low voltage ride through, LVRT). Second, the control of the rotor voltages and currents enables the induction machine to remain synchronized with the grid while the wind turbine speed varies. A variable speed wind turbine utilizes the available wind resource more efficiently than a fixed speed wind turbine, especially during light wind conditions. Third, the cost of the converter is low when compared with other variable speed solutions because only a fraction of the mechanical power, typically 25-30 %, is fed to the grid through the converter, the rest being fed to grid directly from the stator. The efficiency of the DFIG is very good for the same reason.

Brushless doubly-fed versions

Brushless doubly-fed induction electric machines

Brushless doubly-fed *induction* electric machines (i.e., electric motors or electric generators) are constructed by adjacently placing two multiphase winding sets with unlike pole-pairs on the stator body. With unlike pole-pairs between the two winding sets, low frequency magnetic induction is assured over the speed range. One of the stator winding sets (power winding) is connected to the grid and the other winding set (control winding) is supplied from a frequency converter. The shaft speed is adjusted by varying the frequency of the control winding. As a doubly-fed electric machine, the rating of the frequency converter need only be fraction of the machine rating.

The brushless doubly-fed electric machine does not utilize core real-estate efficiently and the dual winding set stator assembly is physically larger than other electric machines of comparable power rating. In addition, a specially designed rotor assembly tries to focus most of the mutual magnetic field to follow an indirect path across the air-gap and through the rotor assembly for inductive coupling (i.e., brushless) between the two adjacent winding sets. As a result, the adjacent winding sets are excited independently and actively participate in the electro-mechanical energy conversion process, which is a criterion of doubly-fed electric machines.

The type of rotor assembly determines if the machine is a reluctance or induction doubly-fed electric machine. The constant torque speed range is always less than 1800 rpm @ 60 Hz because the effective pole count is the average of the unlike pole-pairs of the two active winding sets. Brushless doubly-fed electric machines incorporate a poor electromagnetic design that compromises physical size, cost, and electrical efficiency, to chiefly avoid a multiphase slip ring assembly. Although brushless doubly-fed electric machines have not seen commercial success since their conception in the early 1970s, the promise of a low cost, highly efficient electronic controller keeps the concept under perpetual study, research, and development.

Brushless wound-rotor doubly-fed electric machine

The **brushless *wound-rotor* doubly-fed electric machine** (i.e., electric motor or electric generator) incorporates the electromagnetic structure of the wound-rotor doubly-fed electric machine, but replaces the traditional multiphase slip ring assembly with a brushless means to independently power the rotor winding set (i.e., doubly-fed) with multiphase AC power. Without relying on slip for operation, the brushless wound-rotor doubly-fed electric machine should never be confused with brushless doubly-fed induction electric machines, which rely on very different principles of unlike pole-pair induction for operation. Likewise without an independent means of exciting the rotor winding set, the torque of the wound-rotor doubly-fed electric machine is dependent on both slip and position, which is a classic condition for instability, and cannot produce torque at synchronous speed. For stable operation, the frequency and phase of the multiphase AC power must be synchronized and fixed instantaneously to the stator excitation frequency and the speed and position of the shaft, which is not trivial at any speed and particularly difficult about synchronous speed where induction no longer exists. If these conditions are met without relying on induction, all the attractive attributes of the *synchronous* wound-rotor doubly-fed electric machine, such as high power density, low cost, ultra-high efficiency, and ultra-high torque potential are realized without the traditional slip-ring assembly and instability problems. One company, has patented and is selling a wound-rotor doubly-fed electric machine with a brushless means of independently exciting the wound rotor without relying on slip (induction) with the stator excitation and as a result, is a truly ***synchronous*** **brushless wound-rotor doubly-fed electric machine** with symmetrical quality of *fully stable* motoring or generating, even at synchronous speed where induction no longer exists. Another brushless wound-rotor construction invented by Lars Gertmar has been described in the patent application.