Transformers
(Electrical Engineering)

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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.
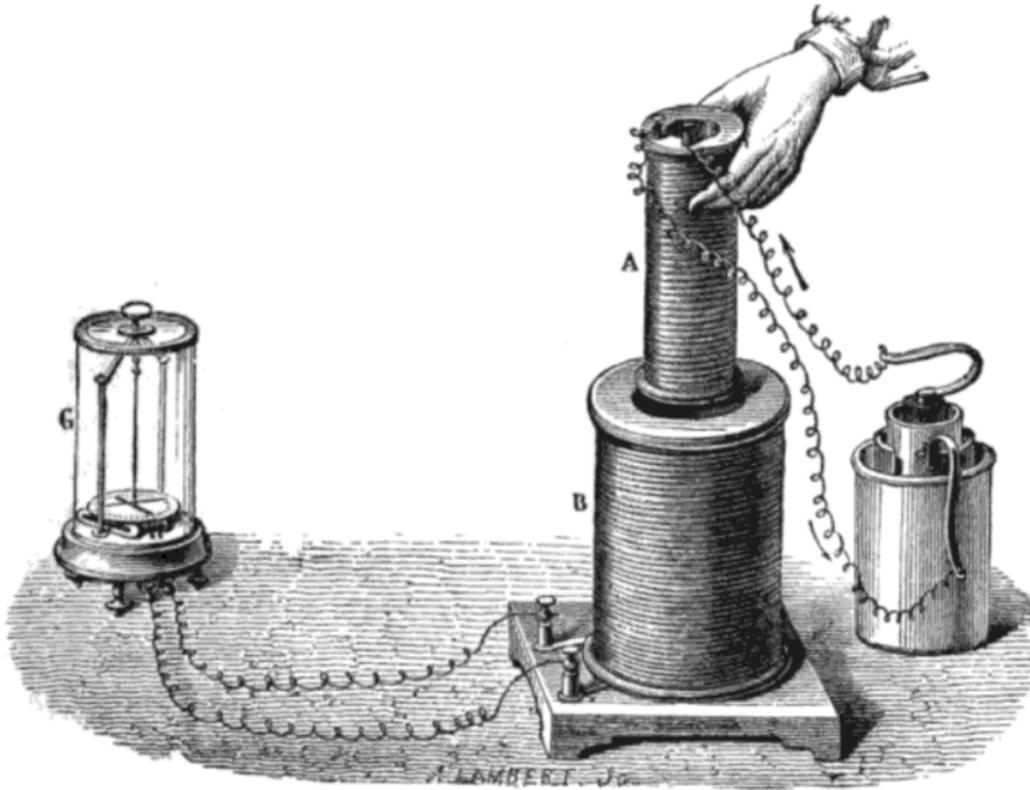
Discovery

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
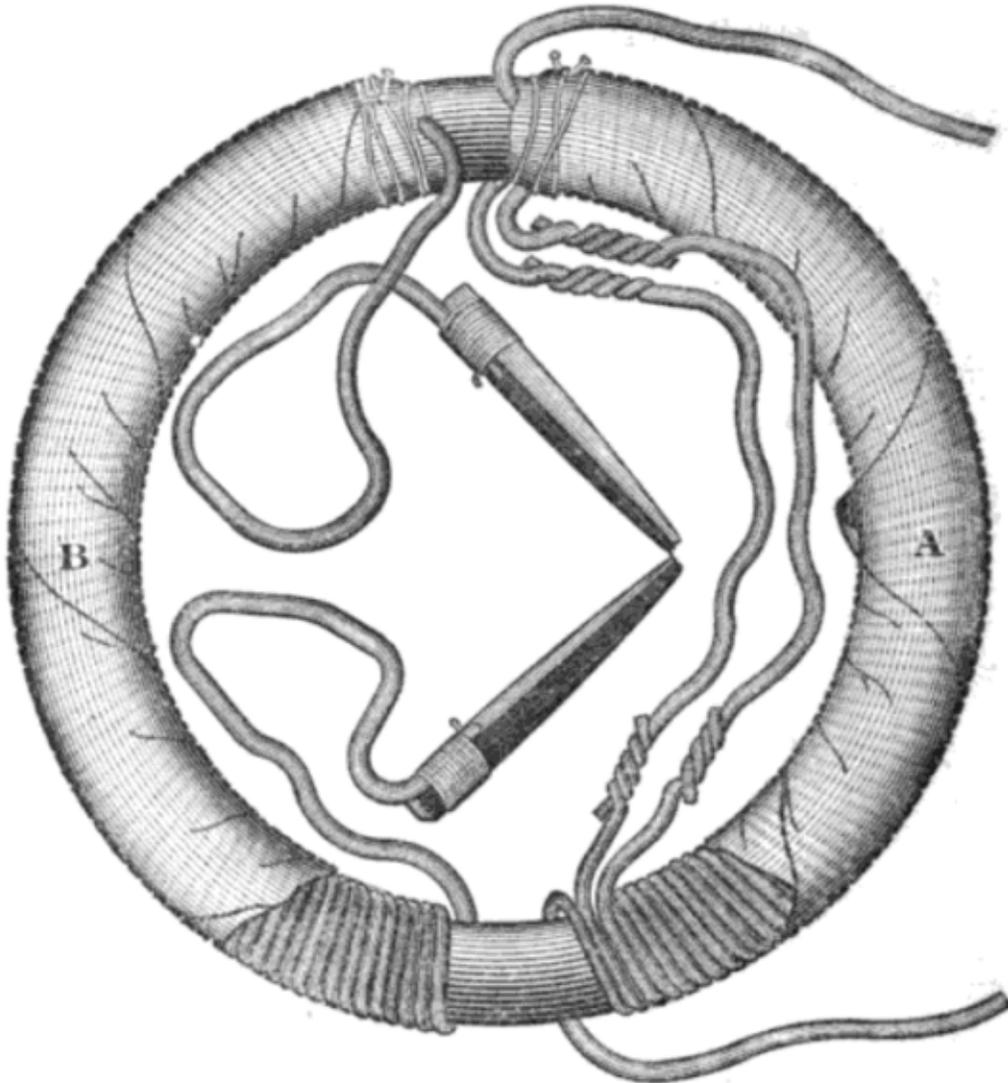
Faraday's ring transformer

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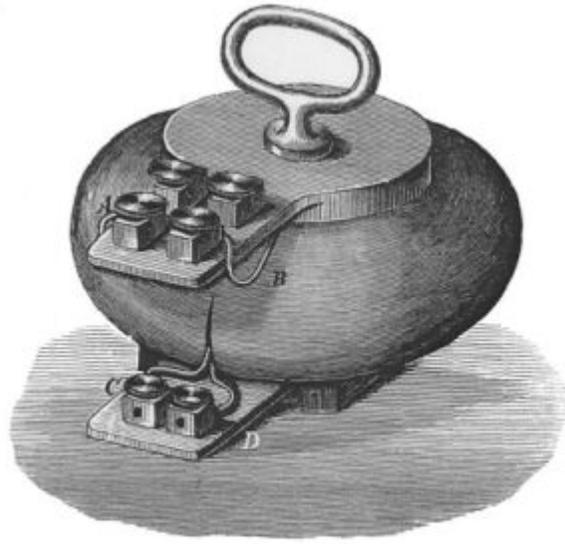
Drawing of Ganz Company's 1885 prototype. Capacity: 1400 VA, frequency: 40 Hz, voltage ratio: 120/72 V

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, Vs/Vp = Ns/Np. The vast majority of transformers in use today rely on the basic principles discovered by the three engineers. They also reportedly popularized the word "transformer" to describe a device for altering the EMF of an electric current, although the term had already been in use by 1882. In 1886, the Ganz Company installed the world's first power station that used AC generators to power a parallel-connected common electrical network, the steam-powered Rome-Cerchi power plant.

W. STANLEY, Jr.
INDUCTION COIL.

No. 349,611
Patented Sept. 21, 1886.
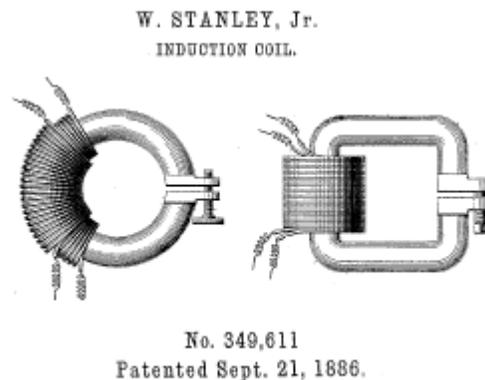
Stanley's 1886 design for adjustable gap open-core induction coils

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.
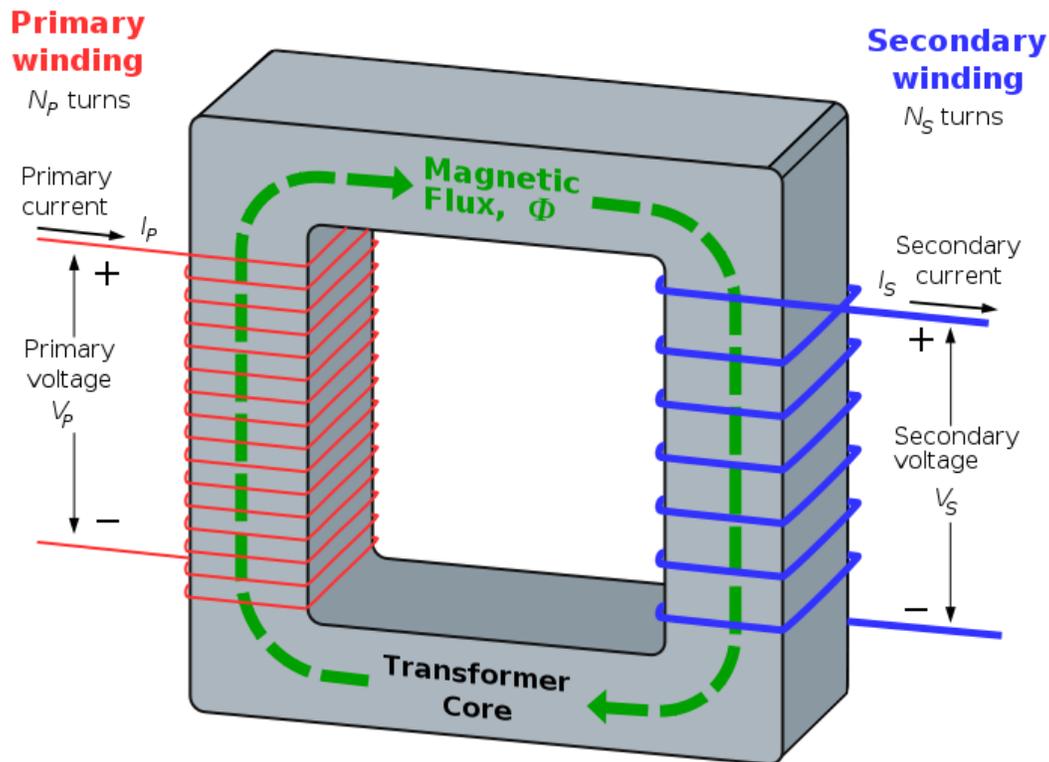
An ideal transformer

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

$$V_\mathrm{P} = N_\mathrm{P} \frac{d\Phi}{dt}.$$

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

$$\frac{V_\mathrm{s}}{V_\mathrm{P}} = \frac{N_\mathrm{s}}{N_\mathrm{P}}.$$

$N_\mathrm{p}/N_\mathrm{s}$ 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, $N_\mathrm{s}/N_\mathrm{p}$. *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

$$\frac{V_P}{V_S} = \frac{I_S}{I_P} = \frac{N_P}{N_S}$$
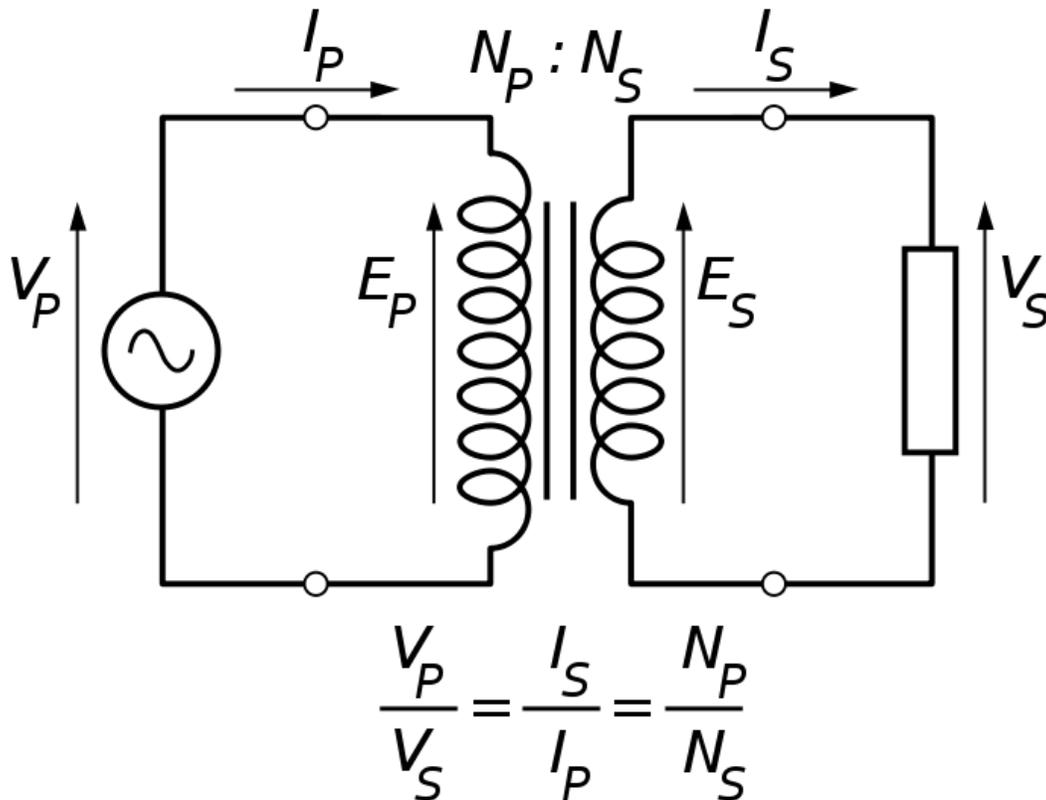
The ideal transformer as a circuit element

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 $(N_{\text{p}}/N_{\text{s}})^2 Z_{\text{s}}$. This relationship is reciprocal, so that the impedance Z_{p} of the primary circuit appears to the secondary to be $(N_{\text{s}}/N_{\text{p}})^2 Z_{\text{p}}$.

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

Primary winding   Secondary winding

Φ_{12} Main flux

$\Phi_{|\sigma 1}$ $\Phi_{|\sigma 2}$

Leakage flux

Φ_{21}
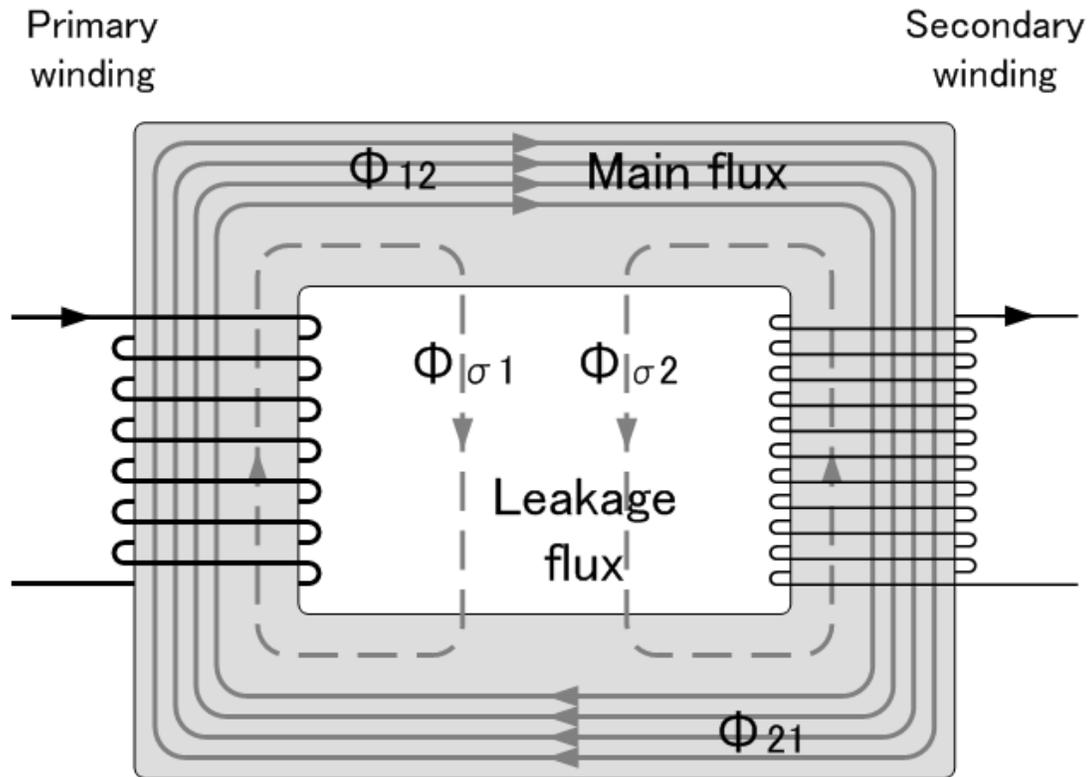
Leakage flux of a transformer

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

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

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

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

Effect of frequency

Transformer universal EMF equation

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

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

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

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

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

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

Operation of a transformer at its designed voltage but at a higher frequency than intended will lead to reduced magnetizing current; at lower frequency, the magnetizing current

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

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

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

Energy losses

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

Experimental transformers using superconducting windings achieve efficiencies of 99.85%. The increase in efficiency 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.
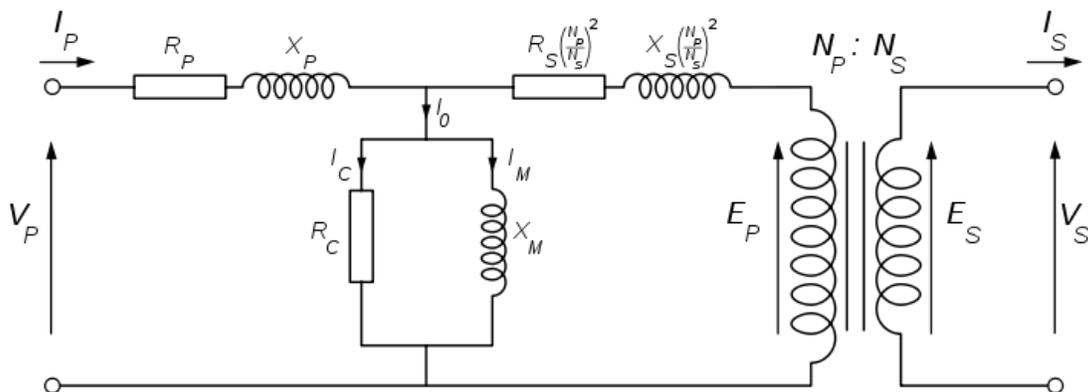
Equivalent circuit

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:
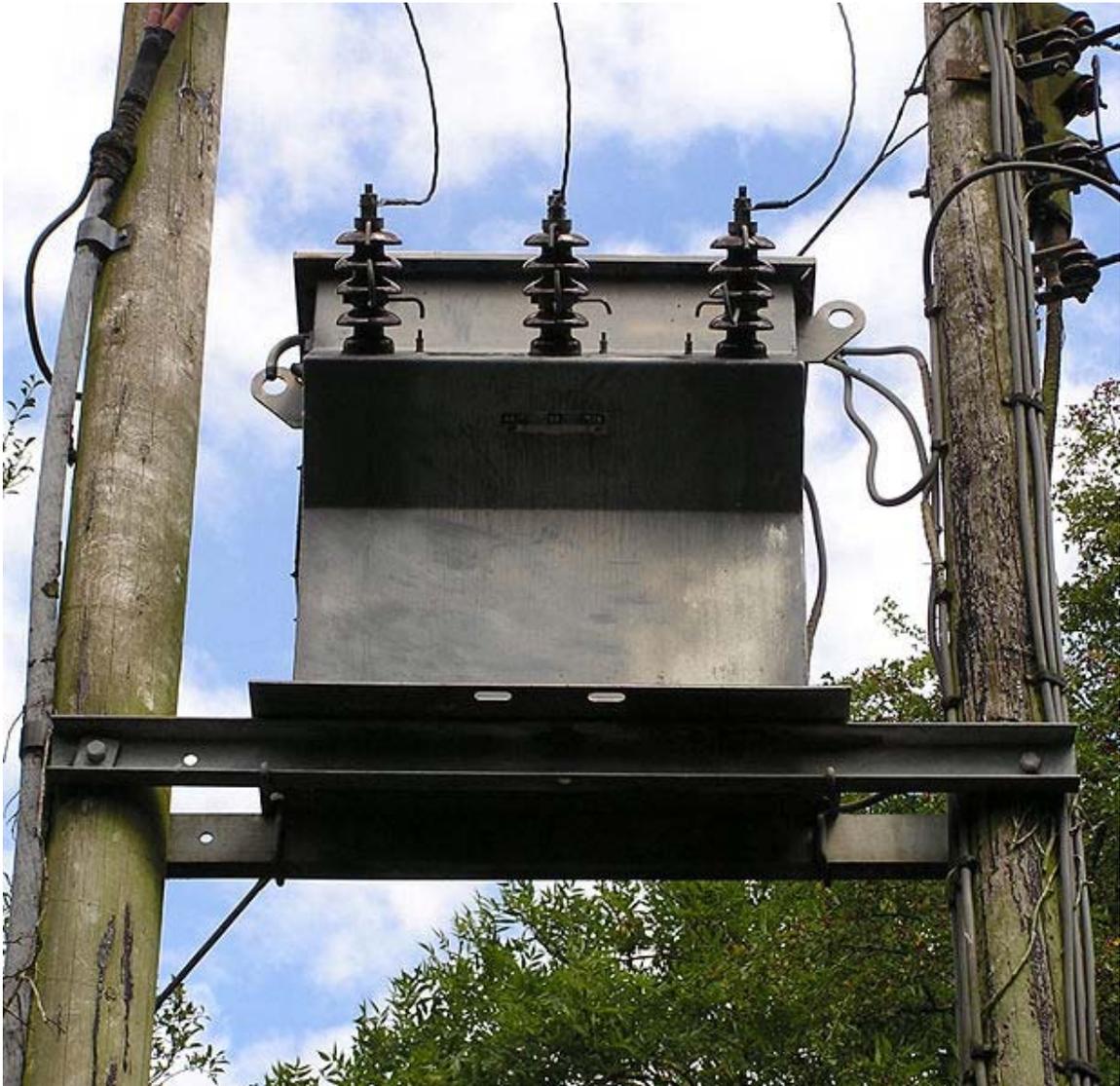
Autotransformer

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*.
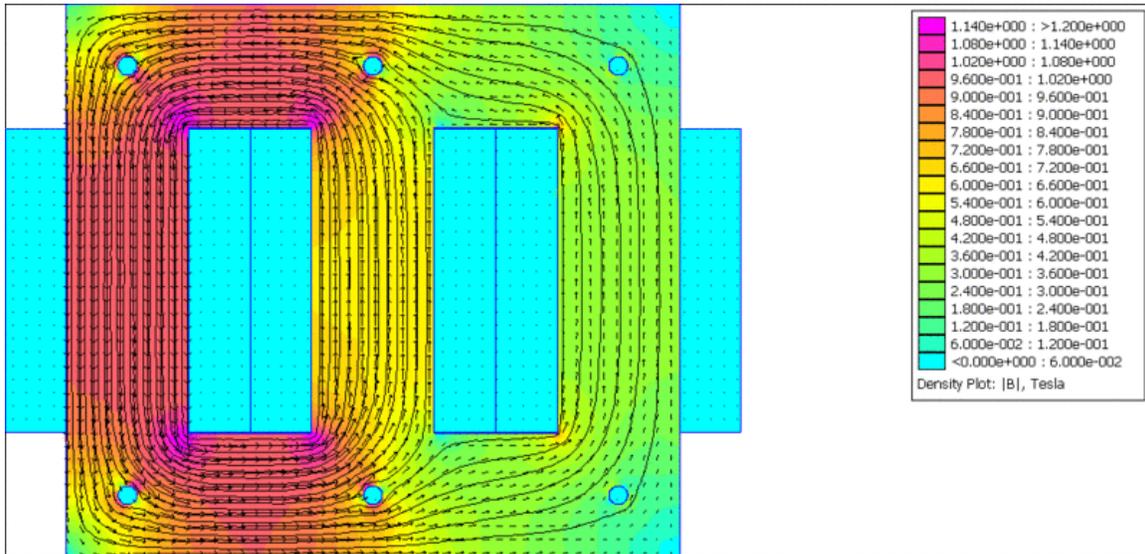
Polyphase transformers

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.
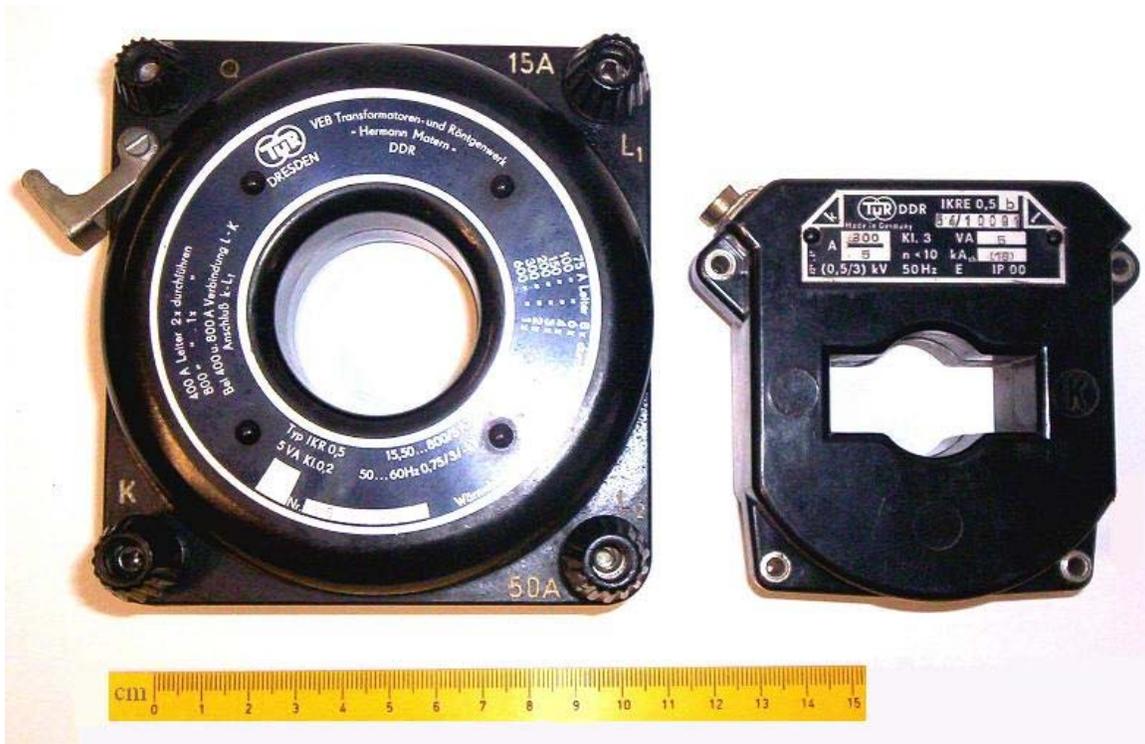
Audio transformers

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
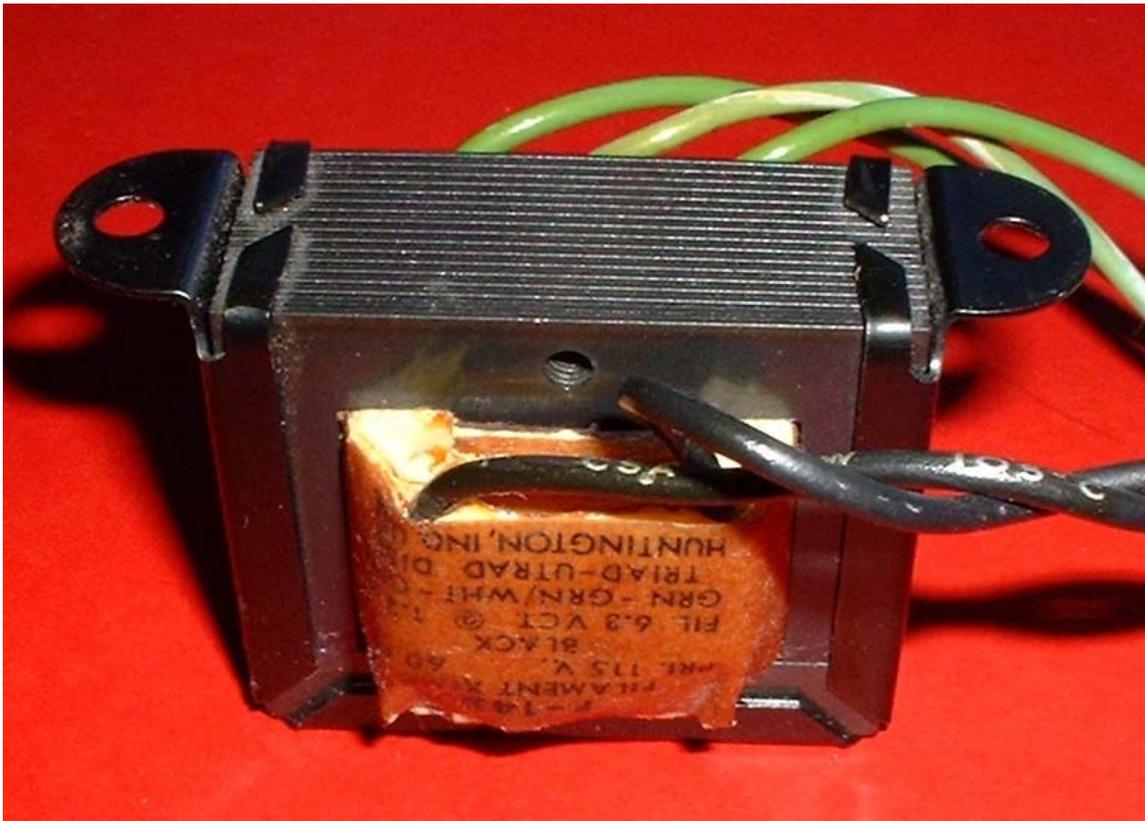
Laminated core transformer showing edge of laminations at top of photo

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 non-

conducting layer of insulation. The universal transformer equation indicates a minimum cross-sectional area for the core to avoid saturation.

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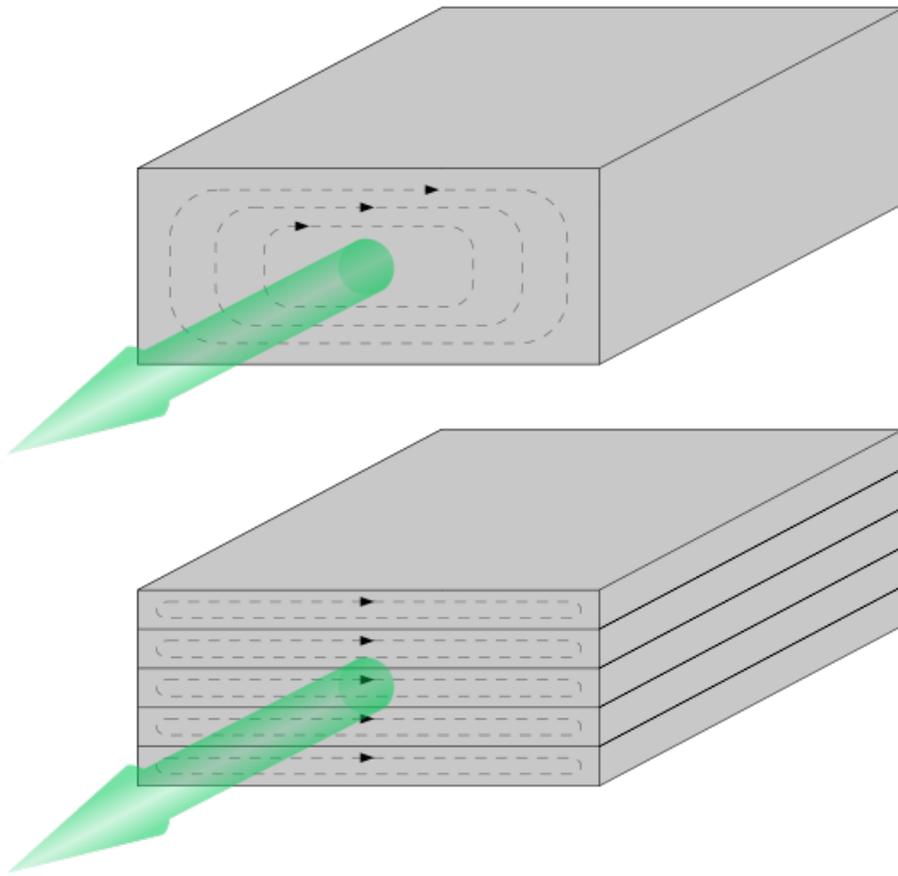
Laminating the core greatly reduces eddy-current losses

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

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

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

Solid cores

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

Toroidal cores
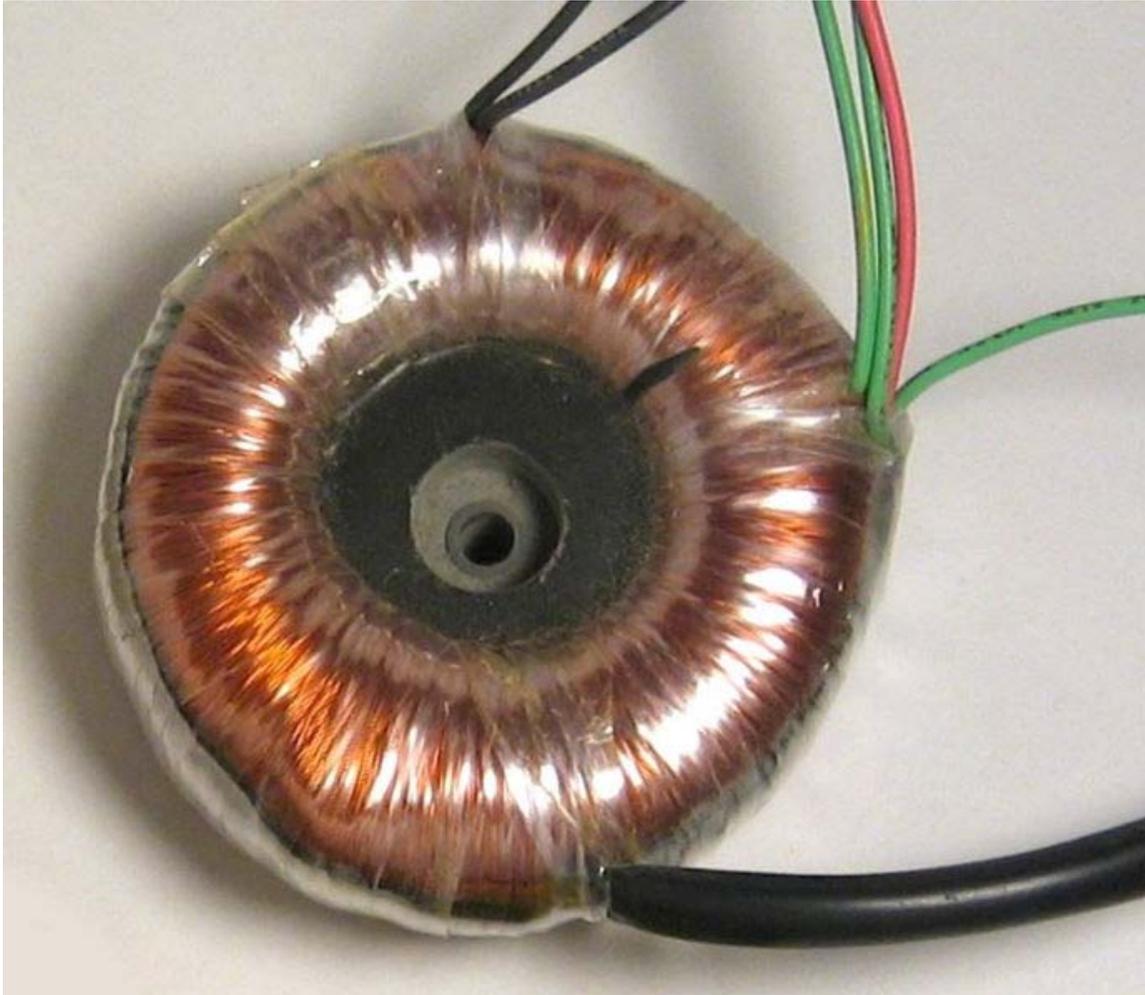
Small toroidal core transformer

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

Toroidal transformers are more efficient than the cheaper laminated E-I types for a similar power level. Other advantages compared to E-I types, include smaller size (about

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

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

Air cores

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

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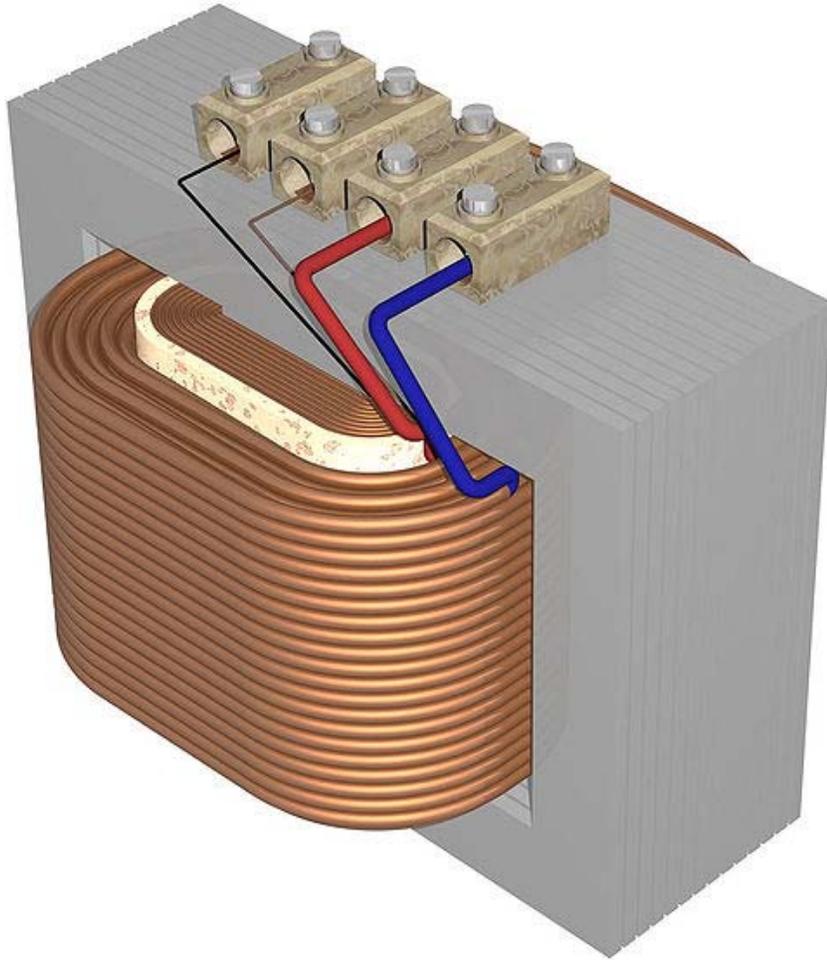
Windings are usually arranged concentrically to minimize flux leakage.
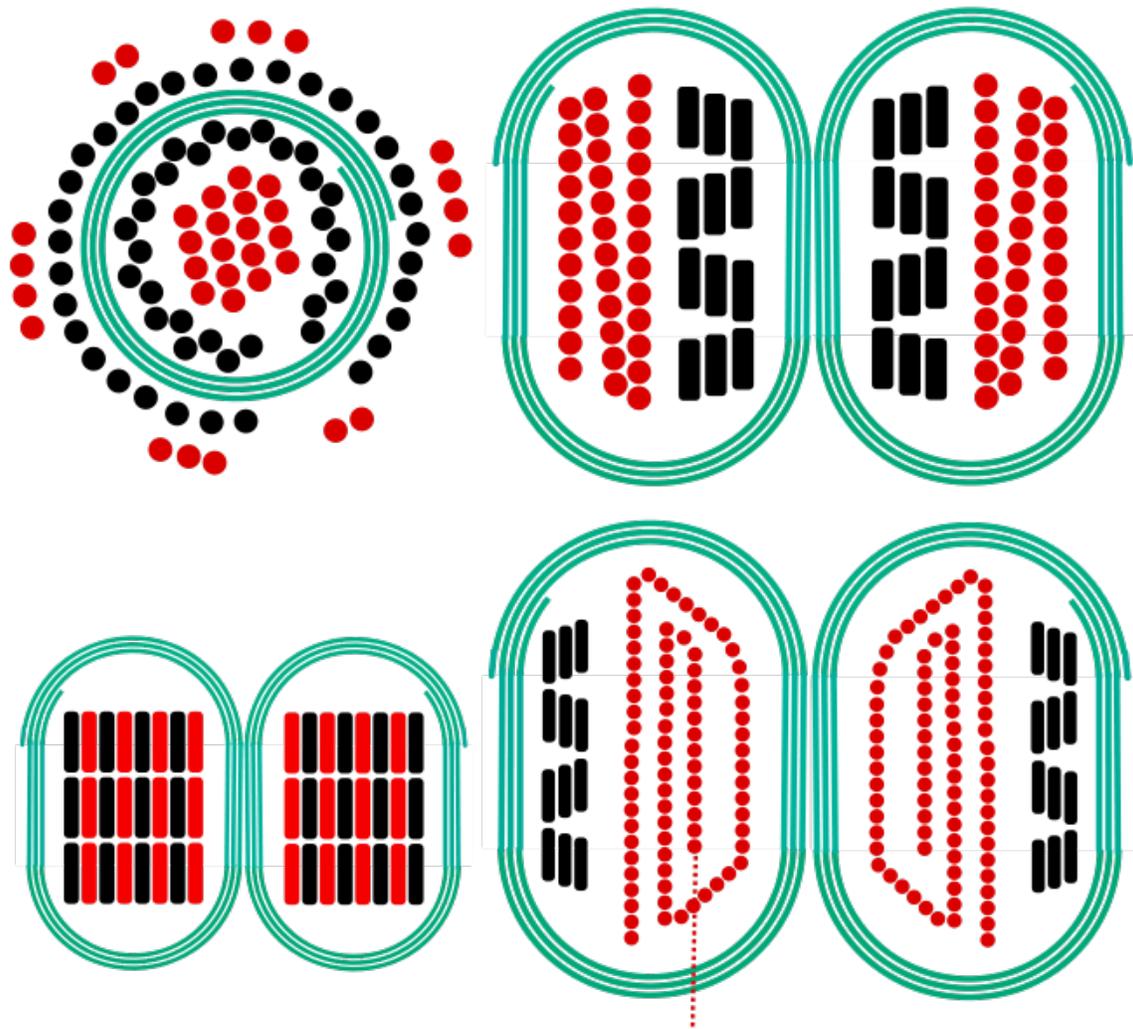
Cut view through transformer windings. White: insulator. Green spiral: Grain oriented silicon steel. Black: Primary winding made of oxygen-free copper. Red: Secondary winding. Top left: Toroidal transformer. Right: C-core, but E-core would be similar. The black windings are made of film. Top: Equally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

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

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

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

Both the primary and secondary windings on power transformers may have external connections, called taps, to intermediate points on the winding to allow selection of the voltage ratio. In 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.
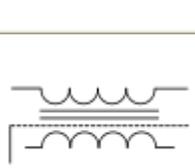
Transformers are also used extensively in electronic products to step down the supply voltage to a level suitable for the low voltage circuits they contain. The transformer also electrically isolates the end user from contact with the supply voltage.

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.
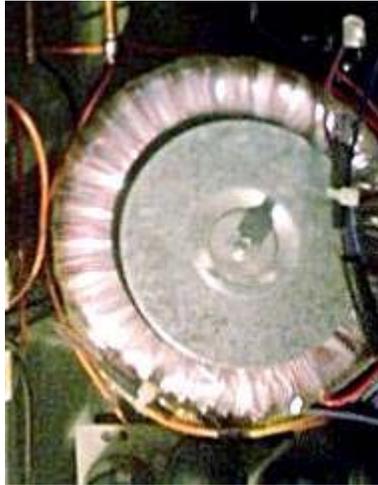
Power transformers

Laminated core
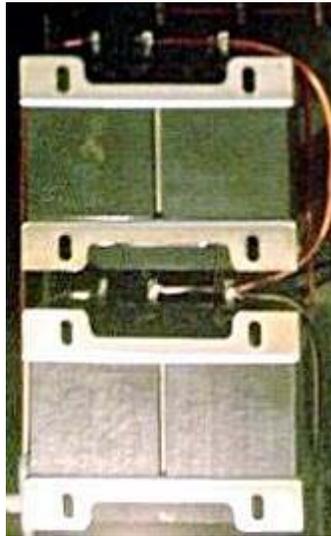
Laminated Core Transformer

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
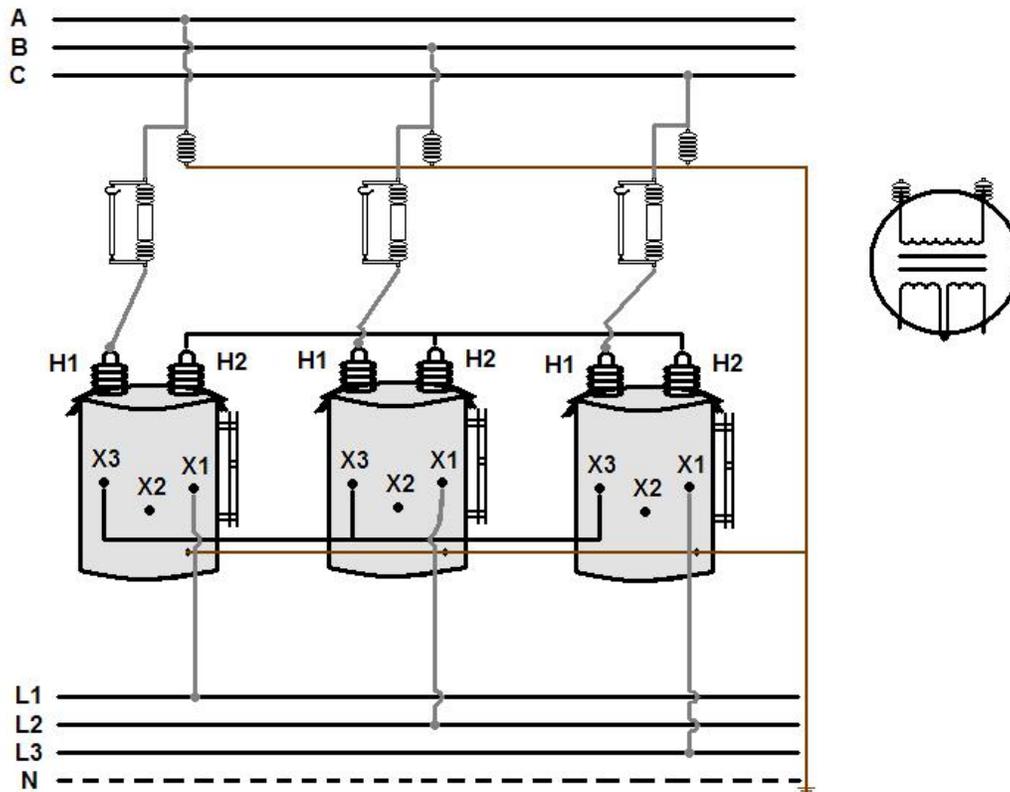
Example of Y Y Connection

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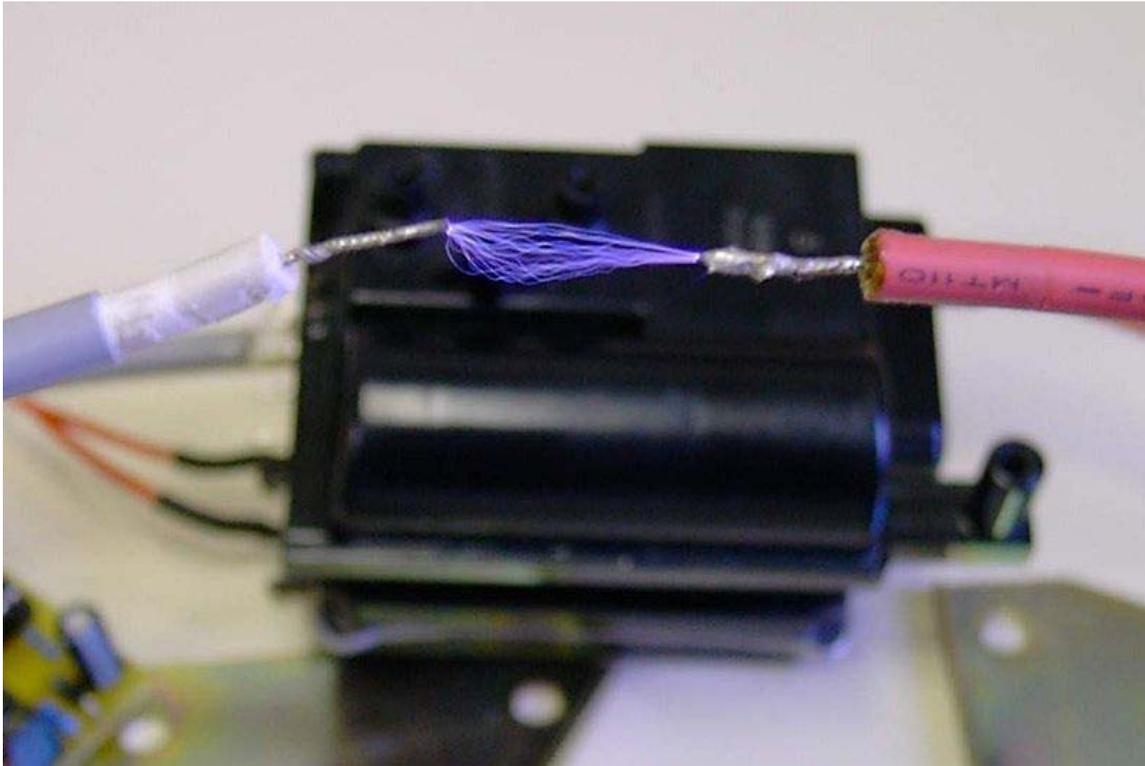
A 25 kV flyback transformer being used to generate an arc.

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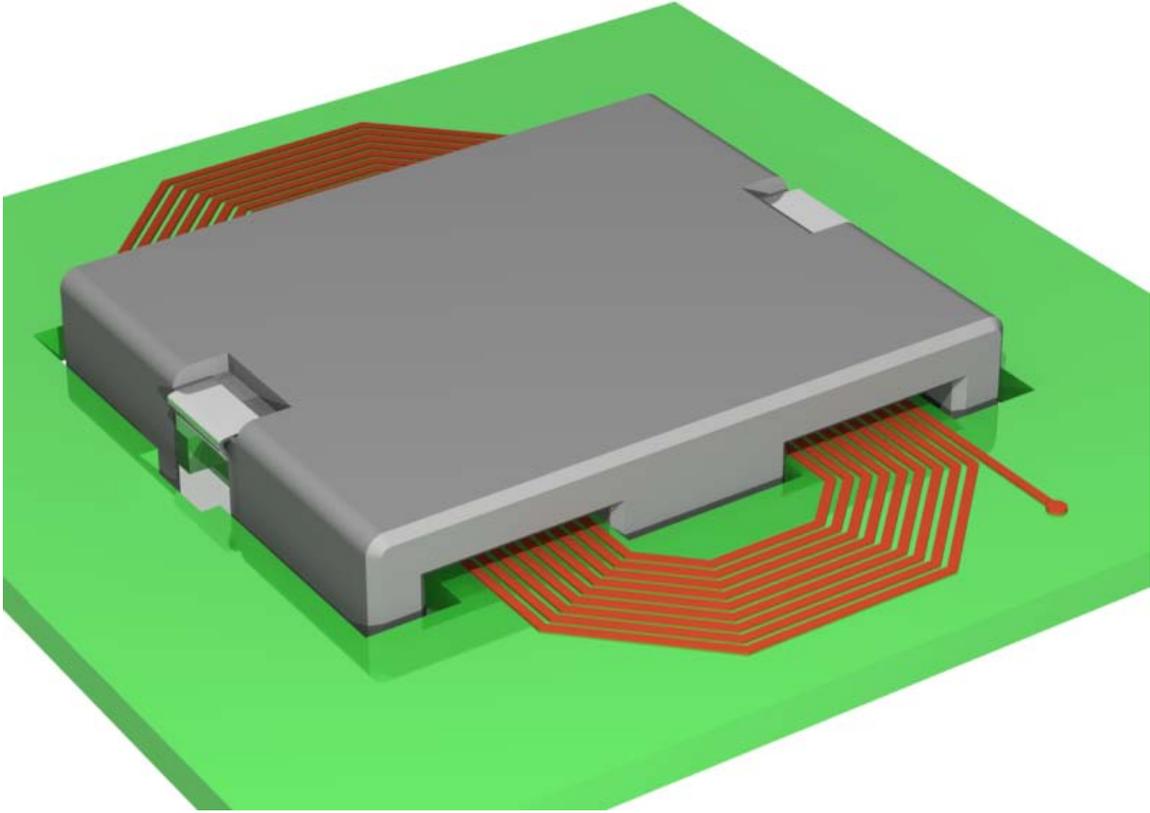
A planar transformer
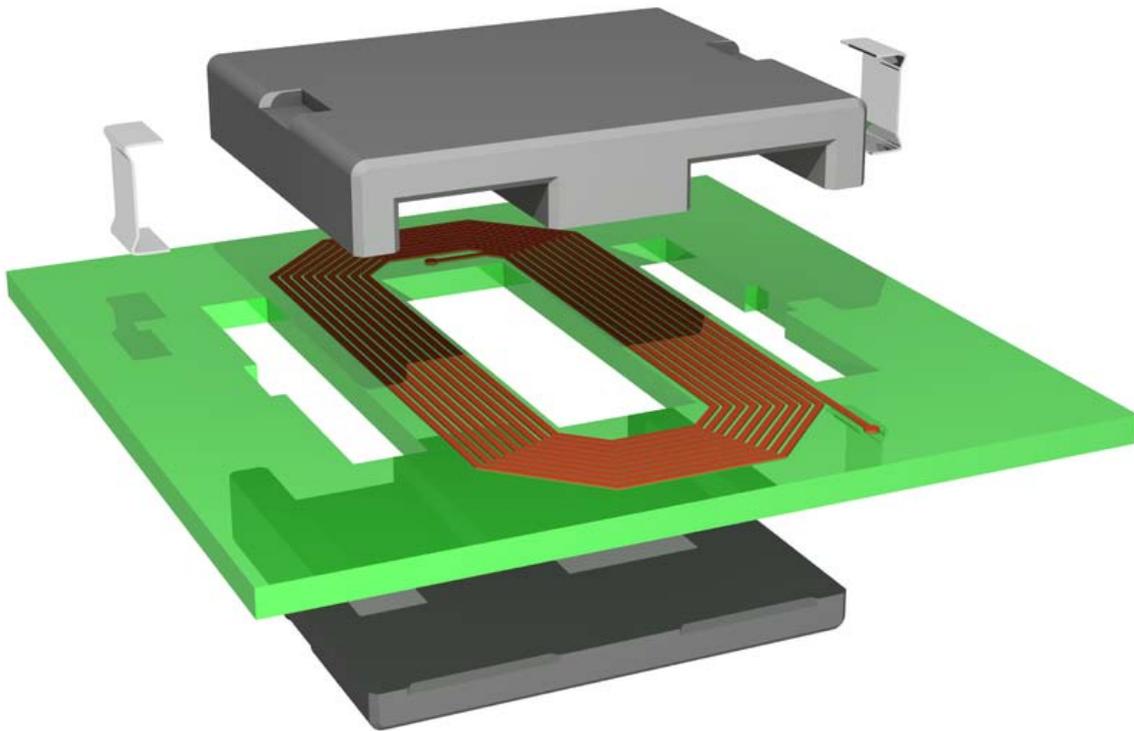
Exploded view: the spiral primary "winding" on one side of the PCB (the spiral secondary "winding" is on the other side of the PCB)

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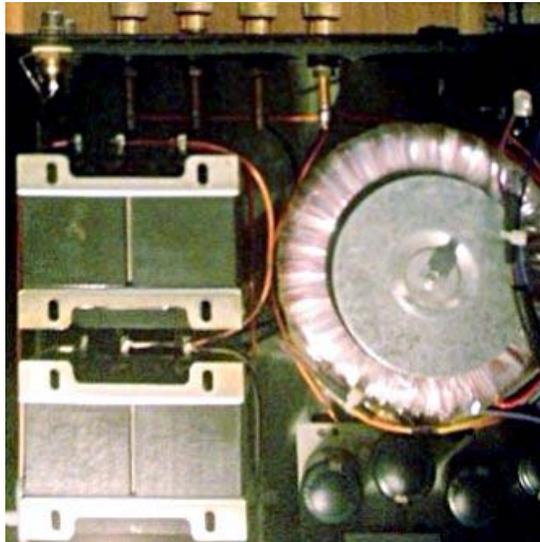
Transformers in a tube amplifier. Output transformers are on the left. The power supply toroidal transformer is on right.

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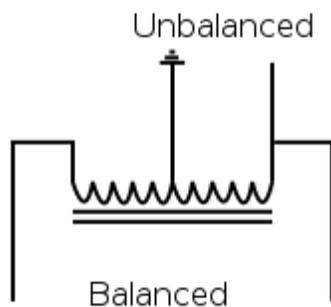
Autotransformer 4:1 wideband balun using two windings on a ferrite rod.

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.

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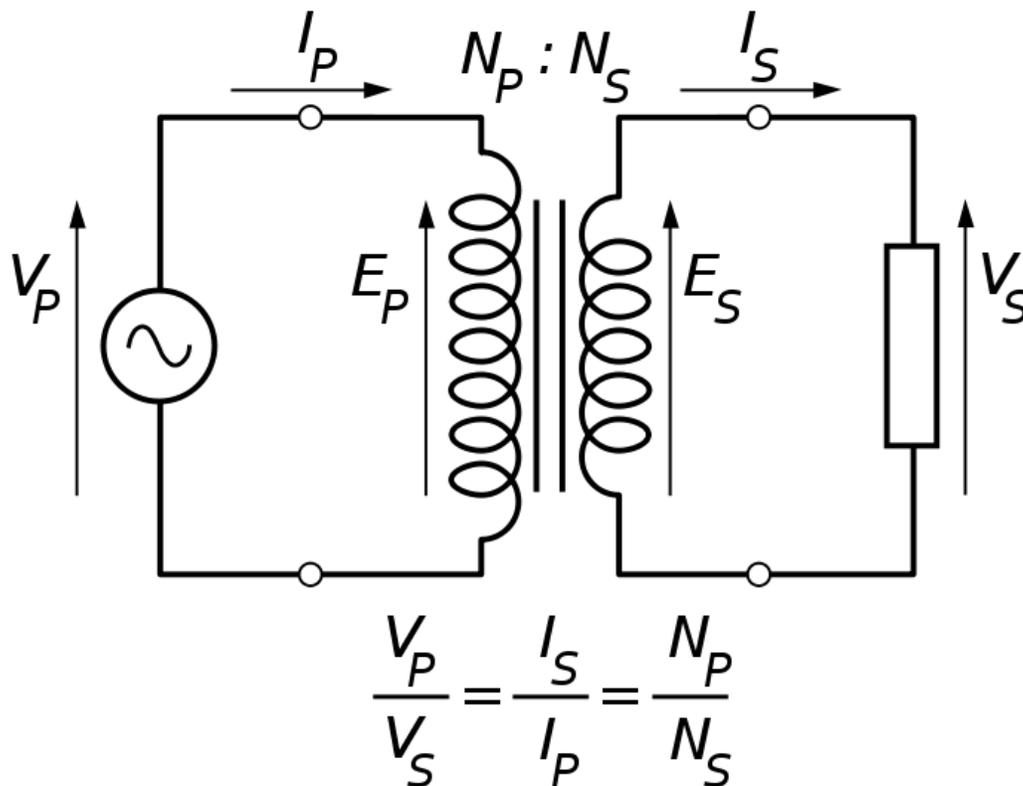
Isolated transformer

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
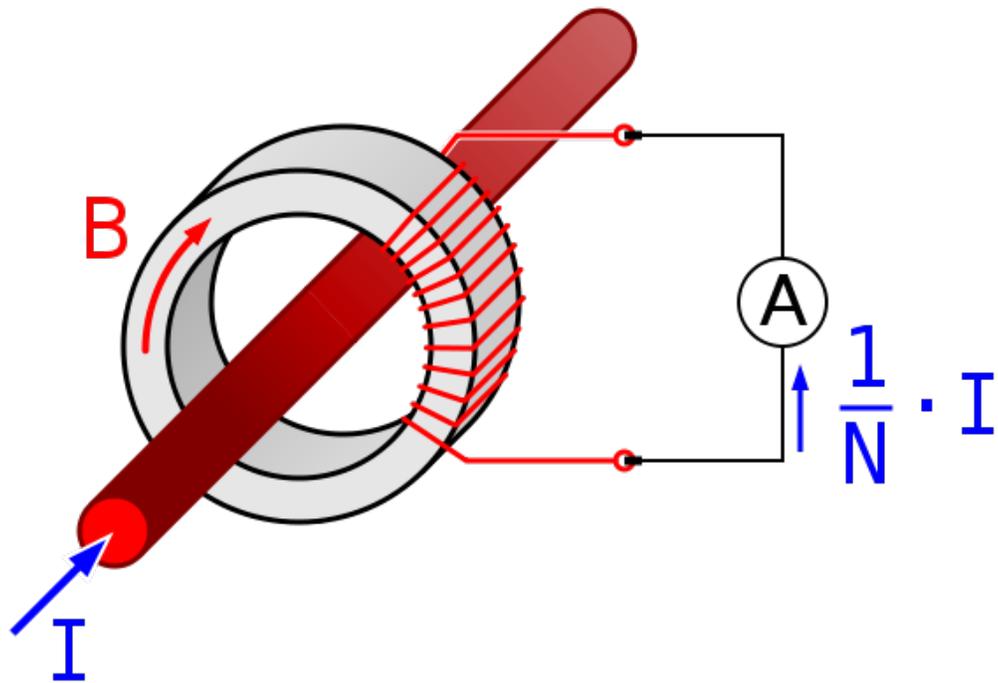
SF$_6$ 110 kV current transformer TGFM series, Russia

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.
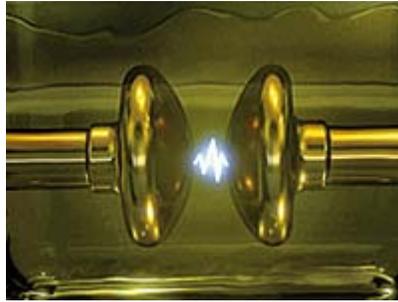
Voltage breakdown during transformer oil testing

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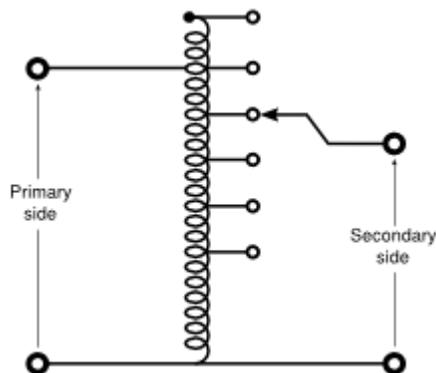
Single-phase tapped autotransformer with output voltage range of 40%–115% of input

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.
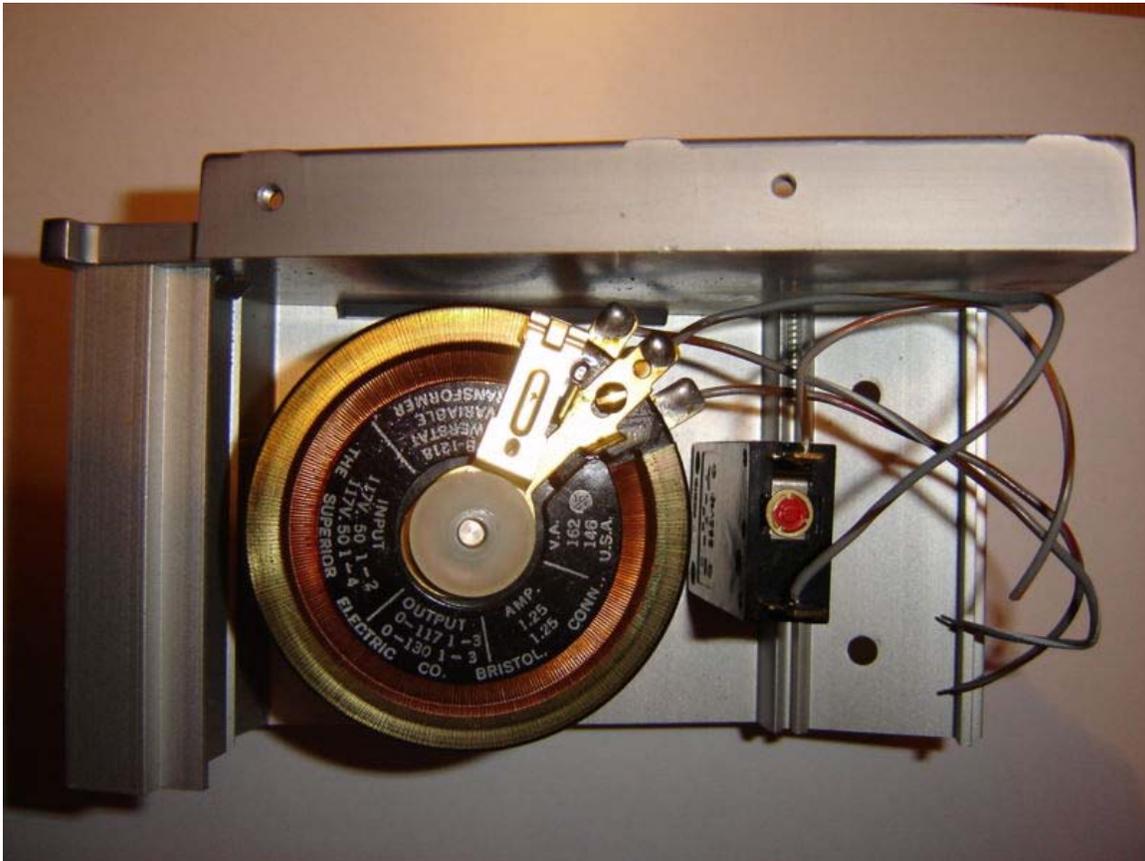
Variable Transformer - part of Tektronix 576 Curve Tracer

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 mm²). Into this is slipped a primary consisting of eight to ten turns of AWG No. 6 B & S wire (13.3 mm²) 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
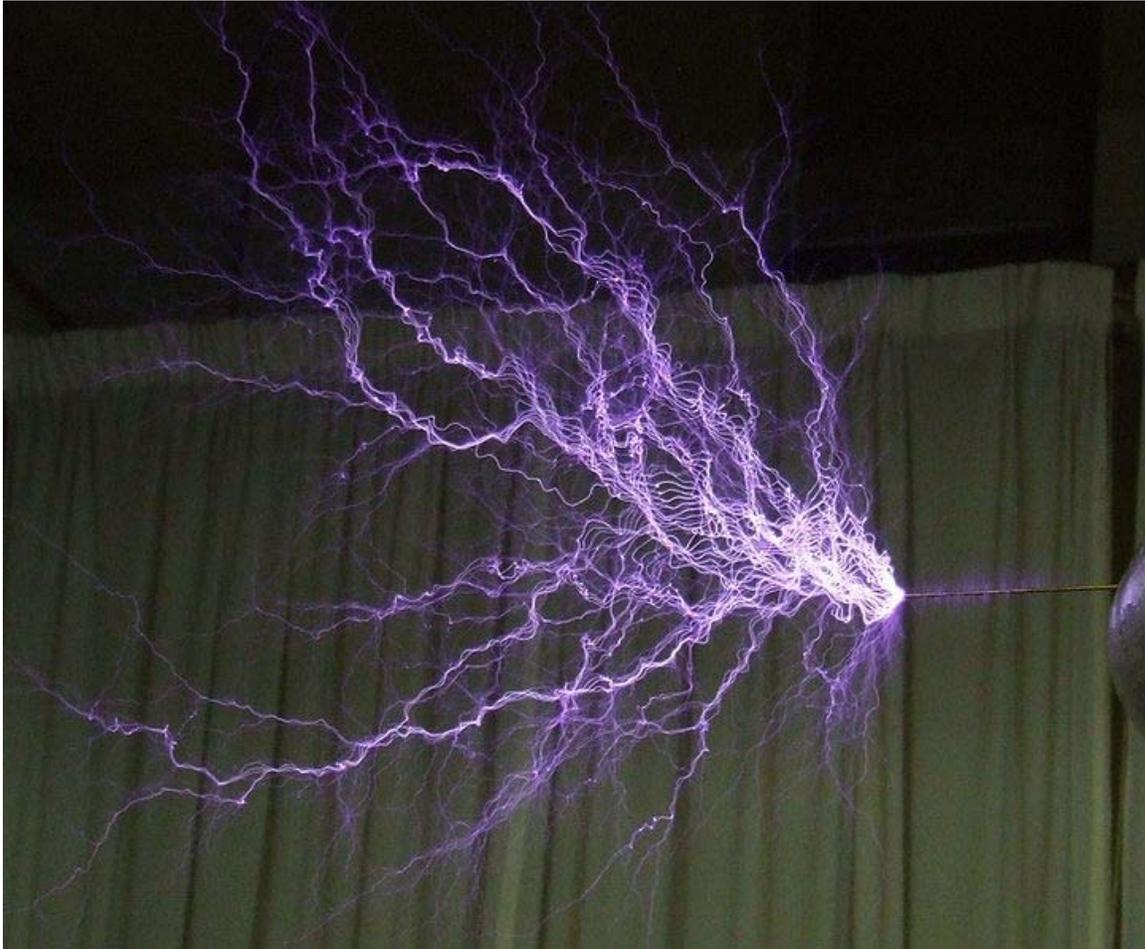
Electric discharge showing the lightning-like plasma filaments from a *Tesla coil*.

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.
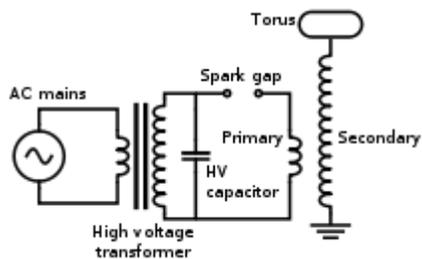
Applications

Transmission
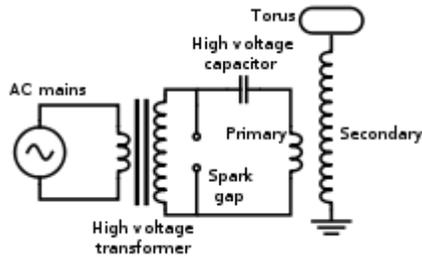
Typical Tesla Coil Schematic
This example circuit is designed to be driven by alternating currents. Here the spark gap shorts the high frequency across the first transformer. An inductance, not shown, protects the transformer. This design is favoured when a relatively fragile Neon Sign Transformer (NST) 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.
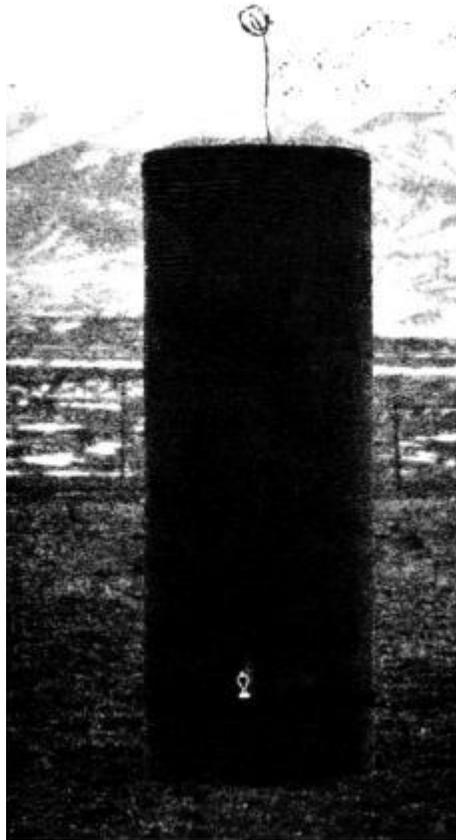
Tesla coil in one experiment of many conducted in Colorado Springs. This is a grounded tuned coil in resonance with a nearby transmitter; Light is glowing near the bottom.

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
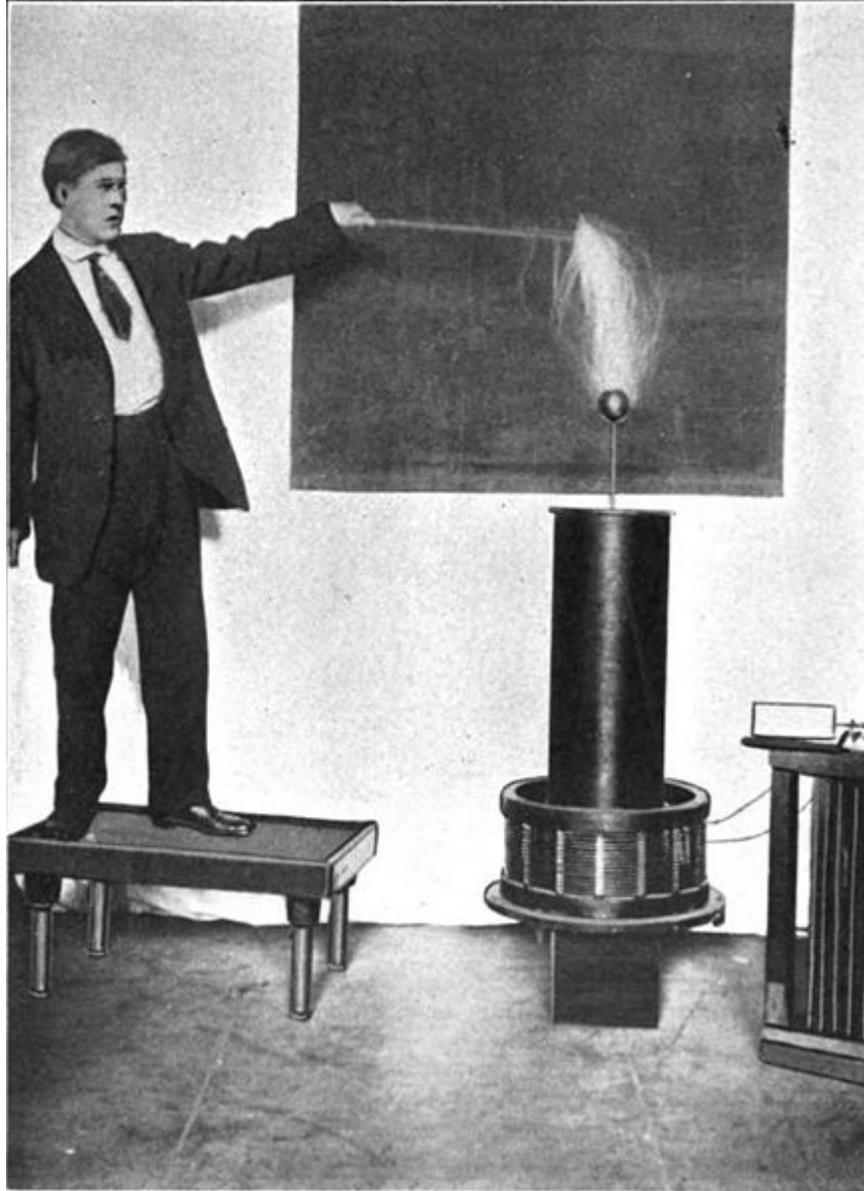
Student conducting Tesla coil streamers through his body, 1909

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
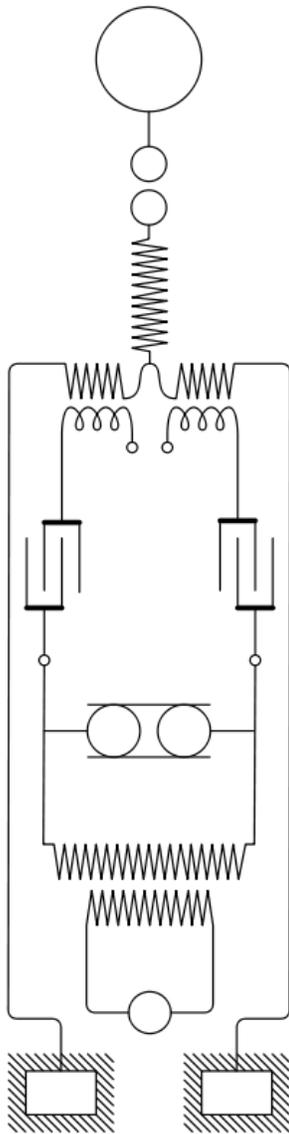
Classically driven configuration.

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

Toroidal Inductors and Transformers

Several small toroidal inductors. The major scale is in inches.
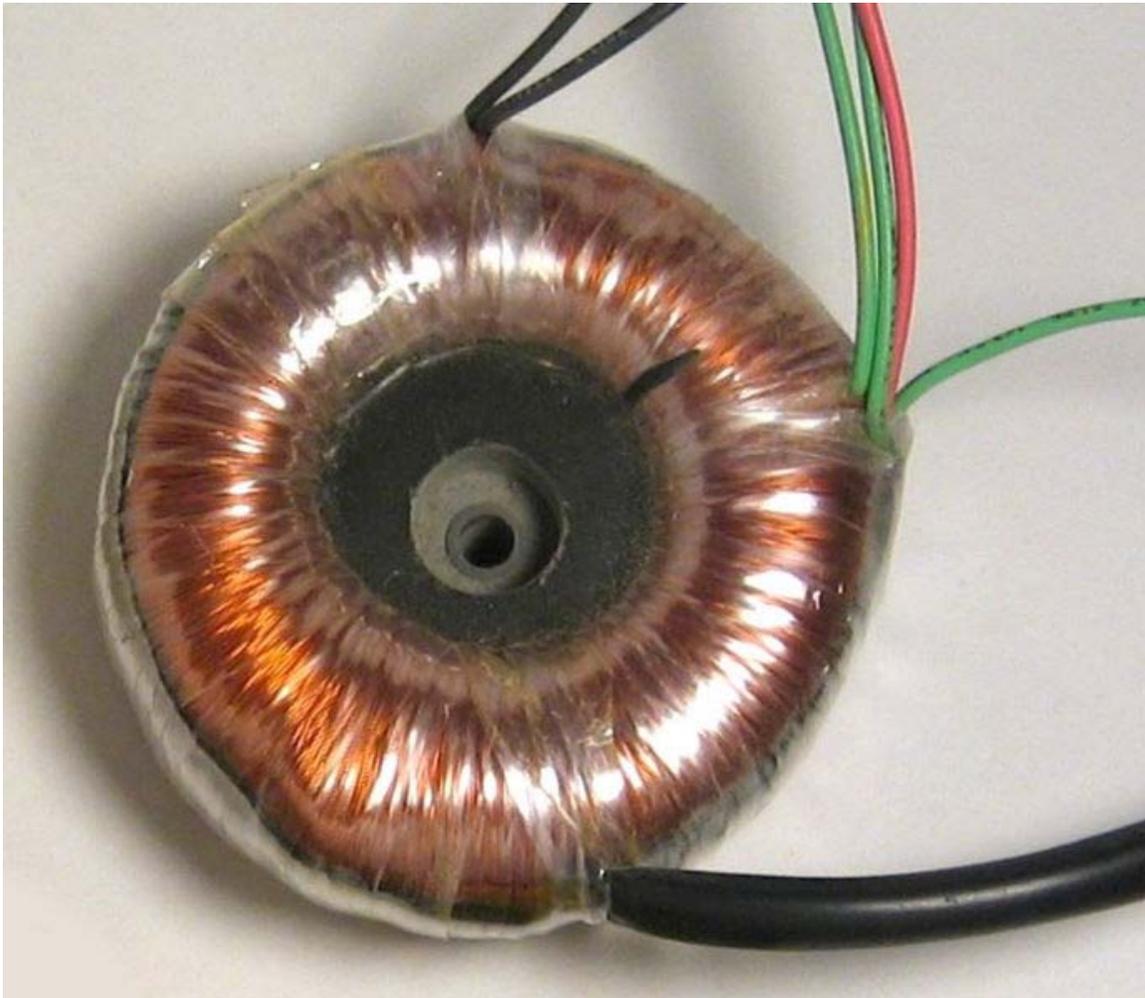
A small toroidal transformer.

Toroidal inductors and transformers are electronic components, typically consisting of a circular ring-shaped magnetic core of iron powder, ferrite, or other material around which wire is coiled to make an inductor. Toroidal coils are used in a broad range of applications, such as high-frequency coils and transformers. Toroidal inductors can have higher Q factors and higher inductance than similarly constructed solenoid coils. This is due largely to the smaller number of turns required when the core provides a closed magnetic path. The magnetic flux in a high permeability toroid is largely confined to the core; the confinement reduces the energy that can be absorbed by nearby objects, so toroidal cores offer some self-shielding.

In the geometry of torus-shaped magnetic fields, the poloidal flux direction threads the "donut hole" in the center of the torus, while the toroidal flux direction is parallel the core of the torus.

Total B Field Confinement by Toroidal Inductors

In some circumstance, the current in the winding of a toroidal inductor contributes only to the **B** field inside the windings and makes no contribution to the magnetic **B** field outside of the windings.

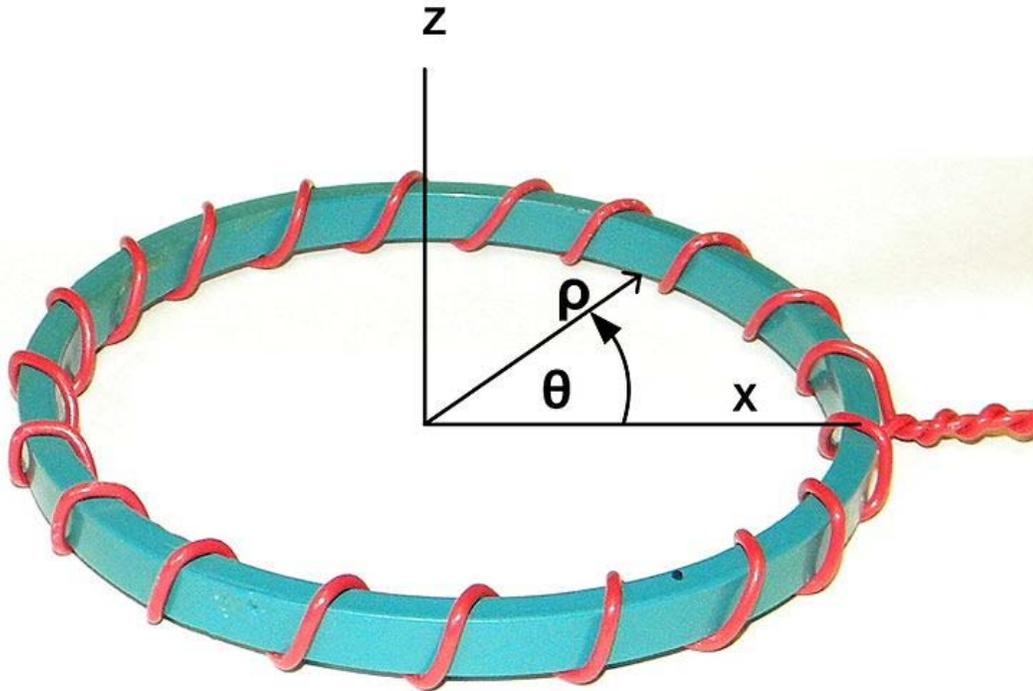## Sufficient conditions for total internal confinement of the B field

Fig. 1. Coordinate system. The Z axis is the nominal axis of symmetry. The X axis chosen arbitrarily to line up with the starting point of the winding. ρ is called the radial direction. θ is called the circumferential direction.
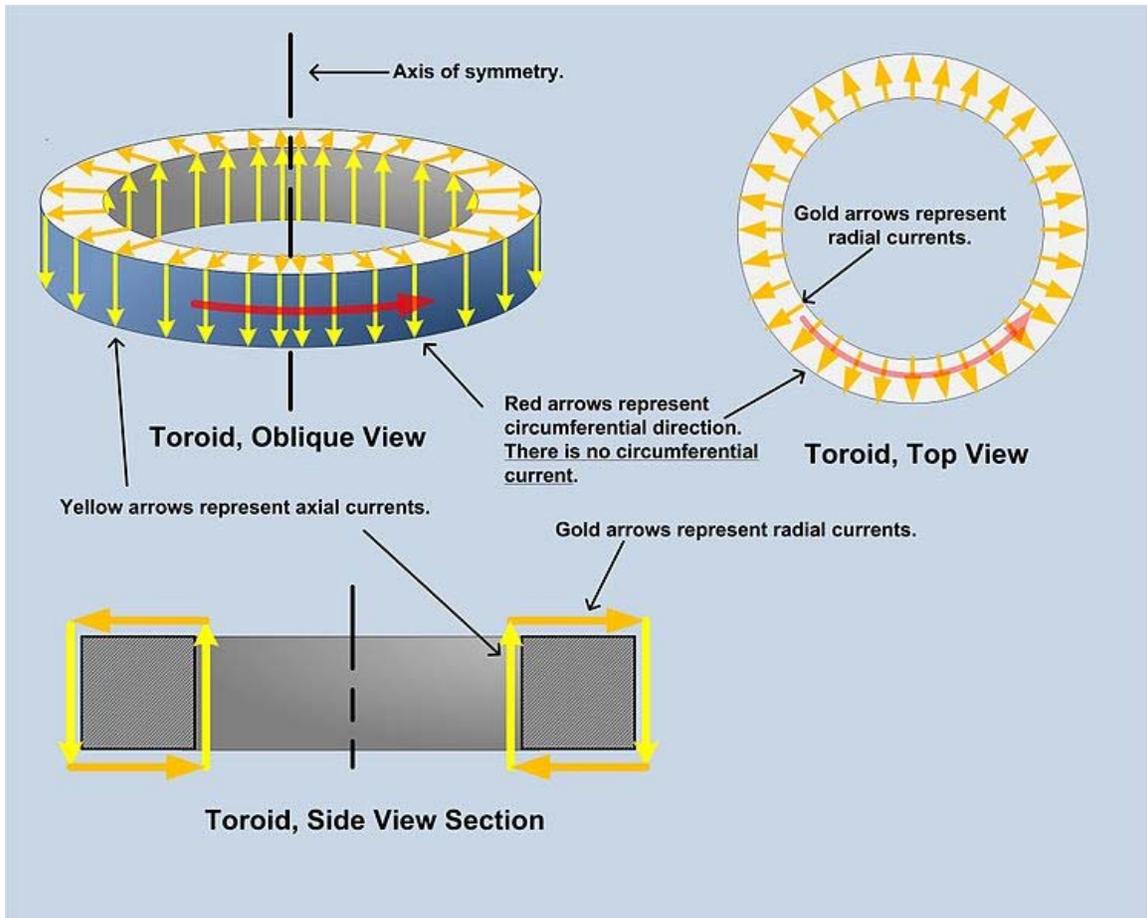
Fig. 2. An axially symmetric toroidal inductor with no circumferential current.

The absence of circumferential current and the axially symmetric layout of the conductors and magnetic materials are sufficient conditions for total internal confinement of the **B** field. (Some authors prefer to use the **H** field). Because of the symmetry, the lines of B flux must form circles of constant intensity centered on the axis of symmetry. The only lines of B flux that encircle any current are those that are inside the toroidal winding. Therefore, from Ampere's circuital law, the intensity of the B field must be zero outside the windings.
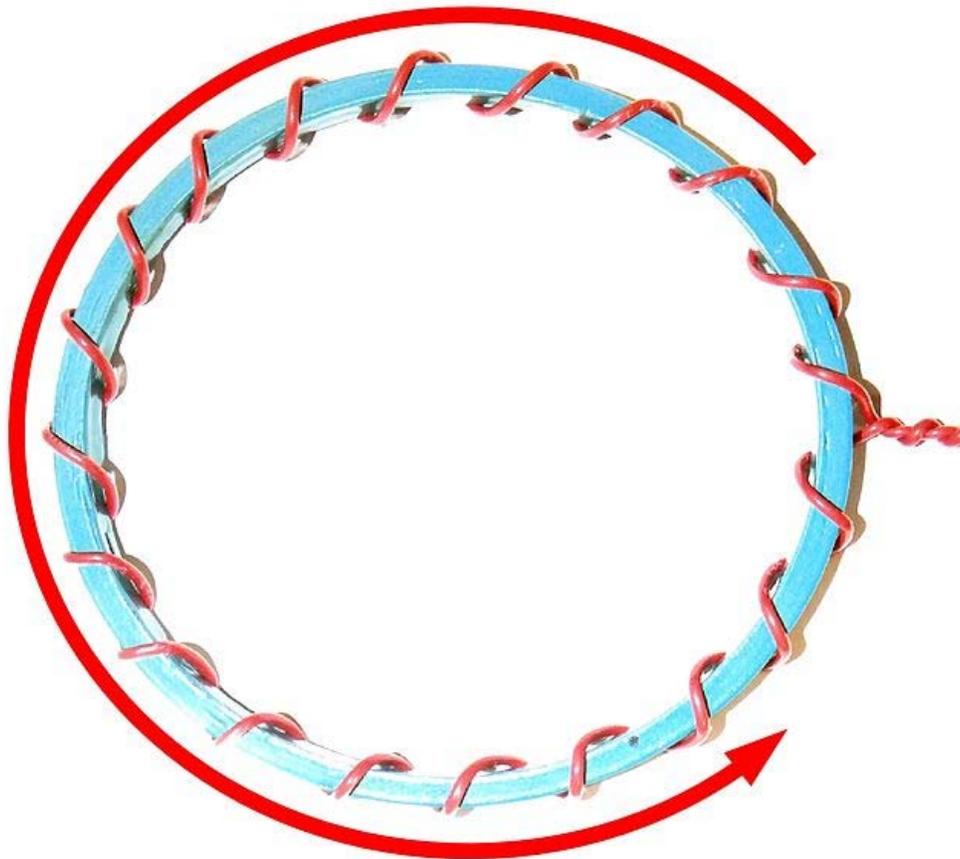
Fig. 3. Toroidal inductor with circumferential current

Figure 3 shows the most common toroidal winding. It fails both requirements for total B field confinement. Looking out from the axis, sometimes the winding is on the inside of the core and sometimes it is on the outside of the core. It is not axially symmetric in the near region. However, at points a distance of several times the winding spacing, the toroid does look symmetric. There is still the problem of the circumferential current. No matter how many times the winding encircles the core and no matter how thin the wire, this toroidal inductor will function as a one coil loop in the plane of the toroid. This winding will also produce and be susceptible to an **E** field in the plane of the inductor.

Figures 4-6 show different ways to neutralize the circumferential current. Figure 4 is the simplest and has the advantage that the return wire can be added after the inductor is bought or built.
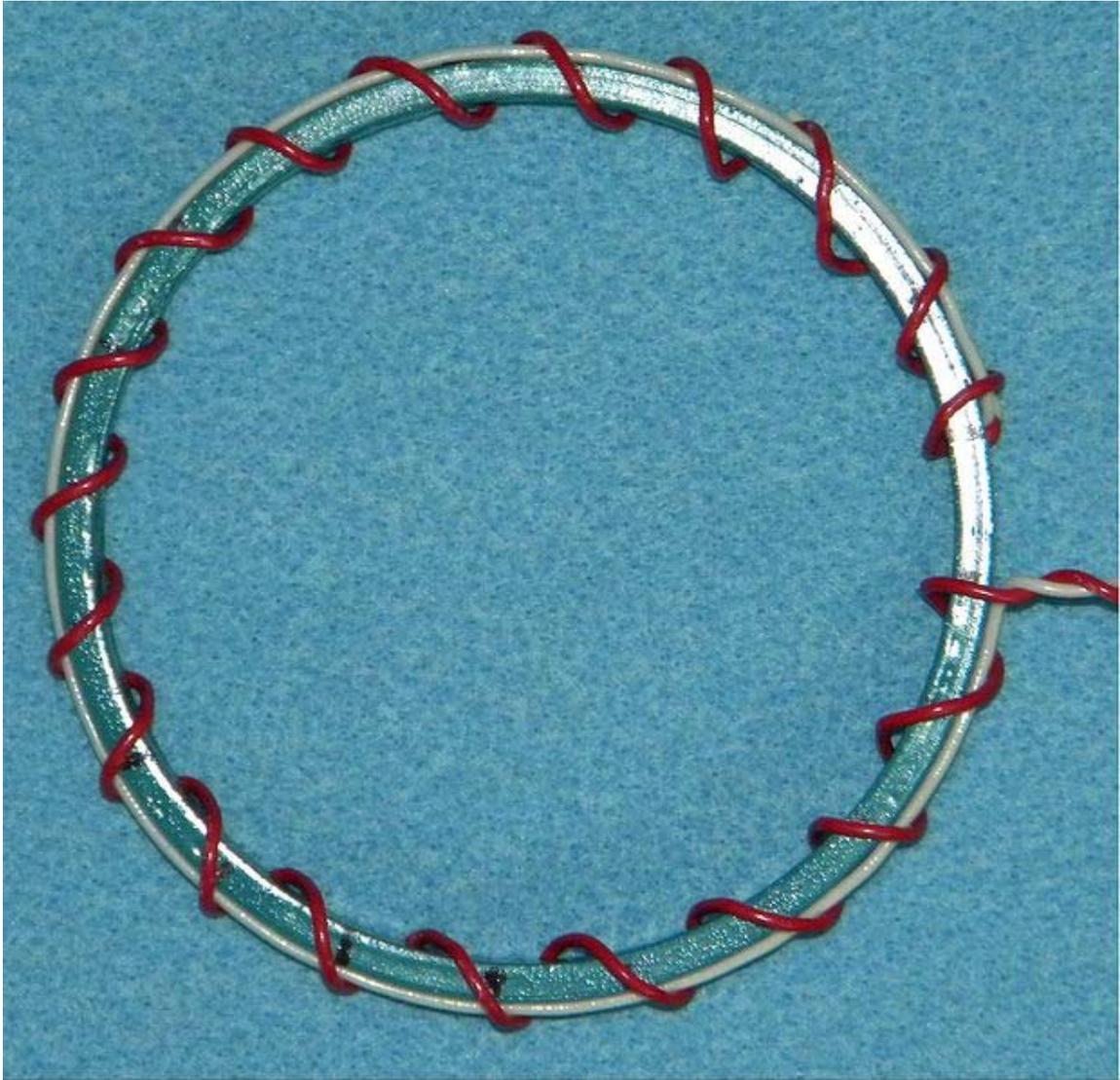
Fig. 4. Circumferential current countered with a return wire. The wire is white and runs between the outer rim of the inductor and the outer portion of the winding.

Fig. 5. Circumferential current countered with a return winding.

Fig. 6. Circumferential current countered with a split return winding.
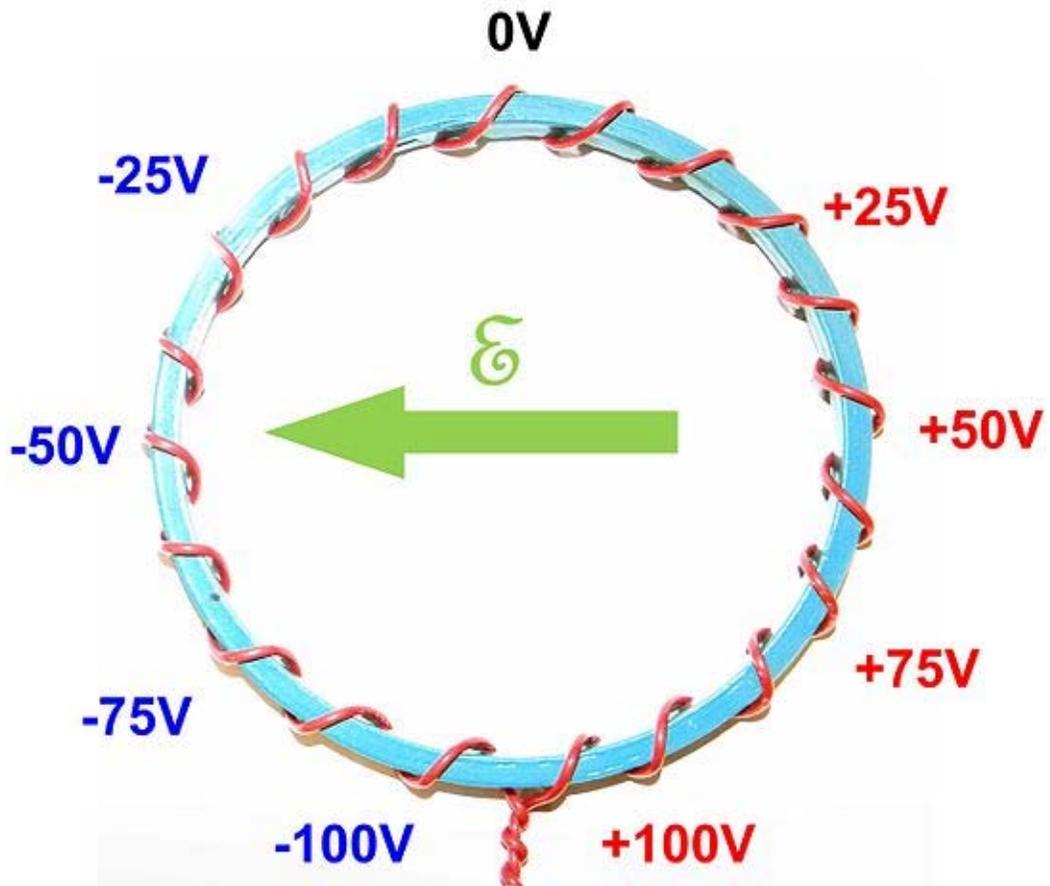
E Field in the Plane of the Toroid

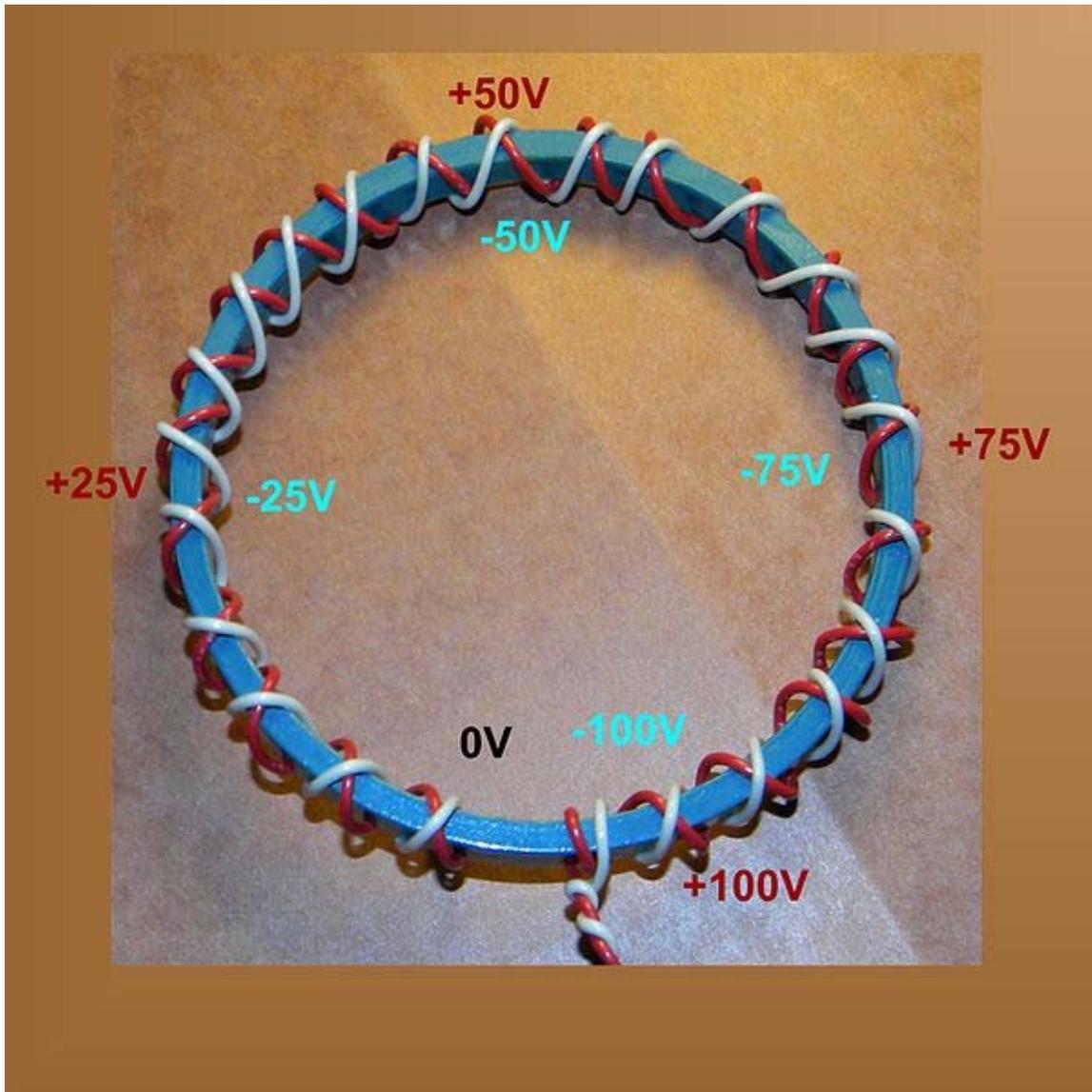Fig. 7. Simple toroid and the E-field produced. +/- 100 Volt excitation assumed.

Fig. 8. Voltage distribtion with return winding. +/- 100 Volt excitation assumed.

There will be a distribution of potential along the winding. This can lead to an **E**-Field in the plane of the toroid and also a susceptibility to an **E** field in the plane of the toroid as shown in figure 7. This can be mitigated by using a return winding as shown on figure 8. With this winding, each place the winding crosses itself, the two parts will be at equal and opposite polarity which substantially reduces the E field generated in the plane.

Torroidal Inductor/Transformer and Magnetic Vector Potential
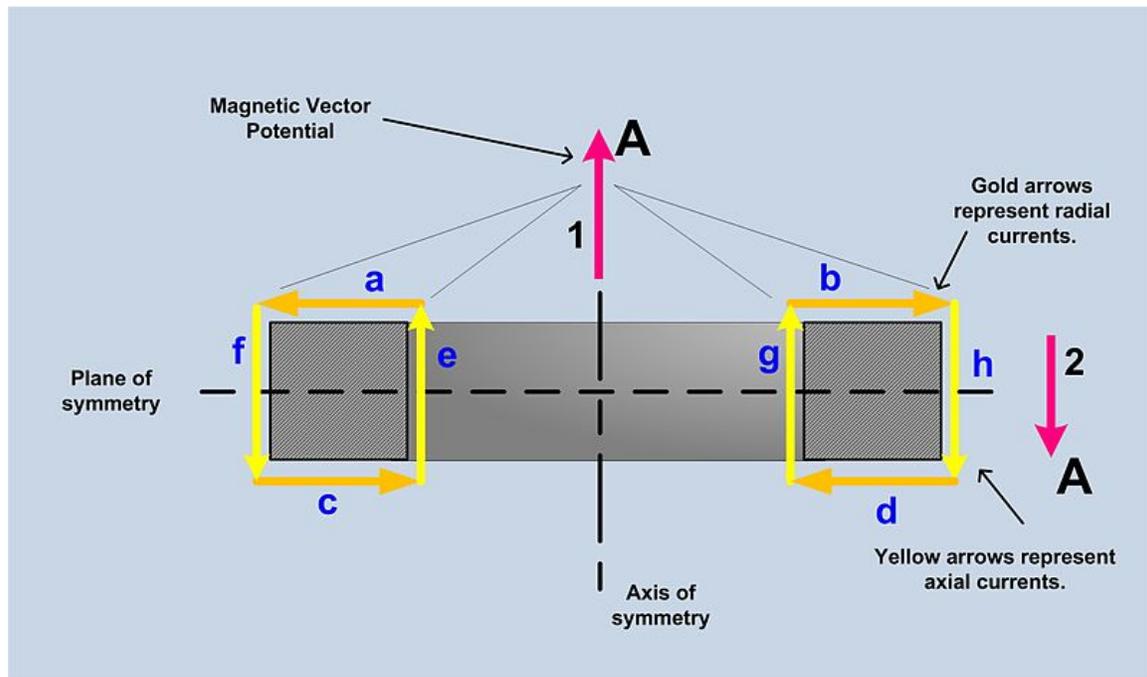
Showing the development of the magnetic vector potential around a symmetric torroidal inductor.

The **A** field is accurate when using the assumption $bfA = 0$. This would be true under the following assumptions:

- 1. the Coulomb gauge is used
- 2. the Lorenz gauge is used and there is no distribution of charge, $\rho = 0$
- 3. the Lorenz gauge is used and zero frequency is assumed
- 4. the Lorenz gauge is used and a non-zero frequency that is low enough to neglect $\dfrac{1}{c^2}\dfrac{\partial \phi}{\partial t}$ is assumed.

Number 4 will be presumed for the rest of this section and may be referred to the "quasi-static condition".

Although the axially symmetric toroidal inductor with no circumferential current totally confines the **B** field within the windings, the **A** field (magnetic vector potential) is not confined. Arrow #1 in the picture depicts the vector potential on the axis of symmetry. Radial current sections a and b are equal distances from the axis but pointed in opposite directions, so they will cancel. Likewise segments c and d cancel. In fact all the radial current segments cancel. The situation for axial currents is different. The axial current on the outside of the toroid is pointed down and the axial current on the inside of the toroid is pointed up. Each axial current segment on the outside of the toroid can be matched

with an equal but oppositely directed segment on the inside of the toroid. The segments on the inside are closer than the segments on the outside to the axis, therefore there is a net upward component of the **A** field along the axis of symmetry.
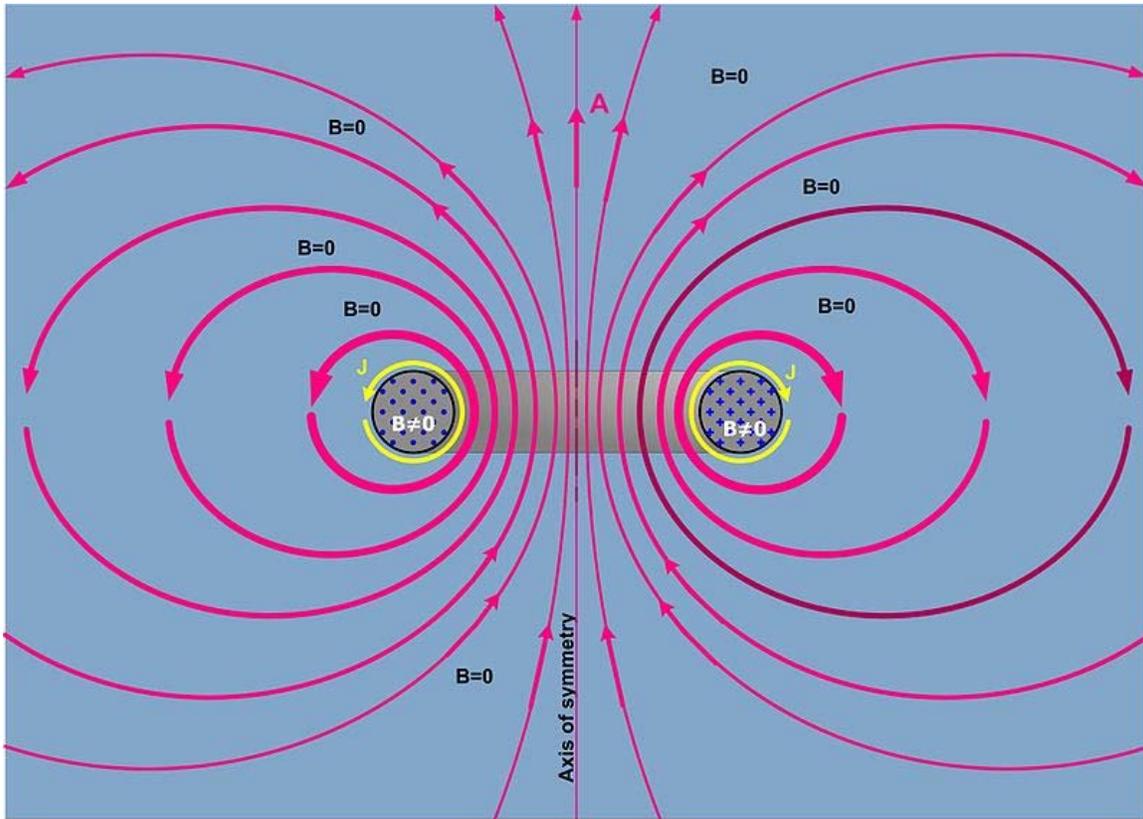
Representing the magnetic vector potential (A), magnetic flux (B), and current density (j) fields around a toroidal inductor of circular cross section. Thicker lines indicate field lines of higher average intensity. Circles in cross section of the core represent B flux coming out of the picture. Plus signs on the other cross section of the core represent B flux going into the picture. Div **A** = 0 has been assumed.

Since the equations $\nabla \times \mathbf{A} = \mathbf{B}$, and $\nabla \times \mathbf{B} = \mu_0 \mathbf{j}$ (assuming quasi-static conditions, i.e. $\frac{\partial E}{\partial t} \to 0$) have the same form, then the lines and contours of **A** relate to **B** like the lines and contours of **B** relate to **j**. Thus, a depiction of the **A** field around a loop of **B** flux (as would be produced in a toroidal inductor) is qualitatively the same as the **B** field around a loop of current. The figure to the left is an artist's depiction of the **A** field around a totoidal inductor. The thicker lines indicate paths of higher average intensity (shorter paths have higher intensity so that the path integral is the same). The lines are just drawn to look good and impart general look of the **A** field.

Toroidal Transformer Action in the Presence of Total B field Confinement

The **E** and **B** fields can be computed from the **A** and ϕ (scalar electric potential) fields

$$\mathbf{B} = \nabla \times \mathbf{A}. \text{ and }: \quad \mathbf{E} = -\nabla\phi - \frac{\partial \mathbf{A}}{\partial t}$$

and so even if the region outside thewindings is devoid of **B** field, it is filled with non-zero **E** field.

The quantity $\frac{\partial \mathbf{A}}{\partial t}$ is responsible for the desirable magnetic field coupling between primary and secondary while the quantity $\nabla\phi$ is responsible for the undesirable electric field coupling between primary and secondary. Transformer designers attempt to minimize the electric field coupling. For the rest of this section, $\nabla\phi$ will assumed to be zero unless otherwise specified.

Stokes theorem applies, so that the path integral of **A** is equal to the enclosed **B** flux, just as the path integral **B** is equal to a constant times the enclosed current

The path integral of **E** along the secondary winding gives the secondary's induced EMF (Electro-Motive Force).

$$\mathbf{EMF} = \oint_{path} \mathbf{E} \cdot dl = -\oint_{path} \frac{\partial \mathbf{A}}{\partial t} \cdot dl = -\frac{\partial}{\partial t} \oint_{path} \mathbf{A} \cdot dl = -\frac{\partial}{\partial t} \int_{surface} \mathbf{B} \cdot ds$$

which says the EMF is equal to the time rate of change of the B flux enclosed by the winding, which is the usual result.

Toroidal Transformer Poynting Vector Coupling from Primary to Secondary in the Presence of Total B field Confinement
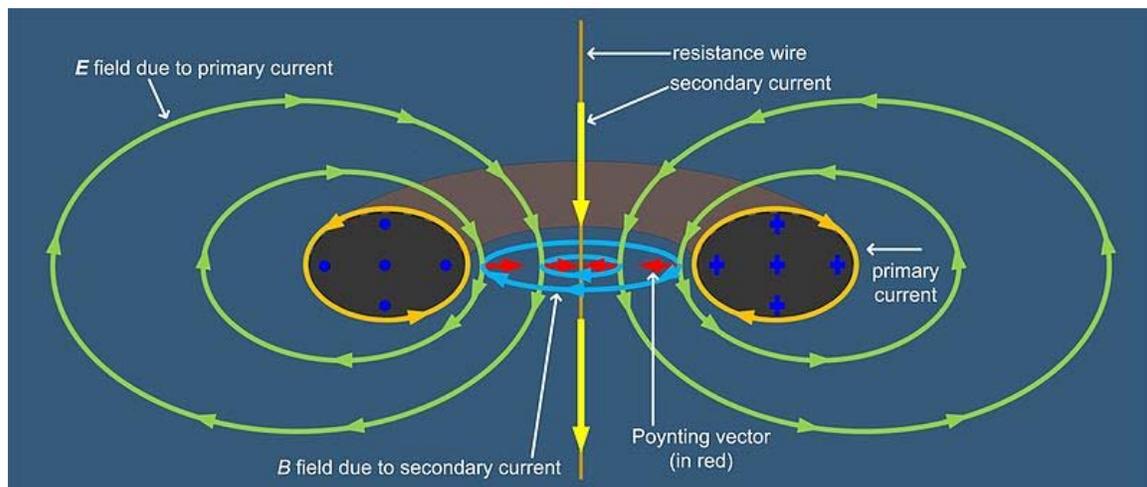
In this figure, blue dots indicate where B flux from the primary current comes out of the picture and plus signs indicate where it goes into the picture.

Explanation of the Figure

This figure shows the half section of a toroidal transformer. Quasi-static conditions are assumed, so the phase of each field is everywhere the same. The transformer, its windings and all things are distributed symmetrically about the axis of symmetry. The windings are such that there is no circumferential current. The requirements are met for full internal confinement of the **B** field due to the primary current. The core and primary winding are represented by the gray-brown torus. The primary winding is not shown, but the current in the winding at the cross section surface is shown as gold (or orange) ellipses. The **B** field caused by the primary current is entirely confined to the region enclosed by the primary winding (i.e. the core). Blue dots on the left hand cross section indicate that lines of **B** flux in the core come out of the left hand cross section. On the other cross section, blue plus signs indicate that the **B** flux enters there. The **E** field sourced from the primary currents is shown as green ellipses. The secondary winding is shown as a brown line coming directly down the axis of symmetry. In normal practice, the two ends of the secondary are connected together with a long wire that stays well away from the torus, but to maintain the absolute axial symmetry, the entire apparatus is envisioned as being inside a perfectly conductive sphere with the secondary wire "grounded" to the inside of the sphere at each end. The secondary is made of resistance wire, so there is no separate load. The **E** field along the secondary causes current in the secondary (yellow arrows) which causes a **B** field around the secondary (shown as blue ellipses). This **B** field fills space, including inside the transformer core, so in the end, there is continuous non-zero **B** field from the primary to the secondary, if the secondary is not open circuited. The cross product of the **E** field (sourced from primary currents) and the **B** field (sourced from the secondary currents) forms the Poynting vector which points from the primary toward the secondary.

Chapter-9

# Induction Coil and Padmount Transformer

Induction coil

An **induction coil** or "spark coil" (archaically known as a **Ruhmkorff coil** after Heinrich Ruhmkorff) is a type of disruptive discharge coil. It is a type of electrical transformer used to produce high-voltage pulses from a low-voltage direct current (DC) supply. To create the flux changes necessary to induce voltage in the secondary, the direct current in the primary is repeatedly interrupted by a vibrating mechanical contact called an *interrupter*. Developed beginning in 1836 by Nicholas Callan and others, the induction coil was the first type of transformer.

The term 'induction coil' is also used for a coil carrying high-frequency alternating current (AC), producing eddy currents to heat objects placed in the interior of the coil, in induction heating or zone melting equipment.
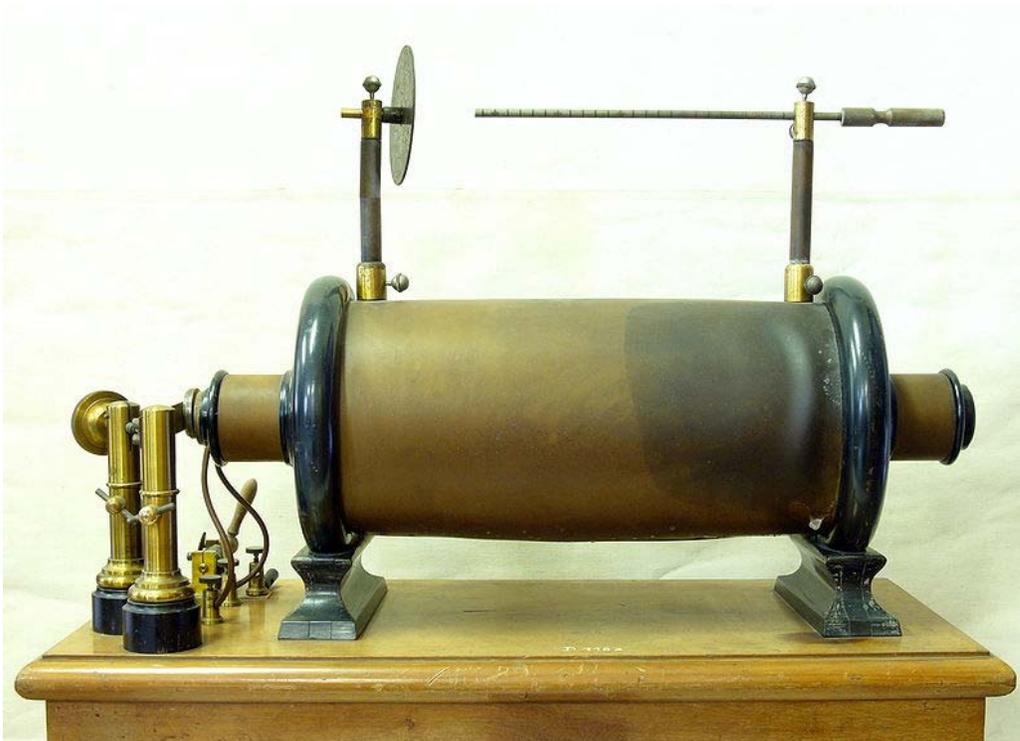
Antique induction coil used in schools, Bremerhaven, Germany

How it works
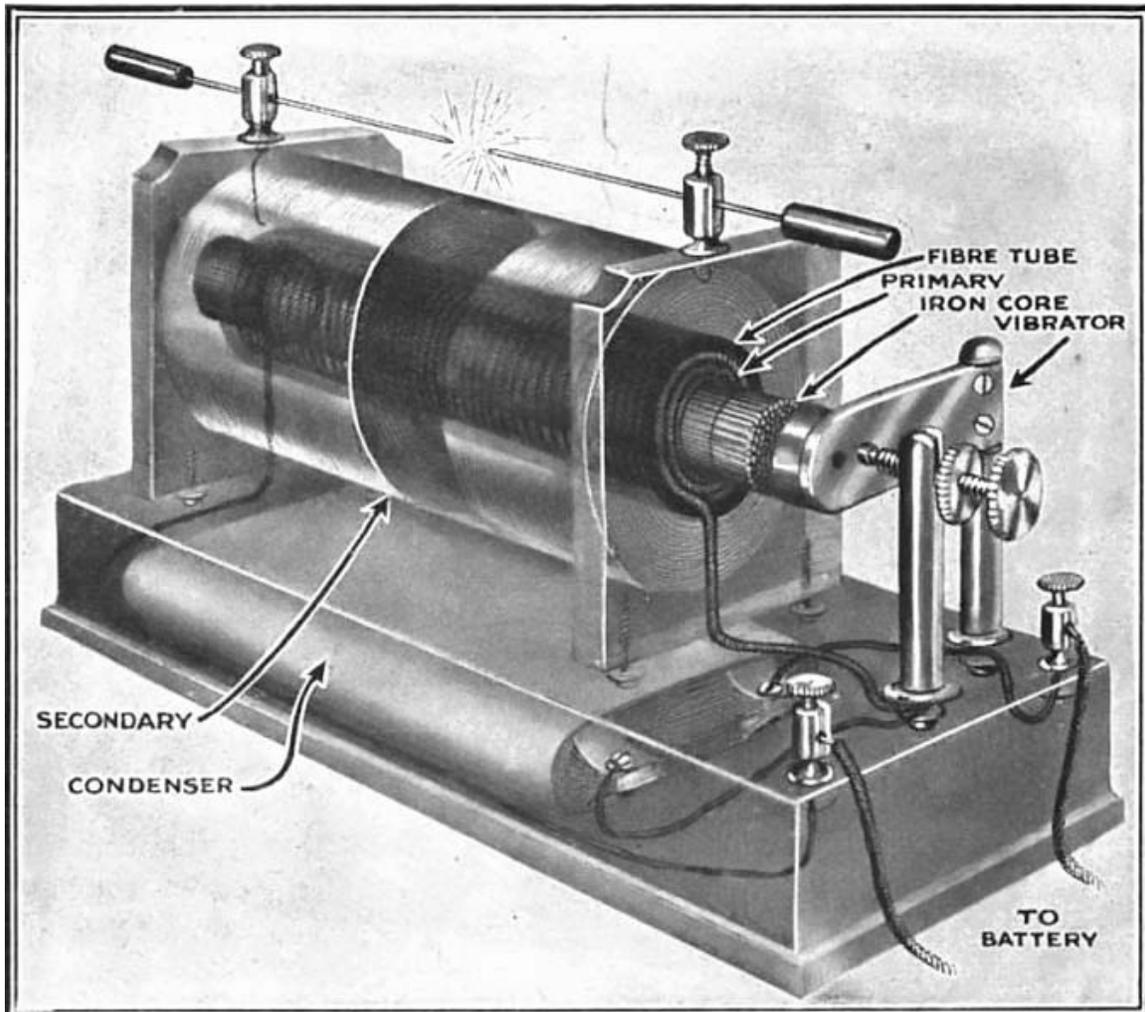
Induction coil showing construction, from 1920.

An induction coil consists of two coils of insulated copper wire wound around a common iron core. One coil, called the *primary winding*, is made from relatively few (tens or hundreds) turns of coarse wire. The other coil, the *secondary winding,* typically consists of many (thousands) turns of fine wire. An electric current is passed through the primary, creating a magnetic field. Because of the common core, most of the primary's magnetic field couples with the secondary winding. The primary behaves as an inductor, storing energy in the associated magnetic field. When the primary current is suddenly interrupted, the magnetic field rapidly collapses. This causes a high voltage pulse to be developed across the secondary terminals through electromagnetic induction. Because of the large number of turns in the secondary coil, the secondary voltage pulse is typically many thousands of volts. This voltage is often sufficient to cause an electric spark, to jump across an air gap separating the secondary's output terminals. For this reason, induction coils were called spark coils.

The size of induction coils was usually specified by the length of spark it could produce; an '8 inch' (20 cm) induction coil was one that could produce an 8 inch arc.

The interrupter
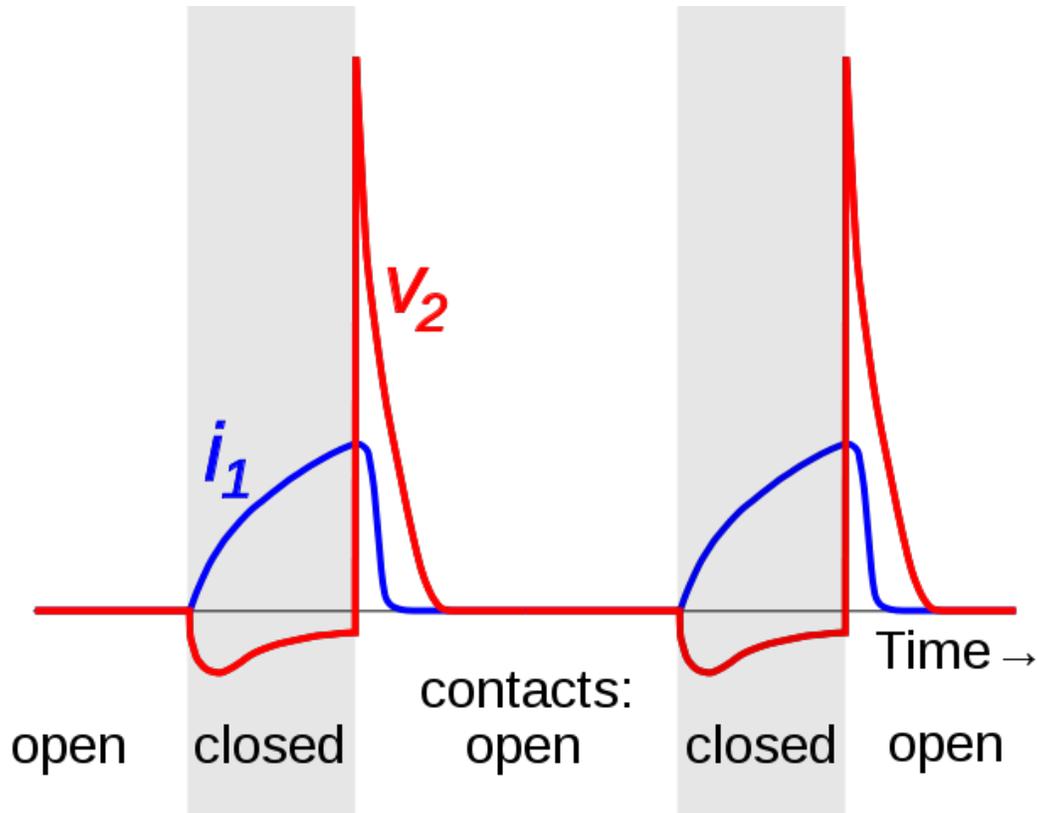
Waveforms in the induction coil, demonstrating how the interrupter works. The blue trace, i_1 is the current in the coil's primary winding. It is broken periodically by the vibrating contact of the interrupter. The changes in current create a changing magnetic flux in the coil which induces a high voltage in the secondary coil v_2 shown in red. Both the "make" and "break" of the current induce pulses of voltage in the secondary, but the current change is much more abrupt on "break", and this generates the high voltage produced by the coil.

To operate the coil continuously, the DC supply current must be broken repeatedly to create the magnetic field changes needed for induction. Induction coils use a magnetically activated vibrating arm called an *interrupter* or *break* to rapidly connect and break the current flowing into the primary coil. The interrupters on small coils were mounted on the end of the coil next to the iron core. The magnetic field created by the current flowing in the primary attracts the interrupter's iron armature attached to a spring, breaking a pair of contacts in the primary circuit. When the magnetic field then collapses, the spring closes the contacts again, and the cycle repeats.

Opposite potentials are induced in the secondary when the interrupter 'breaks' the circuit and 'closes' the circuit. However, the current change in the primary is much more abrupt

when the interrupter 'breaks'. When the contacts close, the current builds up slowly in the primary because the supply voltage has a limited ability to force current through the coil's inductance. In contrast, when the interrupter contacts open, the current falls to zero suddenly. So the pulse of voltage induced in the secondary at 'break' is much larger than the pulse induced at 'close', it is the 'break' that generates the coil's high voltage output. A "snubber" capacitor is used across the contacts to quench the arc on the 'break', which causes much faster switching and higher voltages. So the output waveform of an induction coil is a series of alternating positive and negative pulses, but with one polarity much larger than the other.

Mercury and electrolytic interrupters

The small 'hammer' interrupters described above were used on coils creating up to 8 inch (~120 kV) sparks. Larger coils used motor-driven interrupters. The largest coils, used in radio transmitters, used either electrolytic or mercury turbine 'breaks'.

Construction details

To prevent the high voltages generated in the coil from breaking down the thin insulation and arcing between the secondary wires, the secondary coil uses special construction so as to avoid having wires carrying large voltage differences lying next to each other. The secondary coil is wound in many thin flat pancake-shaped sections (called "pies"), connected in series. The primary coil is first wound on the iron core, and insulated from the secondary with a thick paper or rubber coating. Then each secondary subcoil is coated with an insulating layer like paraffin, connected to the coil next to it, and slid onto the iron core, insulated from adjoining coils with paper disks. The voltage developed in each subcoil isn't large enough to jump between the wires in the subcoil. Large voltages are only developed across many subcoils in series, which are too widely separated to arc over.

To prevent eddy currents, which flow perpendicular to the magnetic axis, and cause energy losses, the iron core is made of a bundle of parallel iron wires, individually coated with shellac to insulate them electrically.

History
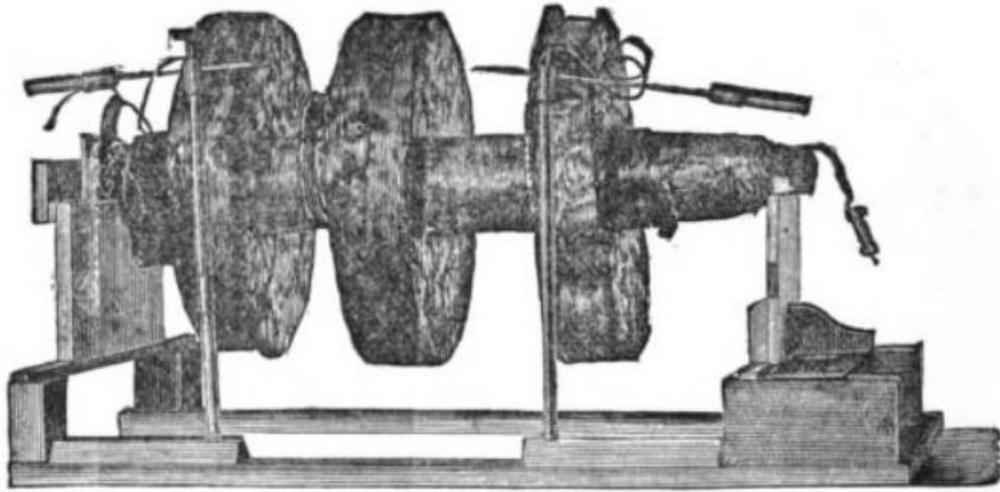
Callan's largest induction coil (Model of 1863), showing 'pancake' secondary construction. It was 42 inches (106 cm) long and could produce 15 inch (38 cm) sparks, corresponding to a potential of approximately 200,000 volts.

Michael Faraday discovered the principle of induction, Faraday's induction law, in 1831 and did the first experiments with induction between coils of wire. The induction coil was invented by the Irish scientist and Catholic priest Nicholas Callan in 1836 at the St. Patrick's College, Maynooth and improved by William Sturgeon and Charles Grafton Page. The early coils had hand cranked interrupters, invented by Callan and Antoine Masson. The automatic 'hammer' interrupter was invented by C. E. Neef, P. Wagner, and J. W. M'Gauley. Hippolyte Fizeau introduced the use of the quenching capacitor. Heinrich Ruhmkorff generated higher voltages by greatly increasing the length of the secondary, in some coils using 5 or 6 miles (10 km) of wire. In the early 1850s, after examining an example of a Ruhmkorff coil, which produced a small spark of around *2 inches* (50 mm) when energized, American inventor Edward Samuel Ritchie perceived that it could be made more efficient and produce a stronger spark by redesigning and improving its secondary insulation. His own design divided the coil into sections, each properly insulated from each other. Ritchie's induction coil proved superior to other designs of the day, initially producing a spark of *10 inches* (25 cm) in length; later versions could produce an electrical bolt *24 inches* (60 cm) or longer in length. The full story of Page's invention of the induction coil in its modern guise is told in Robert Post, "Physics, Patents, and Politics: A Biography of Charles Grafton Page" (Science History Publications, 1976. In 1857, one of Ritchie's induction coils was exhibited in Dublin, Ireland at a conference of the British Association, and later at the University of Edinburgh in Scotland. Ruhmkorff himself purchased a Ritchie induction coil, utilizing its improvements in his own work.

Induction coils were used to provide high voltage for early gas discharge and Crookes tubes and other high voltage research. They were also used to provide entertainment (lighting Geissler tubes, for example) and to drive small "shocking coils", Tesla coils and violet ray devices used in quack medicine. They were used by Hertz to demonstrate the existence of electromagnetic waves, as predicted by James Maxwell and by Lodge and Marconi in the first research into radio waves. Their largest industrial use was probably in early wireless telegraphy spark-gap radio transmitters and to power early cold cathode x-ray tubes. By about 1920 they were supplanted in both these applications by vacuum tubes. However their largest use was as the ignition coil or spark coil in the ignition system of internal combustion engines, where they are still used, although the interrupter contacts are now replaced by solid state switches. A smaller version is used to trigger the flash tubes used in cameras and strobe lights.

Automobile ignition coil, the largest remaining use for induction coils

Wireless charging

Toyota's heavy duty division, Hino Motors, is testing a new kind of hybrid electric vehicle without a plug (hybrid outboard chargeable vehicle). The energy in the batteries doesn't come from a plug and a charging point, but it comes from a wireless charging system built into the road. A series of induction coils built into the road resonate energy at certain frequency, like radio waves. The bus is able to capture those waves and store the energy in its batteries.

Padmount transformer

Padmount or Pad Mounted Transformer is a low kVA ground mounted transformer with self protection and switching options in the form of elbow connectors and built in sectionalizing switches. Appropriate for areas where underground high voltage electrical distribution terminals are located, pad mounted transformers step down voltage before supplying power to end user's electrical system.

Design

Pad mount Transformers are available in various electrical and mechanical configurations. They may be obtained in any voltage, phase or frequency which an application may demand. A Pad mount Transformer is a tank like structure that holds the core/coil assembly, built on top of a wiring cabinet. The wiring cabinet has high and low voltage wiring compartments. High and low voltage underground cables from below enter the terminal compartments directly. The top of the tank has a cover secured with carriage bolt-nut assemblies. The wiring cabinet has sidewalls on two ends with doors that open sideways to expose the high and low voltage wiring compartments.

Pad mount transformers have self protecting fusing comprising of the Bay-O-Net fuse placed in a high voltage compartment with a back-up high energy current limiting fuse in series to protect against secondary faults and transformer overload. The Bay-O-Net fuse protects against secondary faults and transformer overload and is a field replaceable device. The backup current limiting fuse operates only during transformer failure, therefore it is not field replaceable. These transformers also serve the conventional low voltage fusing requirements. The use of polymeric cable and load break elbows enable switching and isolation to be carried out in the HV chamber in what is known as a 'Dead Front' environment, i.e. all terminations are fully screened and watertight.

Single and three phase pad-mounted transformers are available, and can be used in ground level and underground industrial and residential power distribution systems, especially where there is a need for safe, reliable and aesthetically appealing transformer design. Its construction allows installation of pad mount transformers in public areas without the need of protective fencing. In residential areas, which are powered by underground distribution systems, pad mount transformers are usually located at street easements, to regulate electrical voltage requirements for multiple households.

Pad mounted transformers are available in numerous sizes and designs suitable for underground installation as well. Three phase pad mounted transformers range in sizes from 75kVA up to 5000kVA with voltages ranging from 2,400 up to 34,500 delta or wye. Low voltage pad mounted range in size from 208y/120 through 24,940y/14,000.

While most traditional pad mount transformer are fixed on a concrete 'pad', today small 1Ø designs are also available with the transformer already mounted on a 'polypad' base so that they can be mounted on a hard ground, and connected and switched on.

Tanks and Compartments

Pad mount Transformers have tanks and compartments assembled on top of a flat, rigid surface, usually a concrete pad. The pad mounted transformer unit may be rolled, skidded or jacked into place, or raised using hooks. Underground cables are used to step down high voltage, which are connected to the bushings or to factory-installed auxiliary equipment. The high and low voltage compartments are separated by a metal barrier and open sideways.

High and Low Voltage Terminators

Compartmental type pad mounted transformers support underground entrance of primary and secondary conductors. Live and dead front primary termination on radial or loop feed service is provisioned for. Wet process electrical grade porcelain bushings with eyebolt terminals are provided for live front construction. For all voltage ratings, dead front construction with provisions for high voltage terminators is available. Secondary terminals are sealed into molded epoxy bushings and externally clamped to the tank wall.

Primary Switch and Fuse Arrangement

In a 3 phase pad mounted transformer, oil immersed switches that switch in 3 current ratings are available for radial and loop feed. Load break and latch operations are facilitated through spring load mechanism. A three phase gang operated switch is mounted near the core and coil assembly for low cable capacitance. Depending on the customers requirement, and transformer size and rating , the most common fuse options include weak link expulsion fuses; Bay-o-Net fuses; dry well canisters; arc strangler fused switch blades; clip mounted, full range, current limiting fuses; and S&C disconnects with E-rated power fuses.

Installation

Pad mount transformers are constructed particularly for installation in public areas, where there is a need for a tamper -proof design. Depending on the connection and access type, pad mount transformers can be installed indoor and outdoor. Pad mount transformers for indoors require dry type construction.

Usually inspection authorities require pad mount transformers to be located away from the main building. The transformer must have at least 8 feet of unobstructed space in front for the doors to the electrical equipment to open.

Upon installation, there should be a padlock on the transformer and a clearly visible warning sign indicating electrical voltage. Areas where pad mount transformers are located should be well lit, safe and inaccessible to young children.

Application

Pad mount transformers are used in various production applications for management of electrical voltage power systems, such as,

- Refineries
- Office Buildings
- Schools
- Windmill Farms
- Hospitals
- Residential Neighborhoods
- Warehouses
- Retail Stores and Shopping Malls
- Manufacturing Facilities
- Electrical Substations
- Large Chain Type Grocery Store

Inspection and Maintenance

Ageing and corrosion of pad mount transformers can result in outages, safety hazards, and customer complaints. Debris, insects, and pests can lead to possible electrical failure. Laser-guided infrared can be used to detect elevated temperatures on critical transformer components, such as primary elbow connections. To improve safety and reliability of pad mount transformers regular external/internal inspection and maintenance is conducted. Exterior Inspection / Maintenance

- Site clearing
- Assessment of pad condition
- Cabinet leveling
- Cabinet repair
- Replacement of security lock
- Replacement of penta bolt
- Painting
- Tag and decal replacement
- Cleaning and removal of debris, insects, and animals
- Pesticide application
- Tag and label replacement
- Infrared inspection
- Grounding assessment

Chapter-10

Synchro and Tap (transformer)

Synchro
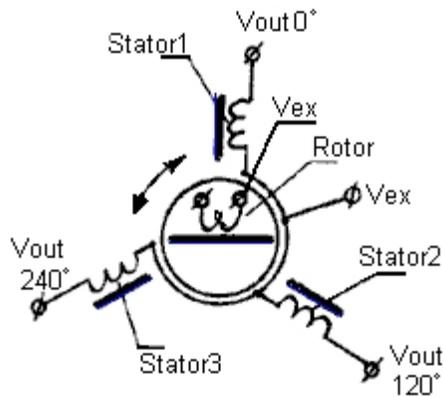
Schematic of Synchro Transducer, the solid bars represent the cores of the windings next to them. Power to the rotor is connected by slip rings and brushes, represented by the circles at the ends of the rotor winding. As shown, the rotor induces equal voltages in the 120° and 240° windings, and no voltage in the 0° winding. [Vex] does not necessarily need to be connected to the common lead of the stator star windings.
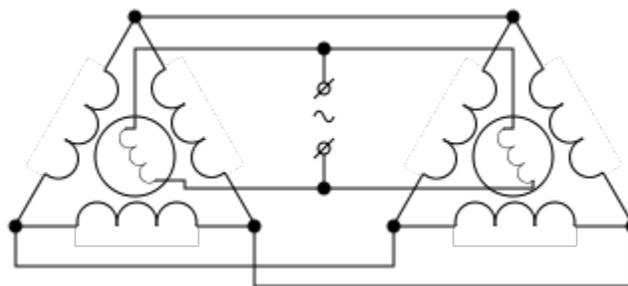
Two simple synchros system

A **synchro** or "selsyn" is a type of rotary electrical transformer that is used for measuring the angle of a rotating machine such as an antenna platform. In its general physical construction, it is much like an electric motor. The primary winding of the transformer, fixed to the rotor, is excited by a sinusoidal electric current (AC), which by electromagnetic induction causes currents to flow in three star-connected secondary windings fixed at 120 degrees to each other on the stator. The relative magnitudes of secondary currents are measured and used to determine the angle of the rotor relative to the stator, or the currents can be used to directly drive a receiver synchro that will rotate in unison with the synchro transmitter. In the latter case, the whole device (in some applications) is also called a **selsyn** (a portmanteau of self and synchronizing). U.S. Naval terminology used the term "synchro" exclusively (possible exception: steering gear—info. needed).

A picture of a synchro transmitter

Synchro systems were first used in the control system of the Panama Canal, to transmit lock gate and valve stem positions, and water levels, to the control desks.

View onto the connection description of a synchro transmitter

Fire-control system designs developed during World War II used synchros extensively, to transmit angular information from guns and sights to an analog fire control computer, and to transmit the desired gun position back to the gun location. Early systems just moved indicator dials, but with the advent of the amplidyne, as well as motor-driven high-powered hydraulic servos, the fire control system could directly control the positions of heavy guns.

Smaller synchros are still used to remotely drive indicator gauges and as rotary position sensors for aircraft control surfaces, where the reliability of these rugged devices is needed. Digital devices such as the rotary encoder have replaced synchros in most other applications.

Synchros designed for terrestrial use tend to be driven at 50 or 60 hertz (the mains frequency in most countries), while those for marine or aeronautical use tend to operate at 400 hertz (the frequency of the on-board electrical generator driven by the engines).

Selsyn motors were widely used in motion picture equipment to synchronize movie cameras and sound recording equipment, before the advent of crystal oscillators and microelectronics.

On a practical level, synchros resemble motors, in that there is a rotor, stator, and a shaft. Ordinarily, slip rings and brushes connect the rotor to external power. A synchro transmitter's shaft is rotated by the mechanism that sends information, while the synchro

receiver's shaft rotates a dial, or operates a light mechanical load. Single and three-phase units are common in use, and will follow the other's rotation when connected properly. One transmitter can turn several receivers; if torque is a factor, the transmitter must be physically larger to source the additional current. In a motion picture interlock system, a large motor-driven distributor can drive as many as 20 machines, sound dubbers, footage counters, and projectors.

Single phase units have five wires: two for an exciter winding (typically line voltage) and three for the output/input. These three are bussed to the other synchros in the system, and provide the power and information to precisely align by rotation all the shafts in the receivers. Synchro transmitters and receivers must be powered by the same branch circuit, so to speak; voltage and phase must match. Different makes of selsyns, used in interlock systems, have different output voltages.

Three-phase systems will handle more power and operate a bit more smoothly. The excitation is often 208/240 V 3-phase mains power.

In all cases, the mains excitation voltage sources must match in voltage and phase. The safest approach is to bus the five or six lines from transmitters and receivers at a common point.

Synchro transmitters are as described, but 50 and 60-Hz synchro receivers require rotary dampers to keep their shafts from oscillating when not loaded (as with dials) or lightly loaded in high-accuracy applications.

Large synchros were used on naval warships, such as destroyers, to operate the steering gear from the wheel on the bridge.

A different type of receiver, called a control transformer (CT), is part of a position servo that includes a servo amplifier and servo motor. The motor is geared to the CT rotor, and when the transmitter's rotor moves, the servo motor turns the CT's rotor and the mechanical load to match the new position. CTs have high-impedance stators and draw much less current than ordinary synchro receivers when not correctly positioned.

Synchro transmitters can also feed synchro to digital converters, which provide a digital representation of the shaft angle.

Synchro variants

So called brushless synchros use rotary transformers (that have no magnetic interaction with the usual rotor and stator) to feed power to the rotor. These transformers have stationary primaries, and rotating secondaries. The secondary is somewhat like a spool wound with magnet wire, the axis of the spool concentric with the rotor's axis. The "spool" is the secondary winding's core, its flanges are the poles, and its coupling does not vary significantly with rotor position. The primary winding is similar, surrounded by

its magnetic core, and its end pieces are like thick washers. The holes in those end pieces align with the rotating secondary poles.

For high accuracy in gun fire control and aerospace work, so called multi-speed synchro data links were used. For instance, a two-speed link had two transmitters, one rotating for one turn over the full range (such as a gun's bearing) , while the other rotated one turn for every 10 degrees of bearing. The latter was called a 36-speed synchro. Of course, the gear trains were made accurately. At the receiver, the magnitude of the 1X channel's error determined whether the "fast" channel was to be used instead. A small 1X error meant that the 36x channel's data was unambiguous. Once the receiver servo settled, the fine channel normally retained control.

For very critical applications, three-speed synchro systems have been used.

So called multispeed synchros have stators with many poles, so that their output voltages go through several cycles for one physical revolution. For two-speed systems, these do not require gearing between the shafts.

Differential synchros are another category. They have three-lead rotors and stators like the stator described above, and can be transmitters or receivers. A differential transmitter is connected between a synchro transmitter {CX} and a receiver {CT}, and its shaft's position adds to (or subtracts from, depending upon definition) the angle defined by the transmitter. A differential receiver is connected between two transmitters, and shows the sum (or difference, again as defined) between the shaft positions of the two transmitters.

A resolver is similar to a synchro, but has a stator with four leads, the windings being 90 degrees apart physically instead of 120 degrees. Its rotor might be synchro-like, or have two sets of windings 90 degrees apart. Although a pair of resolvers could theoretically operate like a pair of synchros, resolvers are used for computation. Both synchros and resolvers have an accurate sine-function relationship between shaft position and transformation ratio for any pair of stator connections. (Of course, there are angular offsets of 120 or 240 degrees for synchros, and multiples of 90 degrees for resolvers, depeding upon the specific pair of leads being considered.)

Resolvers, in particular, can perform very accurate analog conversion from polar to rectangular coordinates. Shaft angle is the polar angle, and excitation voltage is the magnitude. The outputs are the [x] and [y] components. Resolvers with four-lead rotors can rotate [x] and [y] coordinates, with the shaft position giving the desired rotation angle.

Resolvers with four output leads are general sine/cosine computational devices. When used with electronic driver amplifiers and feedback windings tightly coupled to the input windings, their accuracy is enhanced, and they can be cascaded ("resolver chains") to compute functions with several terms, perhaps of several angles, such as gun (position) orders corrected for ship's roll and pitch.

There are synchro-like devices called transolvers, somewhat like differential synchros, but with three-lead rotors and four-lead stators.

A special T-connected transformer arrangement invented by Scott ("Scott T") interfaces between resolver and synchro data formats; it was invented to interconnect two-phase AC power with three-phase power, but can also be used for precision applications.

Tap

A **transformer tap** is a connection point along a transformer winding that allows a certain number of turns to be selected. By this means, a transformer with a variable turns ratio is produced, enabling voltage regulation of the output. The tap selection is made via a **tap changer** mechanism.

Voltage considerations

If only one tap changer is required, tap points are usually made on the high voltage, or low current, side of the winding in order to minimize the current handling requirements of the contacts. However, a transformer may include a tap changer on each winding if there are advantages to do so. For example, in power distribution networks, a large step-down transformer may have an **off-load** tap changer on the primary winding and an **on-load** tap changer on the secondary winding. The high voltage tap is set to match long term system profile on the high voltage network and is rarely changed. The low voltage tap may be requested to change positions once or more each day, without interrupting the power delivery, to follow loading conditions on the low-voltage network.

To minimize the number of windings and thus reduce the physical size of a transformer, a 'reversing' winding may be used, which is a portion of the main winding able to be connected in its opposite direction and thus oppose the voltage. Insulation requirements place the tap points at the low voltage end of the winding. This is near the star point in a star connected winding. In delta connected windings, the tappings are usually at the center of the winding. In an autotransformer, the taps are usually made between the series and common windings, or as a series 'buck-boost' section of the common winding.
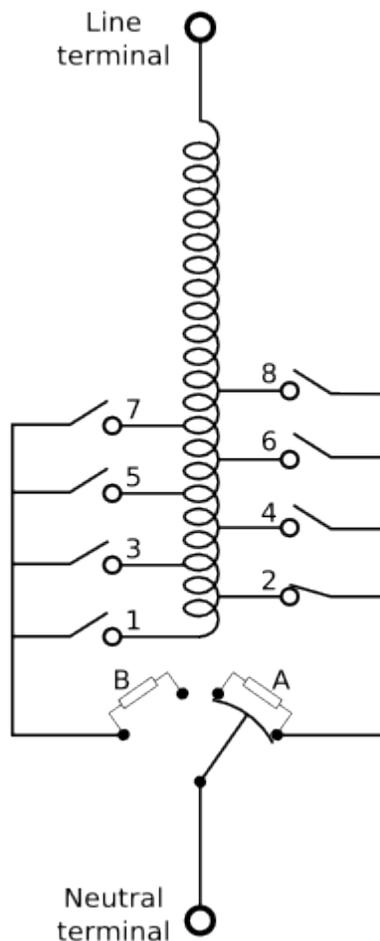
Tap changing

Off-circuit designs (DETC)

In low power, low voltage transformers, the tap point can take the form of a connection terminal, requiring a power lead to be disconnected by hand and connected to the new terminal. Alternatively, the process may be assisted by means of a rotary or slider switch.

Since the different tap points are at different voltages, the two connections can not be made simultaneously, as this would short-circuit a number of turns in the winding and produce excessive circulating current. Consequently, the power to the device must be interrupted during the switchover event. Off-circuit or de-energized tap changing (DETC) is sometimes employed in high voltage transformer designs, although for regular use, it is only applicable to installations in which the loss of supply can be tolerated. In power distribution networks, transformers commonly include an off-circuit tap changer on the primary winding to accommodate system variations within a narrow band around the nominal rating. The tap changer will often be set just once, at the time of installation, although it may be changed later during a scheduled outage in order to accommodate a long-term change in the system voltage profile.

On-load designs

A mechanical **on-load tap changer (OLTC)**, also known as **under- load tap changer (ULTC)** design, changing back and forth between tap positions 2 and 3

For many power transformer applications, a supply interruption during a tap change is unacceptable, and the transformer is often fitted with a more expensive and complex on-

load tap-changing (OLTC, sometimes LTC) mechanism. On-load tap changers may be generally classified as either mechanical, electronically assisted, or fully electronic.

Mechanical tap changers

A mechanical tap changer physically makes the new connection before releasing the old using multiple **tap selector** switches, but avoids creating high circulating currents by using a **diverter switch** to temporarily place a large diverter impedance in series with the short-circuited turns. This technique overcomes the problems with open or short circuit taps. In a resistance type tap changer, the changeover must be made rapidly to avoid overheating of the diverter. A reactance type tap changer uses a dedicated **preventive autotransformer** winding to function as the diverter impedance, and a reactance type tap changer is usually designed to sustain off-tap loading indefinitely.

In a typical diverter switch powerful springs are tensioned by a low power motor (motor drive unit (MDU)), and then rapidly released to effect the tap changing operation. To reduce arcing at the contacts, the tap changer operates in a chamber filled with insulating transformer oil, or inside an SF_6 vessel. Reactance-type tap changers, when operating in oil, must allow for with the additional inductive flyback generated by the autotransformer and commonly include a vacuum bottle in parallel with the diverter switch. During a tap-change operation, the flyback raises the potential between the two electrodes in the bottle, and some of the energy is dissipated in an arc discharge through the bottle instead of flashing across the diverter switch.

Some arcing is unavoidable, and both the tap changer oil and the switch contacts will slowly deteriorate with use. In order to prevent contamination of the tank oil and facilitate maintenance operations, the diverter switch usually operates in a separate compartment from the main transformer tank, and often the tap selector switches will be located in the compartment as well. All of the winding taps will then be routed into the tap changer compartment through a terminal array.

One possible design (flag type) of on-load mechanical tap changer is shown to the right. It commences operation at tap position 2, with load supplied directly via the right hand connection. Diverter resistor A is short-circuited; diverter B is unused.

In moving to tap 3, the following sequence occurs:

1. Switch 3 closes, an off-load operation.
2. Rotary switch turns, breaking one connection and supplying load current through diverter resistor A.
3. Rotary switch continues to turn, connecting between contacts A and B. Load now supplied via diverter resistors A and B, winding turns bridged via A and B.
4. Rotary switch continues to turn, breaking contact with diverter A. Load now supplied via diverter B alone, winding turns no longer bridged.

5. Rotary switch continues to turn, shorting diverter B. Load now supplied directly via left hand connection. Diverter A is unused.
6. Switch 2 opens, an off-load operation.

The sequence is then carried out in reverse to return to tap position 2.

Thyristor-assisted tap changers

Thyristor-assisted tap changers use thyristors to take the on-load current while the main contacts change over from one tap to the next. This prevents arcing on the main contacts and can lead to a longer service life between maintenance activities. The disadvantage is that these tap changers are more complex and require a low voltage power supply for the thyristor circuitry. They also can be more costly.

Solid state (thyristor) tap changers

These are a relatively recent development which uses thyristors both to switch the load current and to pass the load current in the steady state. Their disadvantage is that all of the non-conducting thyristors connected to the unselected taps still dissipate power due to their leakage current and they have smaller short circuit withstand capacity. This power can add up to a few kilowatts which has to be removed as heat and leads to a reduction in the overall efficiency of the transformer, in exchange for a compact design that reduces the size and weight of the tap changer device. Solid state tap changers are typically employed only on smaller power transformers.

Standards considering tap changers

Name	Status
IEC 60214-1:2003	Current
IEC 60214-2:2004	Current
IEEE Std C57.131-1995	Unknown
ГОСТ 24126-80 (СТ СЭВ 634-77)	Current
IEC 214:1997	Replaced by a later version
IEC 214:1989	Replaced by a later version
IEC 214:1985	Replaced by a later version