Transformer

A **transformer** is a static electrical device that transfers energy by inductive coupling between its winding circuits. A varying current in the *primary* winding creates a varying magnetic flux in the transformer's core and thus a varying magnetic flux through the *secondary* winding. This varying magnetic flux induces a varying electromotive force (EMF), or "voltage", in the secondary winding.

Transformers range in size from a thumbnail-sized coupling transformer hidden inside a stage microphone to huge units weighing hundreds of tons used in power stations, or to interconnect portions of power grids. All operate on 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 many electronic devices. Transformers are essential for high-voltage electric power transmission, which makes long-distance transmission economically practical.

History

**Discovery**

The principle behind the operation of a transformer, 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 \( \Phi_B \) 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. However he only applied individual pulses of current to his transformer, and never discovered the relation between the turns ratio and EMF in the windings.
**Induction coils**

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.

**Transformers and power distribution**

**Early devices for use with alternating current**

By the 1870s, efficient generators that produced alternating current (alternators) were available, and it was found that alternating current could power an induction coil directly, without an interrupter. 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 factory, Budapest, 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.

**Early series circuit transformer distribution**

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 (or other electric device) 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 parallel power distribution**

In the autumn of 1884, Károly Zipernowsky, Ottó Bláthy and Miksa Déri (Z.B.D.), three engineers associated with the Ganz factory, had determined that open-core devices were impracticable, as they were incapable of reliably regulating voltage. In their joint 1885 patent applications for novel transformers (later called Z.B.D. transformers), they described two designs with closed magnetic circuits where copper windings were either a) wound around iron wire ring core or b) surrounded by iron wire core. The two designs were the first application of the two basic transformer construction types in common use to this day which can as a class all be termed as either core form or shell form (or alternatively, core-type or shell type), as in a) or b), respectively (see images). The Ganz factory had also in the autumn of 1884 made delivery of the world's first five high-efficiency AC transformers, the first of these units having been shipped on September 16, 1884. This first unit had been manufactured to the following specifications: 1,400 W, 40 Hz, 120:72 V, 11.6:19.4 A, ratio 1.67:1, one-phase, shell form. In both designs, the magnetic flux linking the primary and secondary windings traveled almost entirely within the confines of the iron core, with no intentional path through air (see 'Toroidal cores' below). The new transformers were 3.4 times more efficient than the open-core bipolar devices of Gaulard and Gibbs. Their patents included two other major interrelated innovations: one concerning the use of parallel connected, instead of series connected, utilization loads, the other concerning the ability to have high turns ratio transformers such that the supply network voltage could be much higher (initially 1,400 to 2,000 V) than the voltage of utilization loads (100 V initially preferred). When they employed them 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 parallel shunt connections, and Déri had performed the experiments. Transformers in use today are designed based on principles discovered by the three engineers. They also 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.[27][28] In 1886, the Z.B.D. engineers designed, and the Ganz factory supplied electrical equipment for, 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.[29]

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.[30] 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 (see image).[13] This design[31] was first used commercially in the U.S. in 1886[12] but Westinghouse was intent on improving the Stanley design to make it (unlike the Z.B.D. type) easy and cheap to produce.[31] Westinghouse, Stanley and a few other associates had soon developed a core consisting of 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.[25][32]

**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.[33]

In 1891, Nikola Tesla invented the Tesla coil, an air-cored, dual-tuned resonant transformer for generating very high voltages at high frequency.[34][35]

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 is shown in the figure below. 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. If a load is connected to the secondary winding, the load current and voltage will be in the directions indicated, given the primary current and voltage in the directions indicated (each will be alternating current in practice).
**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 \( \Phi \) is the magnetic flux through one turn of the coil. If the turns of the coil are oriented perpendicularly 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,[36] the instantaneous voltage across the primary winding equals

\[ V_p = N_p \frac{d\Phi}{dt}. \]

Taking the ratio of the two equations for \( V_s \) and \( V_p \) gives the basic equation\(^{[37]}\) for stepping up or stepping down the voltage

\[ \frac{V_s}{V_p} = \frac{N_s}{N_p}. \]

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

**Ideal power equation**

If a load is connected to the secondary winding, current will flow in this winding, and electrical energy will be transferred from the primary circuit through the transformer to the load. Transformers may be used for AC-to-AC conversion of a single power frequency, or for conversion of signal power over a wide range of frequencies, such as audio or radio frequencies.

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 enables 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 \( N_p \). The windings are coils wound around a ferromagnetic core, air-core transformers being a notable exception.

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 input electric power must equal the output power:

\[
P_{\text{incoming}} = I_p V_p = P_{\text{outgoing}} = I_s V_s,
\]

giving the ideal transformer equation

\[
\frac{V_s}{V_p} = \frac{N_s}{N_p} = \frac{I_p}{I_s}.
\]

This formula is a reasonable approximation for commercial transformers.

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.\[^{[36]}\] For example, if an impedance \( Z_s \) is attached across the terminals of the secondary coil, it appears to the primary circuit to have an impedance of \((N_p/N_s)^2 Z_s\). This relationship is reciprocal, so that the impedance \( Z_p \) of the primary circuit appears to the secondary to be \((N_s/N_p)^2 Z_p\).

The ideal model neglects the primary current required to establish a magnetic field in the core, equivalent to assuming the core has negligible reluctance. Since the field generated in the core by current in the secondary winding opposes the field of the primary winding, current in the primary winding must increase to maintain the same relationship between induced EMFs. The simple approximation also neglect the non-zero resistance of the two windings.\[^{[38]}\]

When a voltage is applied to the primary winding, a small current flows, driving flux around the magnetic circuit of the core.\[^{[38]}\] 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.\[^{[39]}\] 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 in accordance with Lenz's law, which states that induction of EMF always opposes development of any such change in magnetic field.

Basic transformer parameters and construction

Leakage flux

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 flux 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 (see "Stray losses" below), but results in inferior voltage regulation, causing the secondary voltage to not be directly proportional to the primary voltage, particularly under heavy load. Transformers are therefore normally designed to have very low leakage inductance. Nevertheless, it is impossible to eliminate all leakage flux because it plays an essential part in the operation of the transformer. The combined effect of the leakage flux and the electric field around the windings is what transfers energy from the primary to the secondary.

In some applications increased leakage is desired, and long magnetic paths, air gaps, or magnetic bypass shunts may deliberately be introduced in a transformer 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 component flowing through the windings.

Knowledge of leakage inductance is for example useful when transformers are operated in parallel. It can be shown that if the percent impedance (Z) and associated winding leakage reactance-to-resistance (X/R) ratio of two transformers were hypothetically exactly the same, the transformers would share power in proportion to their respective volt-ampere ratings (e.g. 500 kVA unit in parallel with 1,000 kVA unit, the larger unit would carry twice the current). However, the impedance tolerances of commercial transformers are significant. Also, the Z impedance and X/R ratio of different capacity transformers tends to vary, corresponding 1,000 kVA and 500 kVA units' values being, to illustrate, respectively, Z ~ 5.75%, X/R ~ 3.75 and Z ~ 5%, X/R ~ 4.75.
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 $E_{\text{rms}}$ 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:[38]

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

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

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

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.[47] Hypothetically an ideal transformer would work with direct-current excitation, with the core flux increasing linearly with time.[48] In practice, the flux rises to the point where magnetic saturation of the core occurs, causing a large increase in the magnetizing current and overheating the transformer. All practical transformers must therefore operate with alternating (or pulsed direct) current.[48]

The EMF of a transformer at a given flux density increases with frequency.[38] 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.[49] 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) were 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 a 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 traction transformers used for electric multiple unit and high speed train service operating across the country border and using different electrical standards, such transformers’ being restricted to be positioned below the passenger compartment. The power supply to, and converter equipment being supply by, such traction transformers have to accommodate different input frequencies and voltage (ranging from as high as 50 Hz down to 16.7 Hz and rated up to 25 kV) while being suitable for multiple AC asynchronous motor and DC converters & motors with varying harmonics mitigation filtering requirements.

Knowledge of natural frequencies of transformer windings is necessary for the determination of winding transient response 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%. [50]

Experimental transformers using superconducting windings achieve efficiencies of 99.85%. [51] 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 current 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 (also see energy efficient transformer). [52]

Transformer losses arise from:

**Winding joule losses**

Current flowing through winding conductors causes joule heating. As frequency increases, Skin effect and proximity effect causes winding resistance and, hence, losses to increase.

**Core 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. [52]

**Eddy current losses**

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. [52] 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.

**Magnetostrictive related losses**

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 [37] that can cause losses due to frictional heating. This buzzing is particularly familiar from low-frequency (50 Hz or 60 Hz) mains hum, and high-frequency (15,734 Hz (NTSC) or 15,625 Hz (PAL)) CRT noise.

**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. [53] There are also radiative losses due to the oscillating magnetic field but these are usually small.

**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
Transformer consuming a small amount of power.\textsuperscript{[54]}

**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.

**Core form and shell form transformers**

Closed-core transformers are constructed in "core form" or "shell form". When windings surround the core, the transformer is core form; when windings are surrounded by the core, the transformer is shell form. Shell form design may be more prevalent than core form design for distribution transformer applications due to the relative ease in stacking the core around winding coils.\textsuperscript{[15]} Core form design tends to, as a general rule, be more economical, and therefore more prevalent, than shell form design for high voltage power transformer applications at the lower end of their voltage and power rating ranges (less than or equal to, nominally, 230 kV or 75 MVA). At higher voltage and power ratings, shell form transformers tend to be more prevalent.\textsuperscript{[15][18][55][56]} Shell form design tends to be preferred for extra high voltage and higher MVA applications because, though more labor intensive to manufacture, shell form transformers are characterized as having inherently better kVA-to-weight ratio, better short-circuit strength characteristics and higher immunity to transit damage.\textsuperscript{[56]}

**Equivalent circuit**

Referring to the diagram, a practical transformer's physical behavior may be represented by an equivalent circuit model, which can incorporate an ideal transformer.\textsuperscript{[57]}

Winding joule losses and leakage reactances are represented by the following series loop impedances of the model:
- Primary winding: $R_P$, $X_P$
- Secondary winding: $R_S$, $X_S$

$R_S$ and $X_S$ are in practice usually referred to the primary side by multiplying these impedances by the scaling factor $(N_P/N_S)^2$.

Core loss and reactance is represented by the following shunt leg impedances of the model:
- Core or iron losses: $R_C$
- Magnetizing reactance: $X_M$

$R_C$ and $X_M$ are sometimes collectively termed the magnetizing branch of the model.
Core 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. The finite permeability core requires a magnetizing current $I_M$ to maintain mutual flux in the core. Magnetizing current is in phase with the flux, the relationship between the two being non-linear due to saturation effects. However, all impedances of the equivalent circuit shown are by definition linear and such non-linearity effects are not typically reflected in transformer equivalent circuits. With sinusoidal supply, core flux lags the induced EMF by 90°. With open-circuited secondary winding, magnetizing branch current $I_0$ equals transformer no-load current. The resulting model, though sometimes termed ‘exact’ equivalent circuit based on linearity assumptions, retains a number of approximations. Analysis may be simplified by assuming that magnetizing branch impedance is relatively high and relocating the branch to the left of the primary impedances, thus allowing combination of primary and referred secondary resistances and reactances by simple summation as two series impedances.

Transformer equivalent circuit impedance and transformer ratio parameters can be derived from the following tests: Open-circuit test, short-circuit test, winding resistance test, and transformer ratio test.

**Construction**

**Cores**

**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.
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 mains 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

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
Transformer (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 (see "Classification" above). 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 inductive components. 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 rated more than a few kVA are uncommon. 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**

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.

Power transformers often have internal connections or taps at intermediate points on the winding, usually on the higher voltage winding side, for voltage regulation control purposes. Such taps are normally manually operated, automatic on-load tap changers being reserved, for cost and reliability considerations, to higher power rated or specialized transformers supplying transmission or distribution circuits or certain utilization loads such as furnace transformers. 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.
Cooling

Small dry and liquid-immersed transformers are often self-cooled by natural convection and radiation heat dissipation. As power ratings increase, transformers are often cooled by forced-air cooling, forced-oil cooling, water-cooling, or combinations of these.[72]

Most outdoor power transformers are filled with transformer oil, a dielectric fluid that both cools and insulates the windings.[73] Transformer oil is a highly refined mineral oil that cools the windings and insulation by circulating within the transformer tank. The mineral oil and paper insulation system has been extensively studied and used for more than 100 years. A new power transformer can be expected to operate for around 50 years, the accepted rule of thumb being that transformer life expectancy is halved for every 8° C increase in operating temperature.[74] With a great body of empirical study as a guide, dissolved gas analysis of transformer oil provides useful maintenance information and, in the case of very large rated, high value transformer assets, this often translates in a need to monitor, model, forecast and manage oil and winding conductor insulation temperature conditions under varying, possibly difficult, power loading conditions.[75][76]

Building regulations in many jurisdictions require indoor liquid-filled transformers to either use dielectric fluids that are less flammable than oil, have spill collection systems, or be installed in fire-resistant rooms.[77] Air-cooled dry transformers are thus preferred for indoor applications even where oil-cooled construction would be more economical because their lower transformer cost would more than offset more stringent building construction requirements.

The oil-filled tank often has radiators through which the oil circulates by natural convection. Some large transformers employ electric fans for forced-air cooling, pumps for forced-oil cooling, or have heat exchangers for water-cooling.[73] 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.[64] 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 dielectric coolant, though concerns over their environmental persistence led to a widespread ban on their use.[78] 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.[79][77] PCBs for new equipment was banned in 1981 and in 2000 for use in existing equipment in United Kingdom.[80] Before 1977, in Canada, 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.[81]

Some transformers, instead of being liquid-filled, have their windings enclosed in sealed, pressurized tanks and cooled by nitrogen or sulfur hexafluoride gas.[79]

Experimental power transformers in the 500-to-1,000 kVA range have been built with liquid nitrogen or helium cooled superconducting windings, which, compared to usual transformer losses, eliminates winding losses without affecting core losses.[82][83]
Insulation drying

Construction of oil-filled transformers requires that the insulation covering the windings be thoroughly dried before the oil is introduced. Drying is carried out at the factory, and may be required as a field service. Drying may be done by circulating hot air around the core, or by vapour-phase drying (VPD) where evaporated solvent transfers heat by condensation on the coil and core. For small transformers resistance heating by injection of current into the windings is used. 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 needed to induce the current can be reduced.[84] The LFH drying method is also used for service of older transformers.[85]

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.[86]

Classification parameters

Transformers can be classified in many ways, such as the following:

- **Power capacity**: From a fraction of a volt-ampere (VA) to over a thousand MVA.
- **Duty of a transformer**: Continuous, short-time, intermittent, periodic, varying.
- **Frequency range**: Power-frequency, audio-frequency, or radio-frequency.
- **Voltage class**: From a few volts to hundreds of kilovolts.
- **Cooling type**: Dry and liquid-immersed - self-cooled, forced air-cooled; liquid-immersed - forced oil-cooled, water-cooled.
- **Circuit application**: Such as power supply, impedance matching, output voltage and current stabilizer or circuit isolation.
- **Utilization**: Pulse, power distribution, rectifier, arc furnace, amplifier output, etc..
- **Basic magnetic form**: Core form, shell form.
- **Constant-potential transformer descriptor**: Step-up, step-down, isolation.
- **General winding configuration**: By EIC vector group - various possible two-winding combinations of the phase designations delta, wye or star, and zigzag or interconnected star;[87] other - autotransformer, Scott-T, zigzag grounding transformer winding.[88][89][90][91]

- **Rectifier phase-shift winding configuration**: 2-winding, 6-pulse; 3-winding, 12-pulse; . . . n-winding, [n-1]*6-pulse; polygon; etc..

Types

For more details, see Transformer types or specific main articles, as shown.

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

- **Autotransformer**: Transformer in which part of the winding is common to both primary and secondary circuits.[92]
- **Capacitor voltage transformer**: Transformer in which capacitor divider is used to reduce high voltage before application to the primary winding.
- **Distribution transformer**: Transformer used to distribute energy from transmission lines and networks for local consumption.[92]
- **Scott-T transformer**: Transformer used for phase transformation from three-phase to two-phase and vice versa.[92]
• **Polyphase transformer**: Any transformer with more than one phase.

• **Zigzag or interconnected star transformer, zigzag grounding transformer winding**: Transformer used for grounding or phase-shifting three-phase circuits.

• **Leakage transformer**: Transformer that has loosely coupled windings.

• **Resonant transformer**: Transformer that uses resonance to generate a high secondary voltage.

• **Audio transformer**: Transformer used in audio equipment.

• **Output transformer**: Transformer used to match the output of a valve amplifier to its load.

• **Instrument transformer**: Potential or current transformer used to accurately and safely represent voltage, current or phase position of high voltage or high power circuits.\[^{92}\]

### Applications

Transformers are used to increase voltage before transmitting electrical energy over long distances through wires. Wires have resistance which loses energy through joule heating at a rate corresponding to square of the current. By transforming electrical power to a higher voltage for transmission and transformers enable economical transmission of power and distribution. Consequently, transformers have shaped the electricity supply industry, permitting generation to be located remotely from points of demand.\[^{94}\] 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.\[^{53}\]

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.\[^{95}\]


[67] McLyman, Chap. 3 p. 1


[71] Heathcote, pp. 720–723

[72] Pansini, p. 32


[79] Kulkarni, pp. 2-3


[83] Pansini, pp. 66–67


[87] For example, the delta-wye transformer, by far the most common commercial three-phase transformer, is known as the Dyn11 vector group configuration, Dyn11 denoting D for delta primary winding, y for wye secondary winding, n for neutral of the wye winding, and 11 for relative phase position on the clock by which the secondary winding leads that of the primary winding, namely, 30°.


[92] Knowlton, p. 549-550


[94] Heathcote, p. 1

References

Bibliography


External links

- *Inside Transformers*, composed by J. B. Calvert, from Denver University (http://www.du.edu/~jcalvert/tech/transfor.htm)
- *Understanding Transformers: Characteristics and Limitations* from Conformity Magazine (http://www.conformity.com/artman/publish/printer_47.shtml)
- 3 Phase Transformer Information and Construction — The 3 Phase Power Resource Site (http://www.3phasepower.org/3phasetransformers.htm)
- Substation and Transmission (http://www.dmoz.org/Business/Electronics_and_Electrical/Substation_and_Transmission/) at the Open Directory Project
- Introduction to Current Transformers (http://www.elkor.net/pdfs/AN0305-Current_Transformers.pdf)
- Transformer (Interactive Java applet) (http://www.phy.hk/wiki/englishhtm/Transformer.htm), 'Physics is fun' by Chui-king Ng
- HD video tutorial on transformers (http://www.afrotechmods.com/videos/transformer_tutorial.htm)
- Three-phase transformer circuits (http://www.allaboutcircuits.com/vol_2/chpt_10/6.html) from All About Circuits
- Bibliography of Transformer Books (http://www.transformerscommittee.org/info/Bibliographybooks.pdf) by P.M. Balma, from IEEE Transformer Committee
- Einschalten des Transformators. German Wikipedia article about transformer inrush current at switch on (in German).