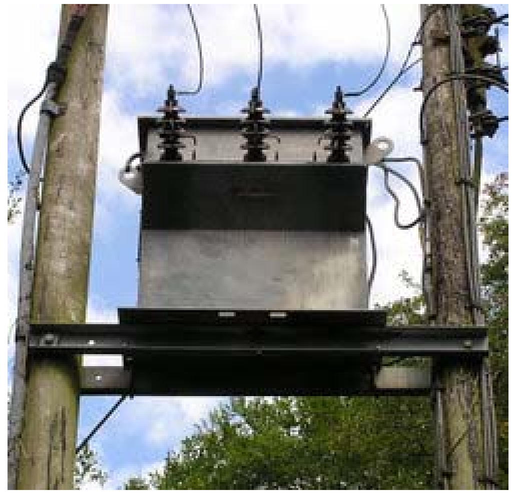
Contents

A **transformer** is an electrical device that transfers energy from one circuit to another by magnetic coupling, without requiring relative motion between its parts. A transformer comprises two or more coupled windings, and, in most cases, a magnetic core to concentrate magnetic flux. A changing voltage applied to one winding creates a time-varying magnetic flux in the core, which induces a voltage in the other windings.



The transformer is one of the simplest of electrical devices, yet transformer designs and materials continue to be improved.

Transformers come in a range of sizes from a thumbnail-sized coupling transformer hidden inside a stage microphone to huge gigawatt units used to interconnect large portions of national power grids. All operate with the same basic principles and with many similarities in their parts.

Background

Michael Faraday built the first transformer in 1831, although he used it only to demonstrate the principle of electromagnetic induction and did not foresee its practical uses.

Lucien Gaulard and John Dixon Gibbs, who first exhibited a device called a 'secondary generator' in London in 1881 and then sold the idea to American company Westinghouse. This may have been the first practical power transformer. They also exhibited the invention in Turin in 1884, where it was adopted for an electric lighting system. Their early devices used an open iron core, which was soon abandoned in favour of a more efficient circular core with a closed magnetic path.

Russian engineer Pavel Yablochkov in 1876 invented a lighting system based on a set of induction coils, where primary windings were connected to a source of alternating current and secondary windings could be connected to several "electric candles". As the patent said, such a system "allows to provide separate supply to several lighting fixtures with different luminous intensities from a single source of electric power". Evidently, the induction coil in this system operated as a transformer.

William Stanley, an engineer for Westinghouse, who built the first practical device in 1885 after George Westinghouse bought Gaulard and Gibbs' patents. The core was made from interlocking E-shaped iron plates. This design was first used commercially in 1886.

Hungarian engineers Károly Zipernowsky, Ottó Bláthy and Miksa Déri at the Ganz company in Budapest in 1885, who created the efficient "ZBD" model based on the design by Gaulard and Gibbs.

Russian engineer Mikhail Dolivo-Dobrovolsky in 1889 developed the first three-phase transformer.

Nikola Tesla in 1891 invented the Tesla coil, which is a high-voltage, air-core, dual-tuned resonant transformer for generating very high voltages at high frequency.

Audio frequency transformers (at the time called repeating coils) were used by the earliest experimenters in the development of the telephone. While new technologies have made some transformers in electronics applications obsolete, transformers are still found in many electronic devices.

Transformers are essential for high voltage power transmission, which makes long distance transmission economically practical. This advantage was the principal factor in the selection of alternating current power transmission in the "War of Currents" in the late 1880s.

Many others have patents on transformers.

Basic principles

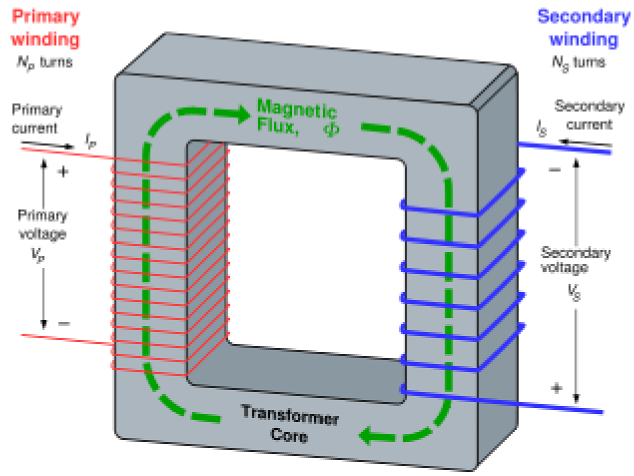
An analogy

A transformer can be likened to a mechanical gearbox, which transfers mechanical energy from a high-speed, low torque shaft to a lower-speed, higher-torque shaft, but which is not a source of energy itself. A transformer transfers electrical energy from a high-current, low-voltage circuit to a lower-current, higher-voltage circuit.

Coupling by mutual induction

The principles of the transformer are illustrated by consideration of a hypothetical ideal transformer. In this case, the core requires negligible magnemotive force to sustain flux, and all flux linking the primary winding also links the secondary winding. The hypothetical ideal transformer has no resistance in its coils. A simple transformer consists of two electrical conductors called the **primary winding** and the **secondary winding**. Energy is coupled between the windings by the time varying magnetic flux that passes through (links) both primary and secondary windings. Whenever the amount of current in a coil changes, a voltage is induced in the neighboring coil. The effect, called mutual inductance, is an example of electromagnetic induction.[1]

An ideal step-down transformer showing flux in the core



If a time-varying voltage v_P is applied to the primary winding of N_P turns, a current will flow in it producing a magnetomotive force (MMF). Just as an electromotive force (EMF) drives current around an electric circuit, so MMF tries to drive magnetic flux through a magnetic circuit. The primary MMF produces a varying magnetic flux Φ_P in the core, and, with an open circuit secondary winding, induces a back electromotive force (EMF) in opposition to v_P. In accordance with Faraday's law of induction, the voltage induced across the primary winding is proportional to the rate of change of flux:

$$v_P = N_P \frac{d\Phi_P}{dt} \quad \text{and} \quad v_S = N_S \frac{d\Phi_S}{dt}$$

where

- v_P and v_S are the voltages across the primary winding and secondary winding,
- N_P and N_S are the numbers of turns in the primary winding and secondary winding,
- $d\Phi_P / dt$ and $d\Phi_S / dt$ are the derivatives of the flux with respect to time of the primary and secondary windings.

In the hypothetical ideal transformer, the primary and secondary windings are perfectly coupled, or equivalently, $\Phi_P = \Phi_S$. Substituting and solving for the voltages shows that:

$$\frac{v_P}{v_S} = \frac{N_P}{N_S}$$

where

- v_p and v_s are voltages across primary and secondary,
- N_p and N_s are the numbers of turns in the primary and secondary, respectively.

Hence in an ideal transformer, the ratio of the primary and secondary voltages is equal to the ratio of the number of turns in their windings, or alternatively, the voltage per turn is the same for both windings. The ratio of the currents in the primary and secondary circuits is inversely proportional to the turns ratio.

The EMF in the secondary winding will cause current to flow in a secondary circuit. The MMF produced by current in the secondary winding opposes the MMF of the primary winding and so tends to cancel the flux in the core. Since the reduced flux reduces the EMF induced in the primary winding, increased current flows in the primary circuit. The resulting increase in MMF due to the primary current offsets the effect of the opposing secondary MMF. In this way, the electrical energy fed into the primary winding is delivered to the secondary winding. In addition, the flux density will always stay the same as long as the primary voltage is steady.

For example, suppose a power of 50 watts is supplied to a resistive load from a transformer with a turns ratio of 25:2.

- $P = EI$ (power = electromotive force × current)

  50 W = 2 V × 25 A in the primary circuit if the load is a resistive load. (See note 1)

- Now with transformer change:

  50 W = 25 V × 2 A in the secondary circuit.

Since a direct current by definition does not change, it produces a steady MMF and so steady flux in the core; this quantity does not change and so cannot induce a voltage in the secondary winding. In a practical transformer, direct current applied to the winding will create only heat.

The universal electromotive force (EMF) equation

If the flux in the core is sinusoidal, the relationship for either winding between its number of turns, voltage, magnetic flux density and core cross-sectional area is given by the universal emf equation (from Faraday's law):

$$E = \frac{2\pi f N a B}{\sqrt{2}} = 4.44 f N a B$$

where

- E is the sinusoidal rms or root mean square voltage of the winding,
- f is the frequency in hertz,
- N is the number of turns of wire on the winding,
- a is the cross-sectional area of the core in square metres

- B is the peak magnetic flux density in teslas,

Other consistent systems of units can be used with the appropriate conversions in the equation.

Operation at different frequencies

The equation shows that the EMF of a transformer at a given flux density increases with frequency. By operating at higher frequencies, transformers can be physically more compact without reaching saturation, and a given core is able to transfer more power. However, other properties of the transformer, such as losses within the core and skin-effect, also increase with frequency. Generally, operation of a transformer at its designed voltage but at a higher frequency than intended will lead to reduced magnetising (no load primary) current. At a frequency lower than the design value, with the rated voltage applied, the magnetising current may increase to an excessive level.

Operation of a power 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 at hydroelectric generating stations may be equipped with over-excitation protection, so-called "volts per hertz" protection relays, to protect the transformer from overvoltage at higher-than-rated frequency which may occur if a generator loses its connected load.

Uses of transformers

- For supplying power from an alternating current power grid to equipment which uses a different voltage.

    - For regulating the secondary output of a constant voltage (or ferro-resonant), in which a combination of core saturation and the resonance of a tank circuit prevents changes in the primary voltage from appearing on the secondary.

- Electric power transmission over long distances.
- Large, specially constructed power transformers are used for electric arc furnaces used in steelmaking.
- Rotating transformers are designed so that one winding turns while the other remains stationary. A common use was the video head system as used in VHS and Beta video tape players. These can pass power or radio signals from a stationary mounting to a rotating mechanism, or radar antenna.

    - Other rotary transformers are precisely constructed in order to measure distances or angles. Usually they have a single primary and two or more secondaries, and electronic circuits measure the different amplitudes of the currents in the secondaries. See synchro and resolver.

- Sliding transformers can pass power or signals from a stationary mounting to a moving part such as a machine tool head.
- A transformer-like device is used for position measurement. See linear variable differential transformer.
- Some rotary transformers are used to couple signals between two parts which rotate in relation to each other.
- Small transformers are often used internally to couple different stages of radio receivers and audio amplifiers.
- Transformers may be used as external accessories for impedance matching; for example to match a microphone to an amplifier.
- Balanced-to-unbalanced conversion. A special type of transformer called a balun is used in radio and audio circuits to convert between balanced linecircuits and unbalanced transmission lines such as antenna downleads.
- Flyback transformers are built using ferrite cores. They supply high voltage to the CRTs at the frequency of the horizontal oscillator. In the case of television sets, this is about 15.7kHz. It may be as high as 75 - 120kHz for high-resolution computer monitors.
- Switching power supply transformers usually operate between 30-1000 kHz. The tiny cores found in wristwatch backlight power supplies produce audible sound (about 1 kHz).

Classifications

Transformers are adapted to numerous engineering applications and may be classified in many ways:

- By power level (from fraction of a volt-ampere(VA) to over a thousand MVA),
- By application (power supply, impedance matching, circuit isolation),
- By frequency range (power, audio, radio frequency(RF))
- By voltage class (a few volts to about 750 kilovolts)
- By cooling type (air cooled, oil filled, fan cooled, water cooled, etc.)
- By purpose (distribution, rectifier, arc furnace, amplifier output, etc.).
- By ratio of the number of turns in the coils

  - **Step-up**

  The secondary has more turns than the primary.

  - **Step-down**

  The secondary has fewer turns than the primary.

  - **Isolating**

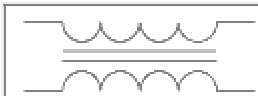
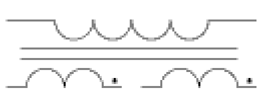
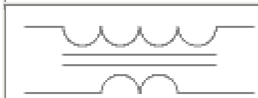
  Intended to transform from one voltage to the same voltage. The two coils have approximately equal numbers of turns, although often there is a slight difference in the number of turns, in order to compensate for losses (otherwise the output voltage would be a little less than, rather than the same as, the input voltage).

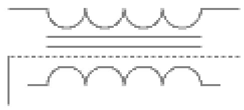
  - **Variable**

  The primary and secondary have an adjustable number of turns, which can be selected without reconnecting the transformer.

Circuit symbols

Standard symbols

	Transformer with two windings and iron core.
	Transformer with three windings. The dots show the relative winding configuration of the windings.
	Step-down or step-up transformer.

	The symbol shows which winding has more turns, but does not usually show the exact ratio.
	Transformer with electrostatic screen, which prevents capacitive coupling between the windings.

Practical considerations

Basic Impulse Insulation Levels (BIL)

Outdoor electrical distribution systems are subject to lightning surges. Even if the lightning strikes the line some distance from the transformer, voltage surges can travel down the line and into the transformer. High voltage switches and circuit breakers can also create similar voltage surges when they are opened and closed. Both types of surges have steep wave fronts and can be very damaging to electrical equipment . To minimize the effects of these surges, the electrical system is protected by lighting arresters but they do not completely eliminate the surge from reaching the transformer. The basic impulse level (BIL) of the transformer measures its ability to withstand these surges. All 600 volt and below transformers are rated 10 kV BIL. The 2400 and 4160 volt transformers are rated 25 kV BIL.

Limitations

Transformers alone cannot do the following:

- Convert DC to AC or vice versa
- Change the voltage or current of DC
- Change the AC supply frequency.

However, transformers are components of the systems that perform all these functions.

Energy losses

An ideal transformer would have no losses, and would therefore be 100% efficient. In practice, energy is dissipated due both to the resistance of the windings known as *copper loss* or I^2R loss, and to magnetic effects primarily attributable to the core (known as *iron loss*). Transformers are, in general, highly efficient: large power transformers (over 50 MVA) may attain an efficiency as high as 99.75%. Small transformers, such as a plug-in "power brick" used to power small consumer electronics, may be less than 85% efficient.

Transformer losses:

- **Winding resistance**

Current flowing through the windings causes resistive heating of the conductors ($I^2 R$ loss). At higher frequencies, skin effect and proximity effect create additional winding resistance and losses.

- **Eddy currents**

Induced eddy currents circulate within the core, causing resistive heating. Silicon is added to the steel to help in controlling eddy currents. Adding silicon also has the advantage of stopping aging of the electrical steel that was a problem years ago.

- **Hysteresis losses**

Each time the magnetic field is reversed, a small amount of energy is lost to hysteresis within the magnetic core. The amount of hysteresis is a function of the particular core material.

- **Magnetostriction**

Magnetic flux in the core causes it to physically expand and contract slightly with the alternating magnetic field (producing a buzzing sound), an effect known as magnetostriction. This in turn causes losses due to frictional heating in susceptible ferromagnetic cores.

- **Mechanical losses**

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

- **Stray losses**

Not all the magnetic field produced by the primary is intercepted by the secondary. A portion of the leakage flux may induce eddy currents within nearby conductive objects, such as the transformer's support structure, and be converted to heat.

- **Cooling system**

Large power transformers may be equipped with cooling fans, oil pumps or water-cooled heat exchangers designed to remove the heat caused by copper and iron losses. The power used to operate the cooling system is typically considered part of the losses of the transformer.

Losses may be either load-dependent('load-losses') or independent of it ('no-load loss'). Winding resistance dominates load-losses, whereas hysteresis and eddy currents losses contribute to over 99% of the no-load loss.

Construction

Cores

Steel cores

Transformers for use at power or audio frequencies have cores made of many thin laminations of silicon steel. By concentrating the magnetic flux, more of it is usefully linked by both primary and secondary windings. Since the steel core is conductive, it, too, has currents induced in it by the changing magnetic flux. Each layer is insulated from the adjacent layer to reduce the energy lost to eddy current heating of the core. The thin laminations are used to reduce the eddy currents, and the insulation is used to keep the laminations from acting as a solid piece of steel. The thinner the laminations, the lower the eddy currents, and the lower the losses. Very thin laminations are generally used on high frequency transformers. The cost goes up when using thinner laminations mainly over the labor in stacking them.

A typical laminated core is made from E-shaped and I-shaped pieces, leading to the name "EI transformer". In the EI transformer, the laminations are stacked in what is known as an interleaved fashion. Due to this interleaving a second gap in parallel (in an analogy to electronic circuits) to the gap between E and I is formed between the E-pieces. The E-pieces are pressed together to reduce the gap width to that of the insulation. The gap area is very large, so that the effective gap width is very small (in analogy to a capacitor). For this to work the flux has to gradually flow from one E to the other. That means that on one end all flux is only on every second E. That means saturation occurs at half the flux density. Using a longer E and wedging it with two small Is will increase the overlap and additionally make the grains more parallel to the flux (think of a wooden frame for a window). If an air gap is needed (which is unlikely considering the low remanence available for steel), all the E's are stacked on one side, and all the I's on the other creating a gap.

The cut core or C-core is made by winding a silicon steel strip around a rectangular form. After the required thickness is achieved, it is removed from the form and the laminations are bonded together. It is then cut in two forming two C shapes. The faces of the cuts are then ground smooth so they fit very tight with a very small gap to reduce losses. The core is then assembled by placing the two C halves together, and holding them closed by a steel strap. Usually two C-cores are used to shorten the return path for the magnetic flux resulting in a form similar to the EI. More cores would necessitate a triangular cross-section. Like toroidal cores, they have the advantage, that the flux is always in the oriented parallel the grains. Due to the bending of the core, some area is lost for a rectangular winging.

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 remanent 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 false operation of transformer protection devices.

Steel cores develop a larger hysteresis loss due to eddy currents as the operating frequency is increased. Ferrite, or thinner steel laminations for the core are typically used for frequencies above 1kHz. The thinner steel laminations serve to reduce the eddy currents. Some types of very thin steel laminations can operate at up to 10 kHz or higher. Ferrite is used in higher frequency applications, extending to the VHF band and beyond. Aircraft traditionally use 400 Hz power systems since the slight increase in thermal losses is more than offset by the reduction in core and winding weight. Military gear includes 400 Hz (and other frequencies) to supply power for radar or servomechanisms.

Distribution transformers can achieve low off-load losses by using cores made with low loss high permeability silicon steel and amorphous (non-crystalline) steel, so-called "metal glasses" — the high cost of the core material is offset by the lower losses incurred at light load, over the life of the transformer. In order to maintain good voltage regulation, distribution transformers are designed to have very low leakage inductance.

Certain special purpose transformers use long magnetic paths, insert air gaps, or add magnetic shunts (which bypass a portion of magnetic flux that would otherwise link the primary and secondary windings) in order to intentionally add leakage inductance. The additional leakage inductance limits the secondary winding's short circuit current to a safe, or a controlled, level. This technique is used to stabilize the output current for loads that exhibit negative resistance such as electric arcs, mercury vapor lamps, and neon signs, or safely handle loads that may become periodically short-circuited such as electric arc welders. Gaps are also used to keep a transformer from saturating, especially audio transformers that have a DC component added.

Solid cores

Powdered iron cores are used in circuits (such as switch-mode power supplies) that operate above mains frequencies and up to a few tens of kilohertz. These materials combine high magnetic permeability with high bulk electrical resistivity.

At even higher, radio-frequencies (RF), other types of cores made from non-conductive magnetic ceramic materials, called *ferrites*, are common. Some RF transformers also have moveable cores (sometimes called slugs) which allow adjustment of the coupling coefficient (and bandwidth) of tuned radio-frequency circuits.

Cores are available in a wide variety of shapes, including toroids. Other shapes include so-called E-cores and C-cores.

Air cores

High-frequency transformers may also use air cores. These eliminate the loss due to hysteresis in the core material. Such transformers maintain high coupling efficiency (low stray field loss) by overlapping the primary and secondary windings.

Toroidal cores

Toroidal transformers are built around a ring-shaped core, which is made from a long strip of silicon steel or permalloy wound into a coil, from powdered iron, or ferrite, depending on operating frequency. The 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 EI 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 minimises the length of wire needed, and also provides screening to minimize the core's magnetic field from generating electromagnetic interference.

Ferrite toroid cores are used at higher frequencies, typically between a few tens of kilohertz to a megahertz, to reduce losses, physical size, and weight of switch-mode power supplies.

Toroidal transformers are more efficient than the cheaper laminated EI types of similar power level. Other advantages, compared to EI 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 more choice of shapes. This last point means that, for a given power output, either a wide, flat toroid or a tall, narrow one with the same electrical properties can be chosen, depending on the space available. The main disadvantages are higher cost and limited size.

A drawback of toroidal transformer construction is the higher cost of windings. 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.

When fitting a toroidal transformer, it is important to avoid making an unintentional short-circuit through the core. This can happen if the steel mounting bolt in the middle of the core is allowed to touch metalwork at both ends, making a loop of conductive material that passes through the hole in the toroid. Such a loop could result in a dangerously large current flowing in the bolt.

Windings

The wire of the adjacent turns in a coil, and in the different windings, must be electrically insulated from each other. The wire used is generally magnet wire. Magnet wire is a copper wire with a coating of varnish or some other synthetic coating. Transformers for years have used Formvar wire, which is a varnished type of magnet wire.

The conducting material used for the winding depends upon the application. Small power and signal transformers are wound with solid copper wire, insulated usually with enamel, and sometimes additional insulation. Larger power transformers may be wound with wire, copper, or aluminium rectangular conductors. Strip conductors are used for very heavy currents. High frequency transformers operating in the tens to hundreds of kilohertz will have windings made of Litz wire to minimize the skin effect losses in the conductors. 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 insulated from the other, 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. This "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 is. (see reference (1) below)

For signal transformers, the windings may be arranged in a way to minimise 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.

Windings on both the primary and secondary of power transformers may have external connections (called taps) to intermediate points on the winding to allow adjustment of the voltage ratio. Taps may be connected to an automatic, on-load tap changer type of switchgear 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 type circuit. Modulation transformers in AM transmitters are very similar. Tapped transformers are also used as components of amplifiers, oscillators, and for feedback linearization of amplifier circuits.

Insulation of windings

The turns of the windings must be insulated from each other to ensure that the current travels through the entire winding. The potential difference between adjacent turns is usually small, so that enamel insulation is usually sufficient for small power transformers. Supplemental sheet or tape insulation is usually employed between winding layers in larger transformers.

The transformer may also be immersed in transformer oil that provides further insulation. Although the oil is primarily used to cool the transformer, it also helps to reduce the formation of corona discharge within high voltage transformers. By cooling the windings, the insulation will not break down as easily due to heat. To ensure that the insulating capability of the transformer oil does not deteriorate, the transformer casing is completely sealed against moisture ingress. Thus the oil serves as both a cooling medium to remove heat from the core and coil, and as part of the insulation system.

Certain power transformers have the windings protected by epoxy resin. By impregnating the transformer with epoxy under a vacuum, air spaces within the windings are replaced with epoxy, thereby sealing the windings and helping to prevent the possible formation of corona and absorption of dirt or water. This produces transformers suitable for damp or dirty environments, but at increased manufacturing cost.

Shielding

Where transformers are intended for minimum electrostatic coupling between primary and secondary circuits, an electrostatic shield can be placed between windings to reduce the capacitance between primary and secondary windings. The shield may be a single layer of metal foil, insulated where it overlaps to prevent it acting as a shorted turn, or a single layer winding between primary and secondary. The shield is connected to earth ground.

Transformers may also be enclosed by magnetic shields, electrostatic shields, or both to prevent outside interference from affecting the operation of the transformer, or to prevent the transformer from affecting the operation of nearby devices that may be sensitive to stray fields such as CRTs.

Coolant

Small signal transformers do not generate significant amounts of heat. Power transformers rated up to a few kilowatts rely on natural convective air-cooling. Specific provision must be made for cooling of high-power transformers. Transformers handling higher power, or having a high duty cycle can be fan-cooled.

Some dry transformers are enclosed in pressurized tanks and are cooled by nitrogen or sulphur hexafluoride gas.

The windings of high-power or high-voltage transformers are immersed in transformer oil — a highly refined mineral oil, that is stable at high temperatures. Large transformers to be used indoors must use a non-flammable liquid. Formerly, polychlorinated biphenyl (PCB) was used as it was not a fire hazard in indoor power transformers and it is highly stable. Due to the stability and toxic effects of PCB by-products, and its accumulation in the environment, it is no longer permitted in new equipment. Old transformers that still contain PCB should be examined on a weekly basis for leakage. If found to be leaking, it should be changed out, and professionally decontaminated or scrapped in an environmentally safe manner. 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. Other less-flammable fluids such as canola oil may be used but all fire resistant fluids have some drawbacks in performance, cost, or toxicity compared with mineral oil.

The oil cools the transformer, and provides part of the electrical insulation between internal live parts. It has to be stable at high temperatures so that a small short or arc will not cause a breakdown or fire. The oil-filled tank may have radiators through which the oil circulates by natural convection. Very large or high-power transformers (with capacities of millions of watts) may have cooling fans, oil pumps and even oil to water heat exchangers. Oil-filled transformers undergo prolonged drying processes, using vapor-phase heat transfer, electrical self-heating, the application of a vacuum, or combinations of these, 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 power transformers may be equipped with Buchholz relays which are safety devices that sense gas build-up inside the transformer (a side effect of an electric arc inside the windings), and thus switches off the transformer.

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.

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 electrical insulation without letting the transformer leak oil.

Enclosure

Small transformers often have no enclosure. Transformers may have a shield enclosure, as described above. Larger units may be enclosed to prevent contact with live parts, and to contain the cooling medium (oil or pressurized gas).

Transformer types and uses

Autotransformers

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. While theoretically separate parts of the winding can be used for input and output, in practice 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 volts across the entire winding, and 115 volts between one end and the tap. It can be connected to a 230-volt supply to drive 115-volt equipment, or reversed to drive 230-volt equipment from 115 volts. As the same winding is used for input and output, the flux in the core is partially cancelled, and a smaller core can be used. For voltage ratios not exceeding about 3:1, an autotransformer is cheaper, lighter, smaller and more efficient than a true (two-winding) transformer of the same rating.

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.

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

Constant voltage transformer (ferro-resonance)

By arranging particular magnetic properties of a transformer core, and installing a resonant tank circuit (a capacitor and an additional winding), a transformer can be arranged to automatically keep the secondary winding voltage constant regardless (within some limits) of any variance in the primary supply without additional circuitry or manual adjustment. CVA transformers run hotter than standard power transformers, for the regulating action is dependent on core saturation, which reduces efficiency somewhat.

Polyphase transformers

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-Δ, Δ-Y, Δ-Δ 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 Δ 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 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.

A voltage-regulating transformer uses a resonant winding and allows part of the core to go into saturation on each half-cycle of the alternating current. This effect stabilizes the output of the regulating transformer, which can be used for equipment that is sensitive to variations of the supply voltage. Saturating transformers provide a simple rugged method to stabilize an AC power supply. However, due to the hysteresis losses accompanying this type of operation, efficiency is low.

Instrument transformers

Current transformers

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

A **current transformer** is a type of "*instrument transformer*" that is designed to provide a current in its secondary which is **accurately** proportional to the current flowing in its primary. This accuracy is directly related to a number of factors including the following:

- burden,
- rating factor,
- load,
- external electromagnetic fields,
- temperature and
- physical CT configuration.

The burden in a CT metering circuit is essentially the amount of impedance (largely resistive) present. Typical burden ratings for CTs 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 0.2Ω 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 times, 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.

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. A CT usually demonstrates reduced capacity to maintain accuracy with rising ambient temperature. 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. For example, a 200:5 CT with a rating factor of 4.0 is most accurate between 20A (light load)and 800A (4.0 times the nominal rating, or "full load," of the CT) of primary current. While previous revisions of CTs were on the order of 500:5 with a rating factor of 1.5 yielding an effective range of 50A to 750A. This is an 11% increase in effective range for two CTs that would be used at similar services. Not to mention, the relative cost of a 500:5 CT is significantly greater than that of a 200:5.

Physical CT configuration is another important factor in reliable CT accuracy. While all electrical engineers are quite comfortable with Gauss' Law, there are some issues when attempting to apply theory to the real world. When conductors passing through a CT are not centered in the circular (or oval) void, slight inaccuracies may occur. It is important to center primary conductors as they pass through CTs to promote the greatest level of CT accuracy. Afterall, in an electric metering circuit, the most inaccurate component is the CT.

Current transformers (CTs) are commonly used in metering and protective relaying in the electrical power industry where they facilitate the 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. Current transformers are used extensively for measuring current and monitoring the operation of the power grid. The CT is typically described by its current ratio from primary to secondary. Common secondaries are 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. Typically, the secondary connection points are labelled as 1s1, 1s2, 2s1, 2s2 and so on. The multi ratio CTs are typically used for current matching in current differential protective relaying applications. Often, multiple CTs will be installed as a "stack" for various uses (for example, protection devices and revenue metering may use separate CTs). For a three-stacked CT application, the secondary winding connection points are typically labelled Xn, Yn, Zn. 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 this will produce a dangerously high voltage across the open secondary and may permanently affect the accuracy of the transformer.

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.

Voltage transformers

Voltage transformers (VTs) or potential transformers (PTs) 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 or 120 Volts at rated primary voltage, to match the input ratings of protection relays.

The transformer winding high-voltage connection points are typically labelled as H1, H2 (sometimes H0 if it is internally grounded) and X1, X2, and sometimes an X3 tap may be present. Sometimes a second isolated winding (Y1, Y2, Y3) 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 (H1, X1, Y1, 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 protection relays.

While VTs were formerly used for all voltages greater than 240V primary, modern meters eliminate the need VTs for most secondary service voltages. For new, or rework, meter packages, VTs are typically only installed in primary voltage (typically 12.5kV) or generation voltage (13.2kV) meter packages.

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 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.

RF transformers (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

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

Transformers are also used in DI boxes to convert impedance from high-impedance instruments (for example, bass guitars) 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.) Solid-state power amplifiers may 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.

Speaker transformers

In the same way that transformers are used to create high voltage power transmission circuits that minimize transmission losses, speaker transformers allow many individual loudspeakers to be powered from a single audio circuit operated at higher-than normal speaker voltages. This application is common in public address (e.g., Tannoy) applications. Such circuits are commonly referred to as *constant voltage* or *70 volt* speaker circuits although the audio waveform is obviously a constantly changing voltage.

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 speaker circuit. Then, a smaller transformer at each speaker returns the voltage and impedance to ordinary speaker levels. The speaker transformers commonly have multiple primary taps, allowing the volume at each speaker to be adjusted in a number of discrete steps.

Use of a constant-voltage speaker circuit means that there is no need to worry about the impedance presented to the amplifier output (which would clearly be too low if all of the speakers were arranged in parallel and would be too complex a design problem if the speakers were arranged in series-parallel). The use of higher transmission voltage and impedance means that power lost in the connecting wire is minimized, even with the use of small-gauge conductors (and leads to the term *constant voltage* as the line voltage doesn't change much as additional speakers are added to the system). In addition, the ability to adjust, locally, the volume of each speaker (without the complexity and power loss of an L pad) is a useful feature.

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.

'Interstage' and coupling transformers

A use for interstage transformers is in the case of push-pull amplifiers where an inverted signal is required. Here two secondary windings wired in opposite polarities may be used to drive the output devices.