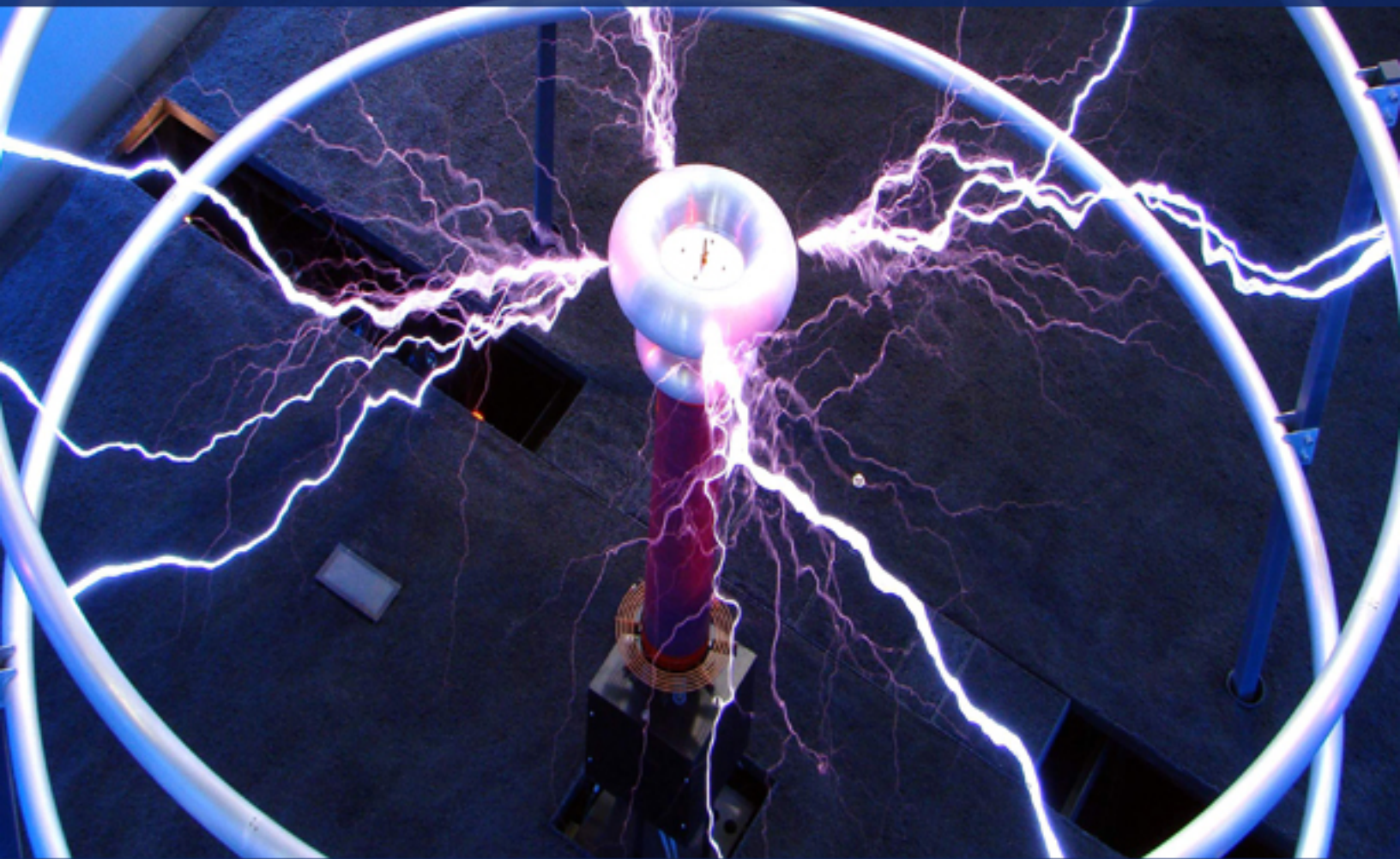


Handbook of
Transformers
and Electromagnetic Coils



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Felicity Salerno

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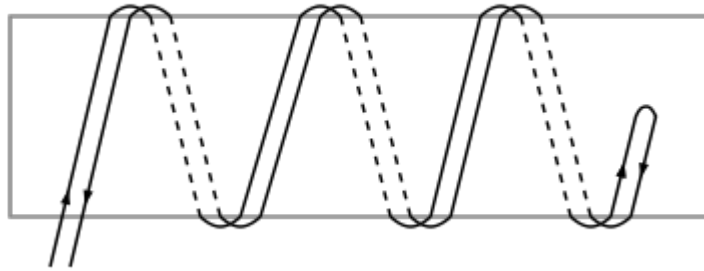
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Chapter-1

Bifilar Coil and Basket Winding

Bifilar Coil

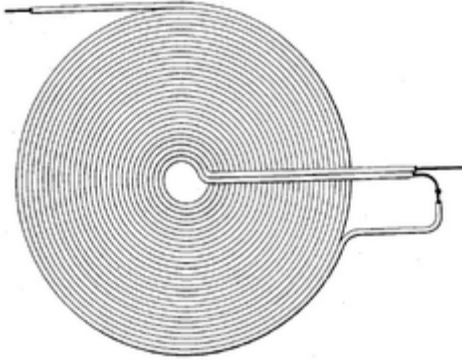


Non-inductive bifilar winding

A **bifilar coil** is an electromagnetic coil that contains two closely spaced, parallel windings. In engineering, the word *bifilar* describes wire which is made of two filaments or strands. It is commonly used to denote special types of winding wire for transformers. Wire can be purchased in bifilar form, usually as different colored enameled wire bonded together. For three strands, the term **trifilar coil** is used.

Description and applications

Bifilar coil configurations



Nikola Tesla's flat bifilar coil.

1. parallel-wound, series connected
2. parallel-wound, parallel connected
3. counter-wound (series)
4. counter-wound (parallel)

Some bifilars have adjacent coils in which the convolutions are arranged so that the potential difference is magnified (i.e., the current flows in same parallel direction). Others are wound so that the current flows in opposite directions. The magnetic field created by one winding is therefore equal and opposite to that created by the other, resulting in a net magnetic field of zero (i.e., neutralizing any negative effects in the coil). In electrical terms, this means that the self-inductance of the coil is zero.

The bifilar coil (more often called the *bifilar winding*) is used in modern electrical engineering as a means of constructing wire-wound resistors with negligible parasitic self-inductance.

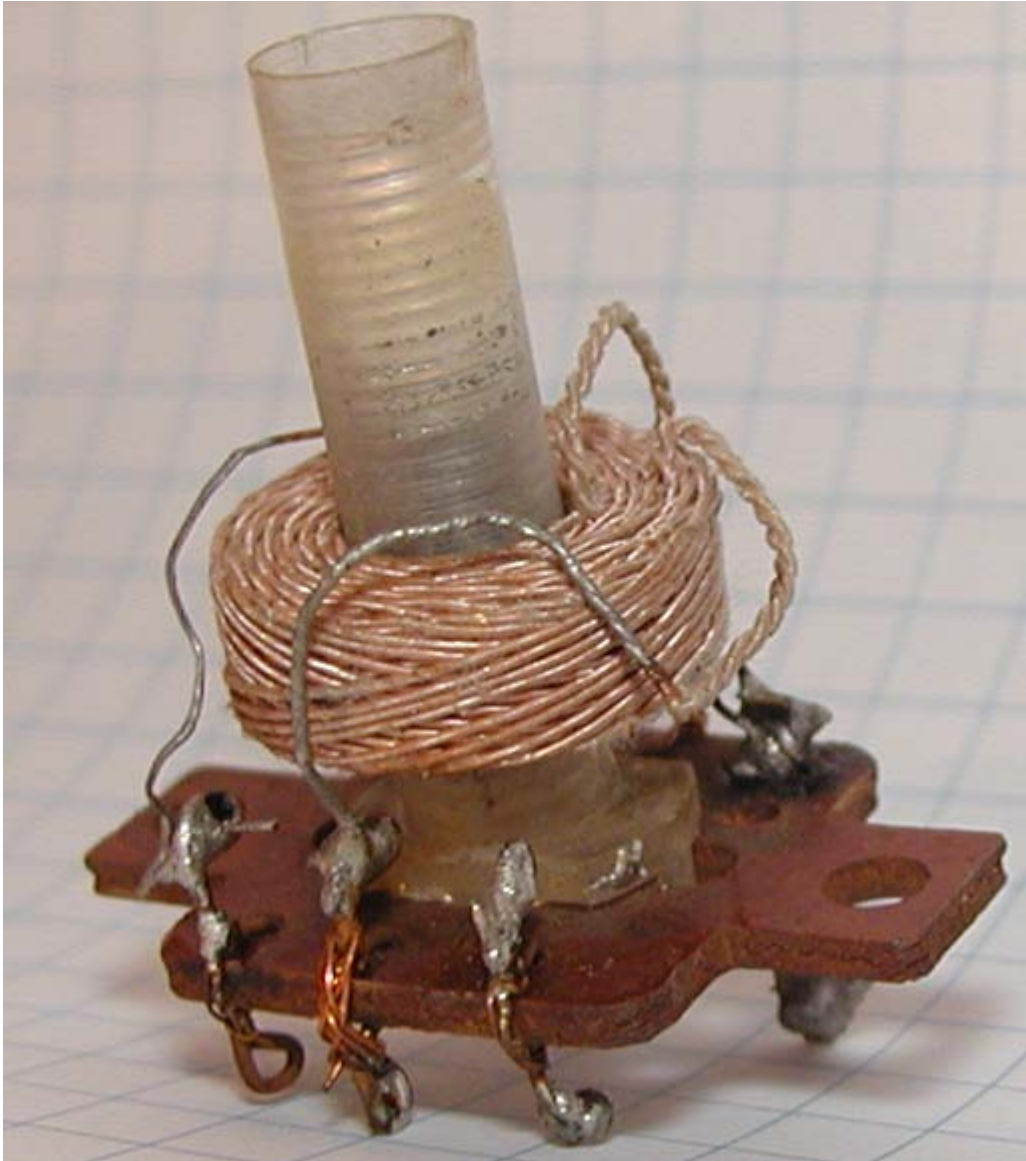
A different type of bifilar coil is used in some relay windings and transformers used for a switched-mode power supply to suppress back-emf. In this case, the two wire coils are closely spaced and wound in parallel but are electrically isolated from each other. The primary coil is driven to operate the relay, and the secondary coil is short-circuited inside the case. When the current through the primary is interrupted, as happens when the relay is switched off, most of the magnetic energy is intercepted by the secondary coil which converts it to heat in its internal resistance. This is only one of several methods of absorbing the energy from the primary coil before it can damage the device (usually a vulnerable semiconductor) that drives the relay. The main disadvantage of this method is that it greatly increases the switching time of the relay.

When used in a switching transformer, one winding of the bifilar coil is used as a means of removing the energy stored in the stray magnetic flux which fails to link the *primary coil* to the *secondary coil* of the transformer. Because of their proximity, the wires of the bifilar coil both "see" the same stray magnetic flux. One wire is clamped to ground usually by a diode so that when the other "primary" wire of the bifilar coil no longer has a voltage applied across it by the switching transistor, the stray magnetic flux generates a current in the clamping coil with the primary side voltage appearing across it, causing an equal voltage to appear across the primary winding. If this clamping coil was not used, the stray magnetic flux would attempt to force a current to flow through the primary wire. Since the primary wire is switched off and the switching transistor is in a high resistance state, the high voltage which would appear on the semiconductor switching transistor would exceed its electrical breakdown or even damage it.

History

An early example of the bifilar coil can be seen in Nikola Tesla's United States patent 512,340 of 1894. Tesla explains that in some applications (which he does not specify) the self-inductance of a conventional coil is undesired and has to be neutralised by adding external capacitors. The bifilar coil in this configuration has increased self-capacitance, thereby saving the cost of the capacitors. It is notable that this is *not* the kind of bifilar winding used in non-inductive wirewound resistors where the windings are wired anti-series to null out self-inductance.

Basket Winding



Basket winding made with a Litz wire

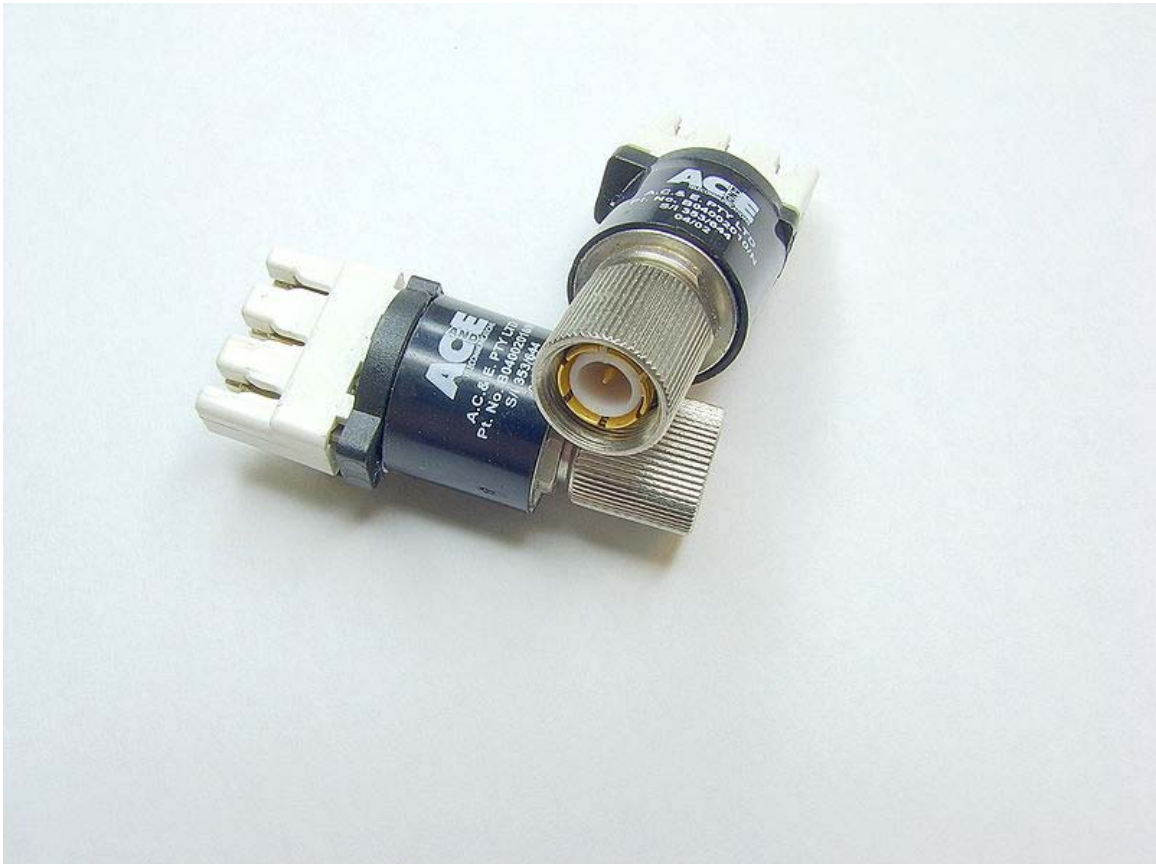
Basket winding is an electromagnetic coil wound in a special way, such that the wires in neighbouring layers cross each other at an angle as close to 90 degrees as possible. Such a winding results in low parasitic capacitance as compared with a regular winding with the same number of turns. However, the physical dimensions are greater which leads to higher leakage inductance.

Basket windings are used for high frequency coils, and are wound with a Litz wire, or a wire isolated with cotton or silk. The type of isolation is important also from mechanical

point of view during the winding, because a common enamelled magnet wire would not provide sufficient surface friction to hold the subsequent turns at the large angle.

Chapter-2

Balun



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

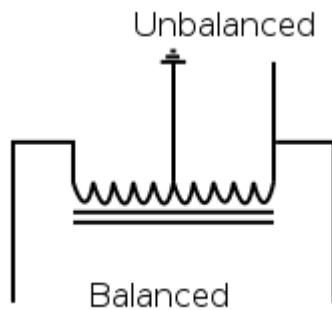


2 balun matching transformers

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

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

Types of balun

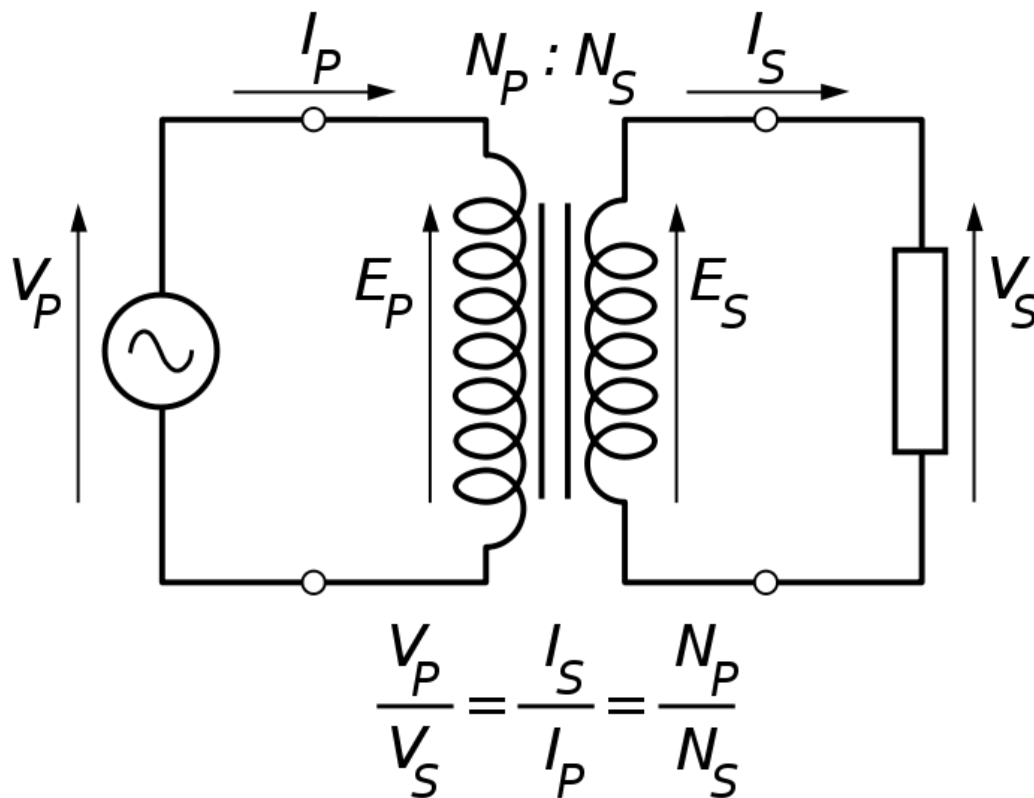


Autotransformer 4:1 wideband balun using two windings on a ferrite rod.

Autotransformer type

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

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



Isolated transformer

Classical transformer type

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

Transmission-line transformer type

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

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



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

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

Delay line type

A large class of baluns uses connected transmission lines of specific lengths, with no obvious "transformer" part. These are usually built for (narrow) frequency ranges where the lengths involved are some multiple of a quarter wavelength of the intended frequency in the transmission line medium. A common application is in making a coaxial

connection to a balanced antenna, and designs include many types involving coaxial loops and variously connected "stubs".

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

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

Balun alternatives

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

Applications

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

Radio and television



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

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

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

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

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

Video

While not as high as most RF applications, baseband video still uses frequencies up to several megahertz. Since this bandwidth is now well within range of modern twisted-pair cables, they are now being used to send video which would otherwise run over coaxial cable. Many better security cameras now have both a balanced UTP output and an unbalanced coaxial one via an internal balun, though any camera can be used with an external balun. A balun is also used on the video recorder end to convert back from the 100-ohm balanced to 75-ohm unbalanced. A balun of this type has a BNC connector with

two screw terminals. VGA/DVI baluns are baluns with electronic circuitry used to connect VGA/DVI sources (laptop, DVD, etc.) to VGA/DVI display devices over long runs of CAT-5/CAT-6 cable. Runs over 130 m (400 ft) may lose quality due to attenuation and variations in the arrival time of each signal. A skew control and special low skew or skew free cable is used for runs over 130 m (400 ft).

Audio



Three audio baluns (transformers).

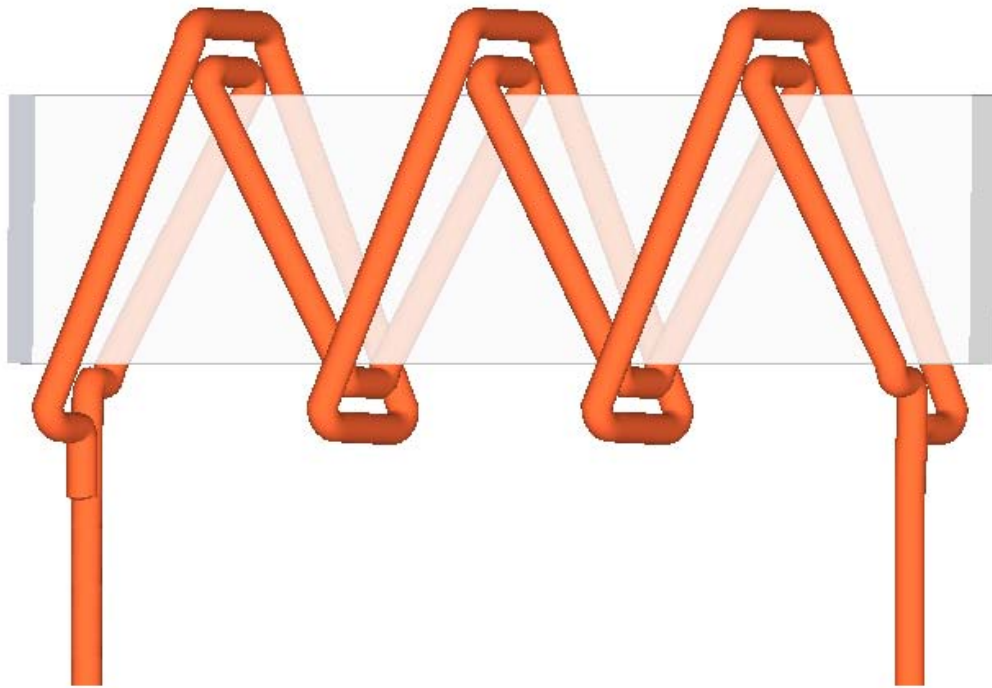
In audio applications, baluns convert between high impedance unbalanced and low impedance balanced lines.

Except for the connections, the three devices in the image are electrically identical, but only the leftmost two can be used as baluns. The device on the left would normally be

used to connect a high impedance source, such as a guitar, into a balanced microphone input, serving as a passive DI unit. The one in the centre is for connecting a low impedance balanced source, such as a microphone, into a guitar amplifier. The one at the right is not a balun, as it provides only impedance matching.

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

Ayrton-Perry Winding



Ayrton-Perry winding

Ayrton-Perry winding is a type of bifilar winding pattern used in winding wire on forms to make electronic components. Its advantage is that the resulting coil of wire has low values of parasitic inductance and parasitic capacitance. Ayrton-Perry windings of resistance wire are used to make wirewound RF resistors that are used at high frequencies, where inductance and capacitance are unwanted.

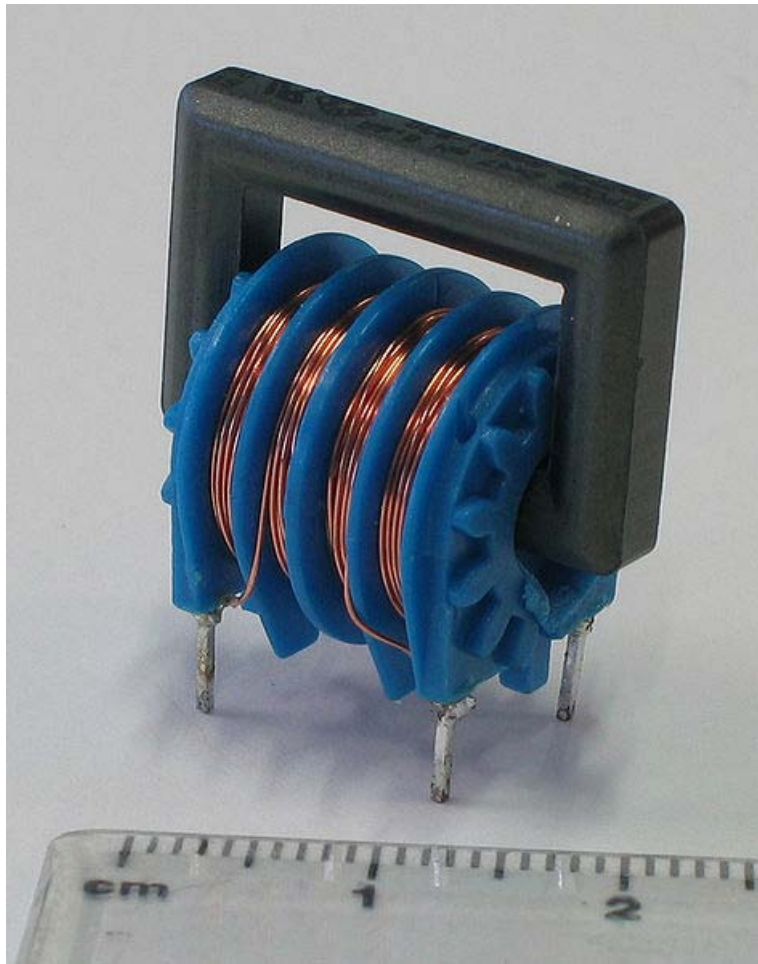
The winding is made of two separate wires wound in opposing directions along an insulating form and connected in parallel at the ends. Since there are the same number of turns of wire in either direction, the magnetic fields of the two wires cancel each other out, so the coil has little inductance. And since adjacent turns of the two wires are at approximately the same voltage, there is little parasitic capacitance between the turns.

One disadvantage is that because the two lengths of resistive wire are connected in parallel, four times the length of wire (twice the length for each coil) is needed to make a given resistance than if a single coil was used.

Chapter-3

Choke (Electronics) and Helmholtz Coil

Choke (Electronics)



A choke, with two 47mH windings and rated to handle 0.6A

A **choke** is an inductor designed to block (have a high reactance to) higher frequencies in an electrical circuit while passing signals of much lower frequency or direct current.

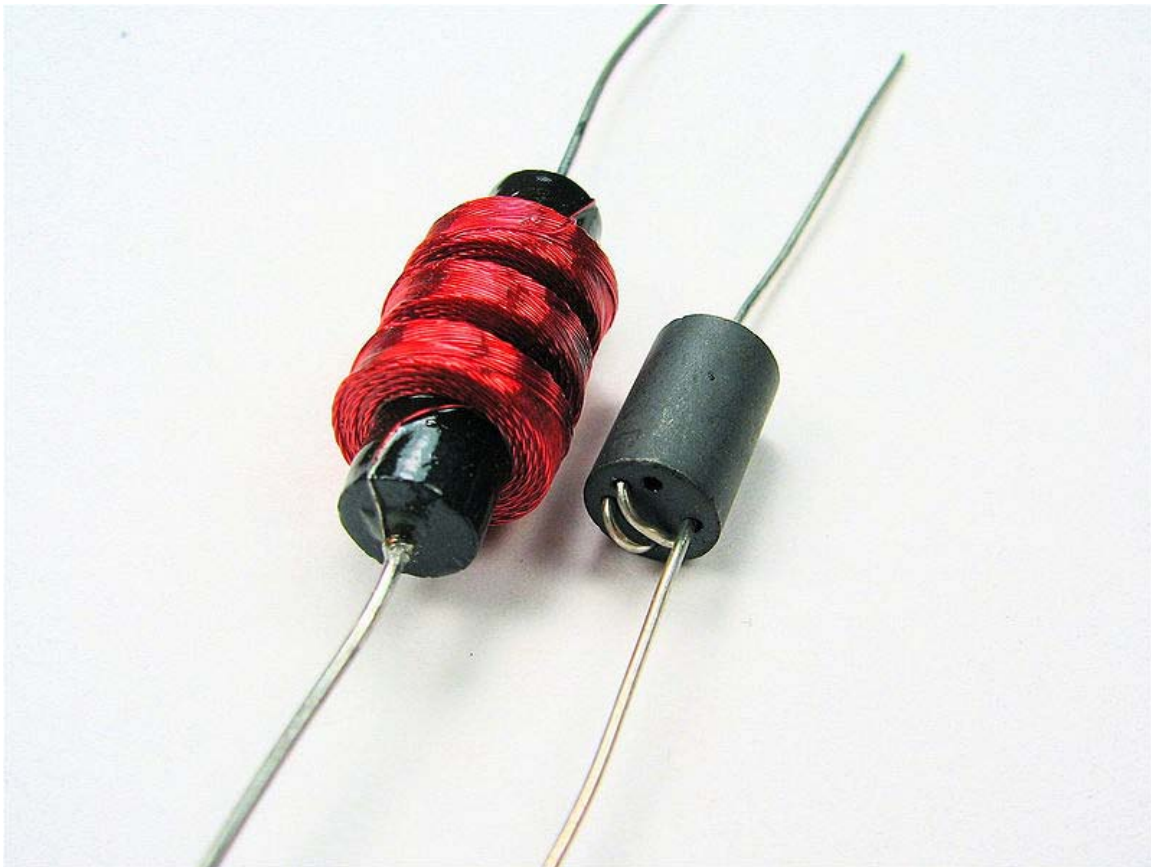
Description

Choke coils are inductances that isolate AC frequency currents from certain areas of a radio circuit. Chokes depend upon the property of self-inductance for their operation. They can be used to block alternating current while passing direct current (contrast with capacitor).

Common-mode choke

Common-mode choke coils are useful in a wide range of prevention of electromagnetic interference (EMI) and radio frequency interference (RFI) from power supply lines and for prevention of malfunctioning of electronic equipment. They pass differential currents (equal but opposite), while blocking common-mode currents.

Types and construction



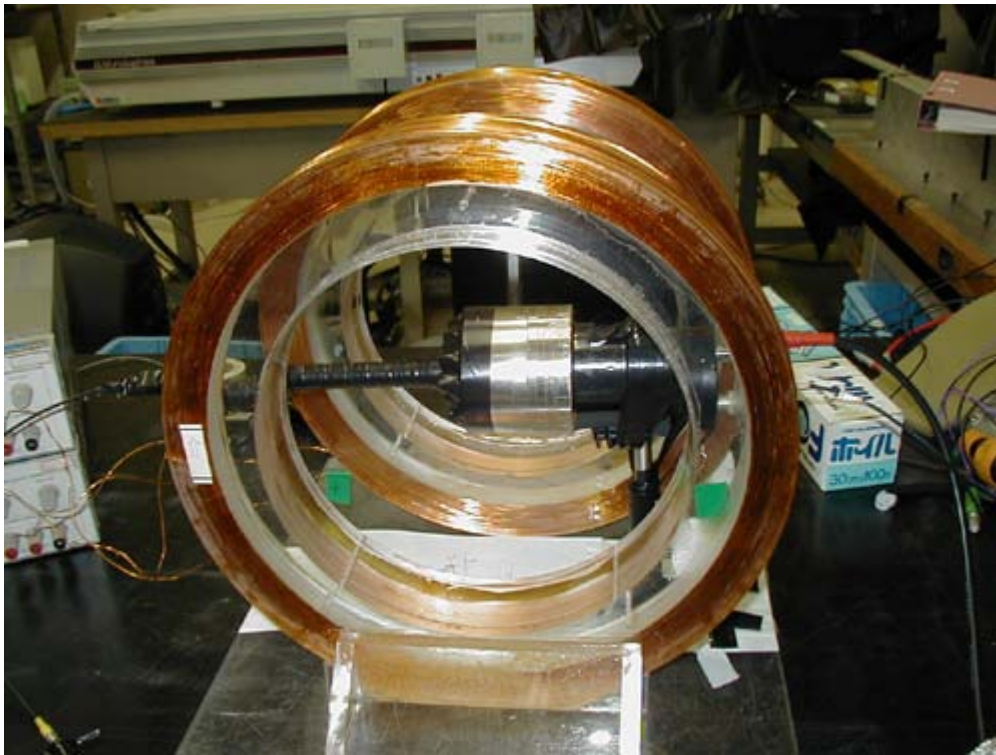
An MF or HF radio choke for tenths of an Ampere and several hundred Volts, and a ferrite bead VHF choke for several Amperes and tens of Volts.

Chokes used in radio circuits are divided into two classes – those designed to be used with audio frequencies, and the others to be used with radio frequencies. Audio frequency coils, usually called A.F. chokes, can have ferromagnetic iron cores to increase their inductance. Chokes for higher frequencies often have iron powder or ferrite cores. Chokes for even higher frequencies have non-magnetic cores and low inductance simulating the effects of an air-core.

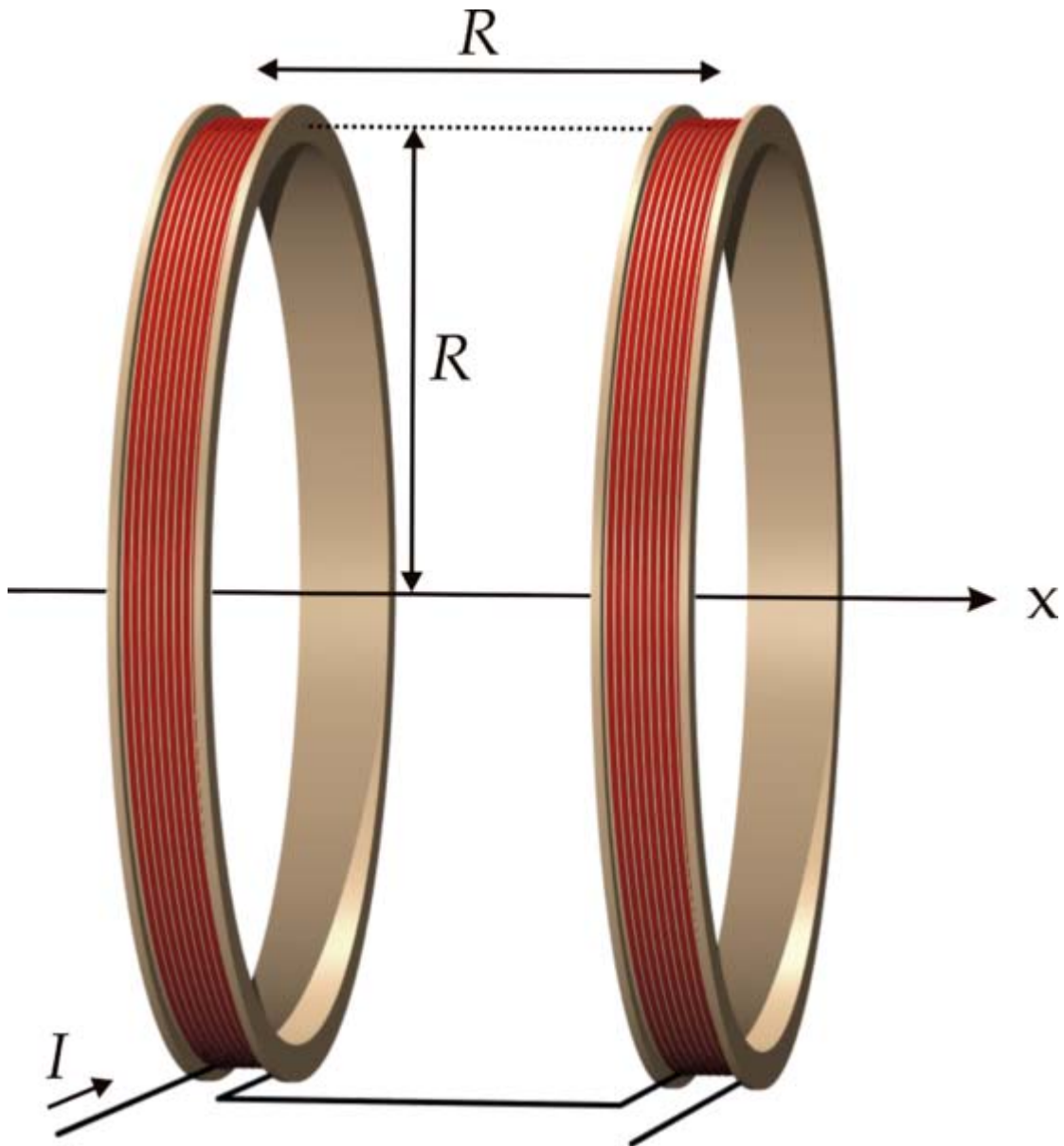
Solid-state chokes

Solid-state chokes (SSC) can manage higher currents than traditional chokes. They can help reduce the high frequency buzzing noises that occur when running under high electrical currents.

Helmholtz Coil



A Helmholtz coil



Helmholtz coil schematic drawing

A **Helmholtz coil** is a device for producing a region of nearly uniform magnetic field. It is named in honor of the German physicist Hermann von Helmholtz.

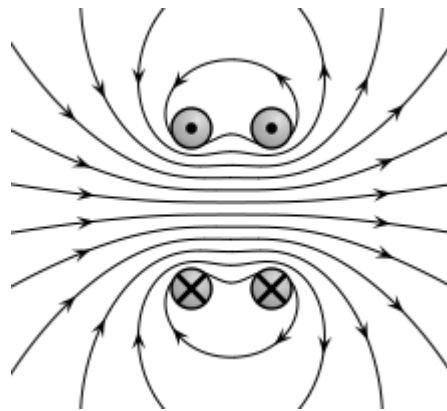
Description

A Helmholtz pair consists of two identical circular magnetic coils that are placed symmetrically one on each side of the experimental area along a common axis, and separated by a distance h equal to the radius R of the coil. Each coil carries an equal electrical current flowing in the same direction.

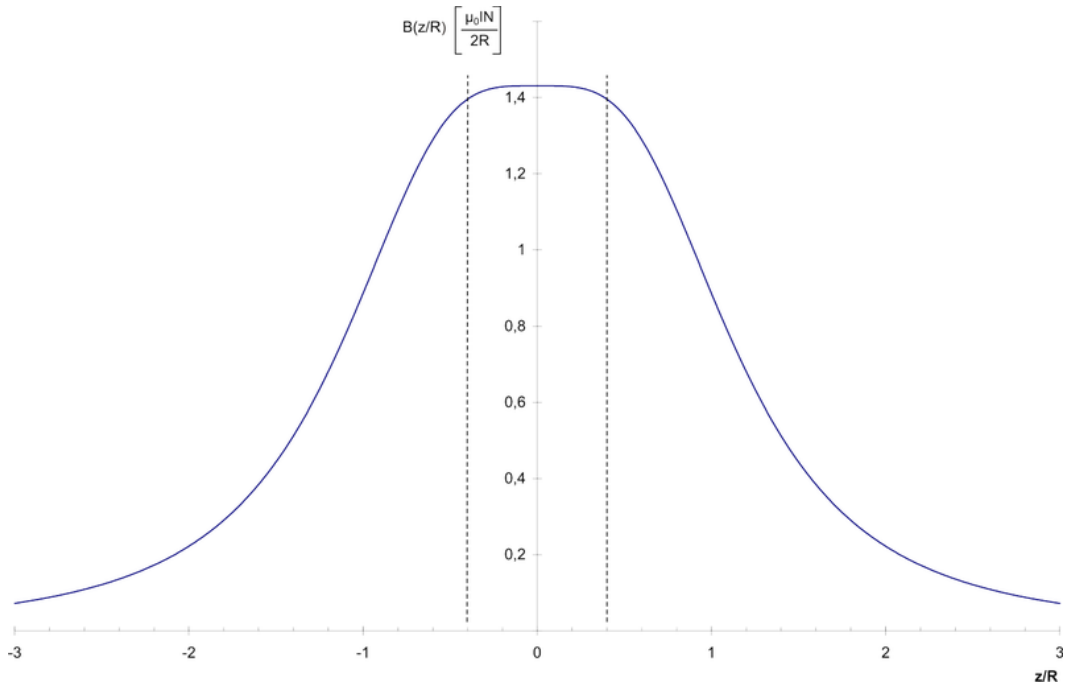
Setting $h = R$, which is what defines a Helmholtz pair, minimizes the nonuniformity of the field at the center of the coils, in the sense of setting $d^2B / dx^2 = 0$ (meaning that the first nonzero derivative is d^4B / dx^4 as explained below), but leaves about 6% variation in field strength between the center and the planes of the coils. A slightly larger value of h reduces the difference in field between the center and the planes of the coils, at the expense of worsening the field's uniformity in the region near the center, as measured by d^2B / dx^2 .

In some applications, a Helmholtz coil is used to cancel out Earth's magnetic field, producing a region with a magnetic field intensity much closer to zero.

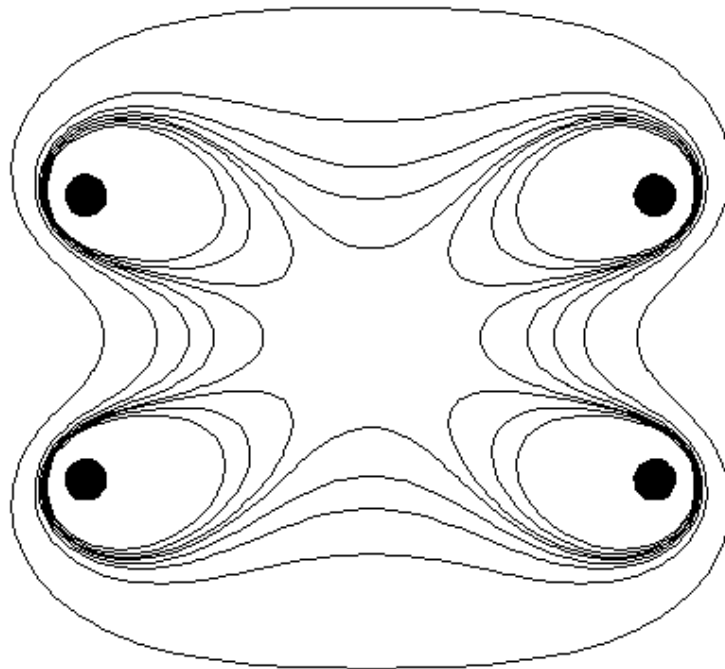
Mathematics



Magnetic field lines in a plane bisecting the current loops. Note the field is approximately uniform in between the coil pair. (In this picture the coils are placed one beside the other: the axis is horizontal)



Magnetic field induction along the axis crossing the center of coils; $z = 0$ is the point in the middle of distance between coils.



Contours showing the magnitude of the magnetic field near the coil pair. Inside the central 'octopus' the field is within 1% of its central value B_0 . The five contours are for field magnitudes of $0.5B_0$, $0.8B_0$, $0.9B_0$, $0.95B_0$, and $0.99B_0$.

The calculation of the exact magnetic field at any point in space has mathematical complexities and involves the study of Bessel functions. Things are simpler along the axis of the coil-pair, and it is convenient to think about the Taylor series expansion of the field strength as a function of x , the distance from the central point of the coil-pair along the axis. By symmetry the odd order terms in the expansion are zero. By separating the coils so that charge $x = 0$ is an inflection point for each coil separately we can guarantee that the order x^2 term is also zero, and hence the leading non-uniform term is of order x^4 . One can easily show that the inflection point for a simple coil is $R/2$ from the coil center along the axis; hence the location of each coil at $x = \pm R/2$

A simple calculation gives the correct value of the field at the center point. If the radius is R , the number of turns in each coil is n and the current flowing through the coils is I , then the magnetic flux density, B at the midpoint between the coils will be given by

$$B = \left(\frac{4}{5}\right)^{3/2} \frac{\mu_0 n I}{R}$$

μ_0 is the permeability of free space ($1.26 \times 10^{-6} \text{ T} \cdot \text{m/A}$), and R is in meters.

Derivation

Start with the formula for the on-axis field due to a single wire loop (which is itself derived from the Biot-Savart law):

$$B = \frac{\mu_0 I R^2}{2(R^2 + x^2)^{3/2}}$$

Where:

μ_0 = the permeability constant =

$$4\pi \times 10^{-7} \text{ T} \cdot \text{m/A} = 1.26 \times 10^{-6} \text{ T} \cdot \text{m/A}$$

I = coil current, in amperes

R = coil radius, in meters

x = coil distance, on axis, to point, in meters

However the coil consists of a number of wire loops, the total current in the coil is given by

nI = total current

Where:

n = number of wire loops in one coil

Adding this to the formula:

$$B = \frac{\mu_0 n I R^2}{2(R^2 + x^2)^{3/2}}$$

In a Helmholtz coil, a point halfway between the two loops has an x value equal to R/2, so let's perform that substitution:

$$B = \frac{\mu_0 n I R^2}{2(R^2 + (R/2)^2)^{3/2}}$$

There are also two coils instead of one, so let's multiply the formula by 2, then simplify the formula:

$$B = \frac{2\mu_0 n I R^2}{2(R^2 + (R/2)^2)^{3/2}}$$
$$B = \left(\frac{4}{5}\right)^{3/2} \frac{\mu_0 n I}{R}$$

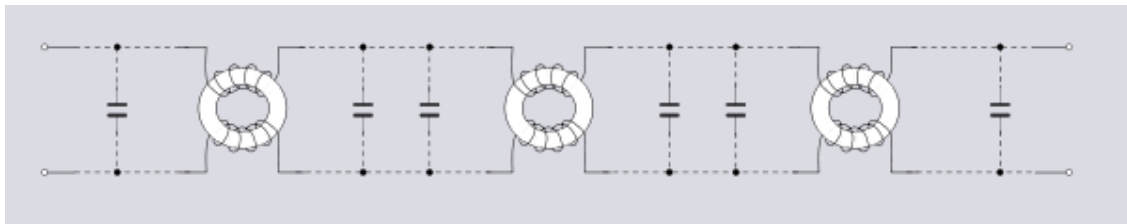
Chapter-4

Loading Coil

In electronics, a **loading coil** or **load coil** is a coil (inductor) that does not provide coupling to any other circuit, but is inserted in a circuit to increase its inductance. The need was discovered by Oliver Heaviside in studying the disappointing slow speed of the Transatlantic telegraph cable. He concluded additional inductance was required to prevent amplitude and time delay distortion of the transmitted signal. The mathematical condition for distortionless transmission is known as the Heaviside condition. Previous telegraph lines were overland or shorter, hence had less delay and the need for extra inductance was not so great. Submarine communications cables are particularly subject to the problem, but early 20th century ones using balanced pairs were often continuously loaded by iron tape rather than discretely by load coils.

Loading coils are archaically known as **Pupin coils** after Mihajlo Pupin (especially when used for the Heaviside condition), and the process of inserting them is sometimes called *pupinization*.

Applications



Schematic of a balanced loaded line. The capacitors are shown connected with dotted lines to indicate that the capacitance is actually distributed along the line rather than the discrete elements shown. The windings of the loading coil are wound such that the magnetic flux induced in the core is in the same direction for both windings.

Voice circuits

A common application of loading coils is to improve the voice-frequency amplitude response characteristics of the twisted balanced pairs in a telephone cable.

Loading coils inserted periodically in series with a pair of wires reduce the attenuation at the higher voice frequencies up to the cutoff frequency of the low-pass filter formed by the inductance of the coils (plus the distributed inductance of the wires) and the distributed capacitance between the wires. Above the cutoff frequency, attenuation increases rapidly. The shorter the interval between the coils, the higher the cut-off frequency.

It should be emphasised that the cutoff effect is an artifact of using lumped inductors. With loading methods using continuous distributed inductance there is no cutoff.

Without loading coils, the line response is dominated by the resistance and capacitance of the line with the attenuation gently increasing with frequency. With loading coils of exactly the right inductance, neither capacitance nor inductance dominate: the response is flat, waveforms are undistorted and the characteristic impedance is resistive up to the cutoff frequency. The coincidental formation of an audio frequency filter is also beneficial in that noise is reduced.

DSL

When loading coils are in place, signal attenuation remains low for signals within the passband of the transmission line but increases rapidly for frequencies above the audio cutoff frequency. Thus, if the pair is subsequently reused to support applications that require higher frequencies (such as analog or digital carrier systems or DSL), any loading coils that were present on the line must be removed or replaced with one which is transparent to DSL. Using coils with parallel capacitors will form a filter with the topology of an m-derived filter and a band of frequencies above the cut-off will also be passed.

If they are not removed, as when the subscriber is an extended distance (e.g. over 4 miles) from the Central Office, DSL can not be supported. This sometimes happens in dense, growing areas (subject to frequent national numbering scheme repartitioning) such as Southern California in the late 1990s and early 21st century.

Carrier systems

American early and middle 20th Century telephone cables had load coils at intervals of a mile (1.61 km), usually in coil cases holding many. The coils must be removed to pass high frequencies, but the coil cases provided convenient places for repeaters for digital T-carrier systems, which could carry 1.5 Mbit/s across that distance. Due to narrower streets and higher cost of copper, European cables had thinner wires and needed closer intervals. Intervals of a kilometer allowed European systems to carry 2 Mbit/s.

Radio antennae

A (mobile) radio antenna, shorter than a quarter wavelength for practical reasons, presents capacitive reactance to a transmission line. This can be canceled by inserting an

equal and opposite (inductive) reactance in series, by means of a loading coil typically at the base or center of the antenna. Consequently the antenna presents a resistance (desirable) to the transmission line.

Campbell equation

The Campbell equation is a relationship due to George Ashley Campbell for predicting the propagation constant of a loaded line. It is stated as;

$$\cosh(\gamma'd) = \cosh(\gamma d) + \frac{Z}{2Z_0} \sinh(\gamma d)$$

where,

γ is the propagation constant of the unloaded line

γ' is the propagation constant of the loaded line

d is the interval between coils on the loaded line

Z is the impedance of a loading coil and

Z_0 is the characteristic impedance of the unloaded line.

A more engineer friendly rule of thumb is that the approximate requirement for spacing loading coils is ten coils per wavelength of the maximum frequency being transmitted. This approximation can be arrived at by treating the loaded line as a constant k filter and applying image filter theory to it. From basic image filter theory the angular cutoff frequency and the characteristic impedance of a low-pass constant k filter are given by;

$$\omega_c = \frac{1}{\sqrt{L_{\frac{1}{2}} C_{\frac{1}{2}}}} \quad \text{and} \quad Z_0 = \sqrt{\frac{L_{\frac{1}{2}}}{C_{\frac{1}{2}}}}$$

where $L_{\frac{1}{2}}$ and $C_{\frac{1}{2}}$ are the half section element values.

From these basic equations the necessary loading coil inductance and coil spacing can be found;

$$L = \frac{Z_0}{\omega_c} \quad \text{and} \quad d = \frac{2}{\omega_c Z_0 C}$$

where C is the capacitance per unit length of the line.

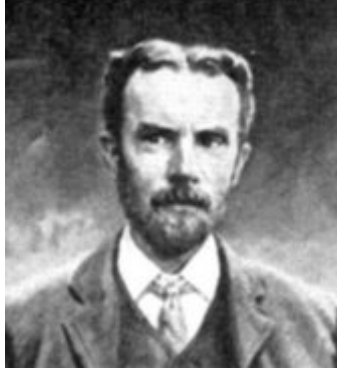
Expressing this in terms of number of coils per cutoff wavelength yields;

$$\frac{\lambda_c}{d} = \pi v Z_0 C$$

where v is the velocity of propagation of the cable in question.

History

Oliver Heaviside



Oliver Heaviside

The origin of the loading coil can be found in the work of Oliver Heaviside on the theory of transmission lines. Heaviside (1881) represented the line as a network of infinitesimally small circuit elements. By applying his operational calculus to the analysis of this network he discovered (1887) what has become known as the Heaviside condition. This is the condition that must be fulfilled in order for a transmission down a line to be free from distortion. The Heaviside condition is that the line series impedance, Z , must be proportional to the line shunt admittance, Y , at all frequencies. In terms of the primary line coefficients this is the condition;

$$\frac{R}{G} = \frac{L}{C}$$

where;

R is the series resistance of the line per unit length

L is the series self-inductance of the line per unit length

G is the shunt leakage conductance of the line insulator per unit length

C is the shunt capacitance between the line conductors per unit length

Heaviside was aware that this condition was not met in the practical telegraph cables in use in his day. In general, a real cable would have,

$$\frac{R}{G} \gg \frac{L}{C}$$

This is mainly due to the low value of leakage through the cable insulator, which is even more pronounced in modern cables which have better insulators than in Heaviside's day. In order to meet the condition, the choices are therefore to try and increase G or L or to decrease R or C . Decreasing R requires larger conductors. Copper was already in use in telegraph cables and this is the very best conductor available short of using silver. Decreasing R means using more copper and a more expensive cable. Decreasing C would

also mean a larger cable (although not necessarily more copper). Increasing G is highly undesirable, while it would reduce distortion, it would at the same time increase the signal loss. Heaviside considered, but rejected, this possibility which left him with the strategy of increasing L as the way to reduce distortion.

Heaviside immediately (1887) proposed several methods of increasing the inductance, including spacing the conductors further apart and loading the insulator with iron dust. Finally, Heaviside made the proposal (1893) to use discrete inductors at intervals along the line. However, he never succeeded in persuading the British GPO to take up the idea. Brittain attributes this to Heaviside's failure to provide engineering details on the size and spacing of the coils for particular cable parameters. Heaviside's eccentric character and setting himself apart from the establishment may also have played a part in their ignoring of him.

John Stone

John S. Stone worked for the American Telephone & Telegraph Company (AT&T) and was the first to attempt to apply Heaviside's ideas to real telecommunications. Stone's idea (1896) was to use a bimetallic iron-copper cable which he had patented. This cable of Stone's would increase the line inductance due to the iron content and had the potential to meet the Heaviside condition. However, Stone left the company in 1899 and the idea was never implemented.

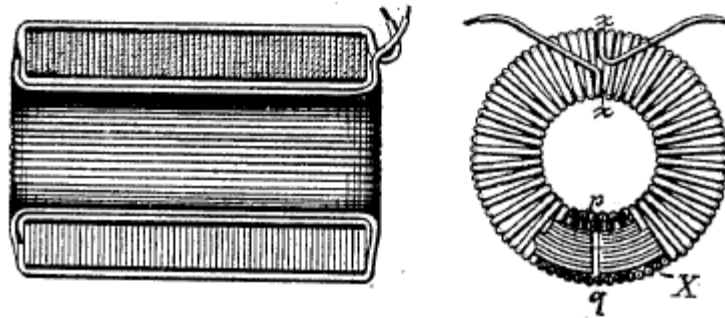
George Campbell

George Campbell was another AT&T engineer working for them in their Boston facility. Campbell was tasked with continuing the investigation into Stone's bimetallic cable, but soon abandoned this in favour of the loading coils idea. This was an independent discovery, Campbell being aware of Heaviside's work in discovering the Heaviside condition, but apparently not aware of Heaviside's suggestion of using loading coils to force a line to meet it. The motivation for the change of direction was Campbell's limited budget.

Campbell was struggling to set up a practical demonstration over a real telephone route with the budget he had been allocated. After considering that his artificial line simulators used lumped components rather than the distributed quantities found in a real line, he wondered if he could not insert the inductance with lumped components instead of using Stone's distributed line. When his calculations showed that the manholes on telephone routes were sufficiently close together to be able to insert the loading coils without the expense of either having to dig up the route or lay in new cables he changed to this new plan. The very first demonstration of loading coils on a telephone cable was on a 46-mile length of the so-called Pittsburgh cable (the test was actually in Boston, the cable had previously been used for testing in Pittsburgh) on September 6, 1899 carried out by Campbell himself and his assistant. The first telephone cable using loaded lines put into public service was between Jamaica Plain and West Newton in Boston on May 18, 1900.

Campbell's work on loading coils provided the theoretical basis for his subsequent work on filters which proved to be so important for frequency-division multiplexing. The cut-off phenomena of loading coils, an undesirable side-effect, can be exploited to produce a desirable filter frequency response.

Michael Pupin



Pupin's design of loading coil

Michael Pupin, inventor and Serbian immigrant to the USA, also played a part in the story of loading coils. Pupin filed a rival patent to the one of Campbell's. This patent of Pupin's dates from 1899. There is an earlier patent (1894, filed December 1893) which is sometimes cited as Pupin's loading coil patent but is, in fact, something different. The confusion is easy to understand, Pupin himself claims that he first thought of the idea of loading coils while climbing a mountain in 1894, although there is nothing from him published at that time.

Pupin's 1894 patent "loads" the line with capacitors rather than inductors, a scheme that has been criticised as being theoretically flawed and never put into practice. To add to the confusion, one variant of the capacitor scheme proposed by Pupin does indeed have coils. However, these are not intended to compensate the line in any way. They are there merely to restore DC continuity to the line so that it may be tested with regular equipment. Pupin states that the inductance is to be so large that it will block all AC signals above 50 Hz. Consequently, only the capacitor is adding any significant impedance to the line and "the coils will not exercise any material influence on the results before noted".

Legal battle

Heaviside never patented his idea; indeed, he took no commercial advantage of any of his work. Despite the legal disputes surrounding this invention, it is unquestionable that Campbell was the first to actually construct a telephone circuit using loading coils. There also can be little doubt that Heaviside was the first to publish and many would dispute Pupin's priority.

AT&T fought a legal battle with Pupin over his claim. Pupin was first to patent but Campbell had already conducted practical demonstrations before Pupin had even filed his patent (December 1899). Campbell's delay in filing was due to the slow internal machinations of AT&T.

However, AT&T foolishly deleted from Campbell's proposed patent application all the tables and graphs detailing the exact value of inductance that would be required before the patent was submitted. Since Pupin's patent contained a (less accurate) formula, AT&T was open to claims of incomplete disclosure. Fearing that there was a risk that the battle would end with the invention being declared unpatentable due to Heaviside's prior publication, they decided to desist from the challenge and buy an option on Pupin's patent for a yearly fee so that AT&T would control both patents. By January 1901 Pupin had been paid \$200,000 and by 1917, when the AT&T monopoly ended and payments ceased, he had received a total of \$455,000.

Benefit to AT&T

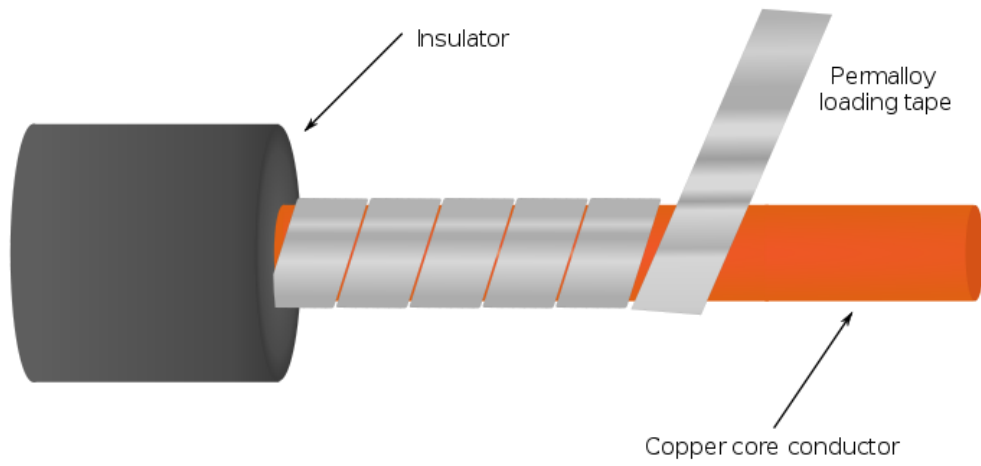
The invention was of enormous value to AT&T. Telephone cables could now be used to twice the distance previously possible, or alternatively, a cable of half the previous quality (and cost) could be used over the same distance. When considering whether to allow Campbell to go ahead with the demonstration, their engineers had estimated that they stood to save \$700,000 in new installation costs in New York and New Jersey alone. It has been estimated that AT&T saved \$100 million in the first quarter of the 20th century. Heaviside, who began it all, came away with nothing. He was offered a token payment but would not accept, wanting the credit for his work. He remarked ironically that if his prior publication had been admitted it would "interfere . . . with the flow of dollars in the proper direction . . .".

Krarup cable

Loading coils were not without their problems. For submarine cables where they were of most benefit, they were difficult to lay. The cable needed to be heavier and both this and the discontinuities in the profile where the coils occurred caused stresses in the cable during laying. Without great care, the cable might part and would be enormously expensive, possibly impossible, to fix. A second problem was that the material science of the time had difficulties sealing the joint between coil and cable against ingress of seawater. When this occurred, of course, the cable was ruined.

A Danish engineer, Carl Emil Krarup, invented a form of continuously loaded cable which solved these problems and the cable is named for him. Krarup cable has iron wires continuously wound around the central copper conductor with adjacent turns in contact with each other. This cable was the first use of continuous loading on any telecommunication cable. In 1902 Krarup both wrote his paper on this subject and saw the installation of the first cable between Helsingør (Denmark) and Helsingborg (Sweden).

Permalloy cable

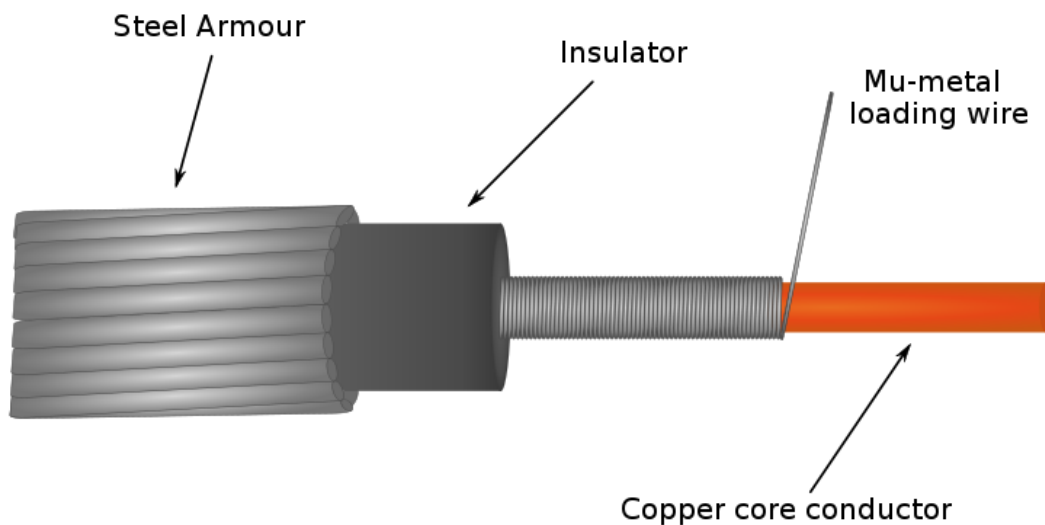


Permalloy cable construction

Even though Krarup cable added inductance to the line, it did not add enough to meet the Heaviside condition. AT&T searched for a better material with higher magnetic permeability. In 1914 Gustav Elmen discovered permalloy, a magnetic nickel-iron annealed alloy. Oliver E. Buckley, along with his colleagues at Bell Labs, H. D. Arnold and Elmen, c.1915 proposed a method of constructing submarine cable using permalloy tape wrapped around the copper conductors. This construction greatly improved the performance of the cable.

The cable was tested in a trial in Bermuda in 1923. The first permalloy cable to be put into service was between New York and Horta (Azores) in September 1924.

Mu-metal cable



Mu-metal cable construction

Mu-metal has similar magnetic properties to permalloy but the addition of copper to the alloy increases the ductility and allows the metal to be drawn into wire. Mu-metal cable is easier to construct than permalloy cable, the mu-metal being wound around the core copper conductor in much the same way as the iron wire in Krarup cable. A further advantage with mu-metal cable is that the construction lends itself to a variable loading profile whereby the loading is tapered towards the ends.

Mu-metal was invented (1923) by The Telegraph Construction and Maintenance Company Ltd., London, who made the cable, initially, for the Western Union Telegraph Co. Western Union were in competition with AT&T and the Western Electric Company who were using permalloy (the patent for permalloy was held by Western Electric).

Current practice

Loaded cable is no longer a useful technology for submarine communication cables, having first been superseded by co-axial cable using electrically powered in-line repeaters and then by fibre-optic cable. Manufacture of loaded cable declined in the 1930s and was then superseded by other technologies post-war. Loading coils can still be found in some telephone landlines today but new installations would use more modern technology.

Chapter-5

Low Tension Coil and Ignition Coil

Low Tension Coil

A **low tension coil** is an electrical device used to create a spark across the points of an ignitor on early 1900s gasoline engines, generally flywheel engines, hit and miss engines, and other engines of that era. In modern electronic terms, a low tension coil is simply a large inductor, an electrical device that stores energy for brief periods. The term "low tension" was the terminology of the day used to differentiate it from the term "high tension", and generally meant "low voltage" (tension) as opposed to "high voltage" (tension). High tension coils produce high voltages, generally meant to produce a spark across a spark plug.

Construction



A typical low tension coil (reproduction) used in the ignition system of an ignitor fired engine

A low tension coil consists of an iron core that has wire wrapped around it. The size of the iron core, the number of turns of wire, and the size of the wire determine the electrical properties of the coil. Terminals are provided to connect the coil into the ignition circuit. The wood ends are provided for mechanical stability, to provide for the terminal placement and to hold the wire on the coil over time. A cloth or tape covering is provided to protect the windings.

Use

A low tension coil for engine ignition is used in conjunction with a battery and an ignitor. The ignitor is no more than a set of contacts that reside inside the combustion chamber of the engine. A series circuit is made between the three components: battery connects to coil, second terminal on the coil connects to the ignitor, second terminal on the ignitor (usually connected electrically and mechanically to the engine itself) connects to the second terminal of the battery.

Theory of Operation

An inductor attempts to maintain a constant current flow through it. If the current in the circuit in which the inductor is connected goes down for some reason, the voltage developed across the inductor will go up in an attempt to try to maintain the constant current. When used with an ignitor ignition system in an engine, there is current flow when the ignitor contacts are closed. When the ignitor contacts are opened by the mechanical parts of the engine, current flow is interrupted. Because the low tension coil wants to maintain that current flow, the voltage across the coil rapidly goes up (usually to several hundred volts). When the voltage rises high enough, the voltage will jump the still very small gap of the ignitor contacts and create a spark which ignites the fuel mixture in the engine. Since there is a finite amount of energy stored in the coil, as soon as the spark jumps the gap the voltage across the coil collapses. As soon as the engine rotates and the ignitor contacts again close, current starts to flow through the coil and it again stores energy for the next cycle. A good description and moving gif of a low tension coil in operation can be found on [Harrys Old Engines Ignition Page](#)

Ignition Coil



Dual ignition coils (top of picture) on a Saab 92.



Bosch ignition coil.

An **ignition coil** (also called a **spark coil**) is an induction coil in an automobile's ignition system which transforms the battery's 12 volts (6 volts in some older vehicles) to the thousands of volts (20 to 30 thousand volts or more) needed to spark the spark plugs. Some coils have an internal resistor to reduce the voltage and some rely on a resistor wire or an external resistor to reduce the voltage from the cars 12 volt wiring flowing into the coil. The wire which goes from the ignition coil to the distributor and the wires which go from the distributor to each of the spark plugs are called spark plug wires or high tension leads.

This specific form of the autotransformer, together with the contact breaker and a capacitor (still referred to in automobile parlance by its old name of "condensor"), converts low voltage from a battery into the high voltage required by spark plugs in an internal combustion engine.

Basic principles

When the contact breaker closes, it allows a current from the battery to build up in the primary winding of the ignition coil. (The current does not flow instantly because of the inductance of the coil.) Once the current has built up to its full level, the contact breaker opens. Since it has a capacitor connected across it, the primary winding and the capacitor form a tuned circuit, and as the stored energy oscillates between the inductor formed by the coil and the capacitor, the changing magnetic field in the core of the coil induces a much larger voltage in the secondary of the coil. More modern electronic ignition systems operate on exactly the same principle, but some rely on charging the capacitor to around 400 volts rather than charging the inductance of the coil.

Use in cars

In older vehicles a single (large) coil would serve all the spark plugs via the ignition distributor. Notable exceptions are the Saab 92, and the Wartburg 353 which have one ignition coil per cylinder.

Modern ignition systems

In modern systems, the distributor is omitted and ignition is instead electronically controlled. Much smaller coils are used with one coil for each spark plug or one coil serving two spark plugs (for example two coils in a four-cylinder engine, or three coils in a six-cylinder engine). A large ignition coil puts out about 20 kV, and a small one such as from a lawn mower puts out about 15 kV. These coils may be remotely mounted or they may be placed on top of the spark plug (*coil-on-plug* or *Direct Ignition*). Where one coil serves two spark plugs (in two cylinders), it is through the "waste spark" system. In this arrangement the coil generates two sparks per cycle to both cylinders. The fuel in the cylinder that is nearing the end of its compression stroke is ignited, whereas the spark in its companion that is nearing the end of its exhaust stroke has no effect. The wasted spark system is more reliable than a single coil system with a distributor and cheaper than coil-on-plug.

Where coils are individually applied per cylinder, they may all be contained in a single molded block with multiple high-tension terminals. This is commonly called a coil-pack.

A bad coil pack may cause a slight or not so slight misfire, bad fuel economy, loss in power, and in some rare cases loss of braking performance and power steering problems.

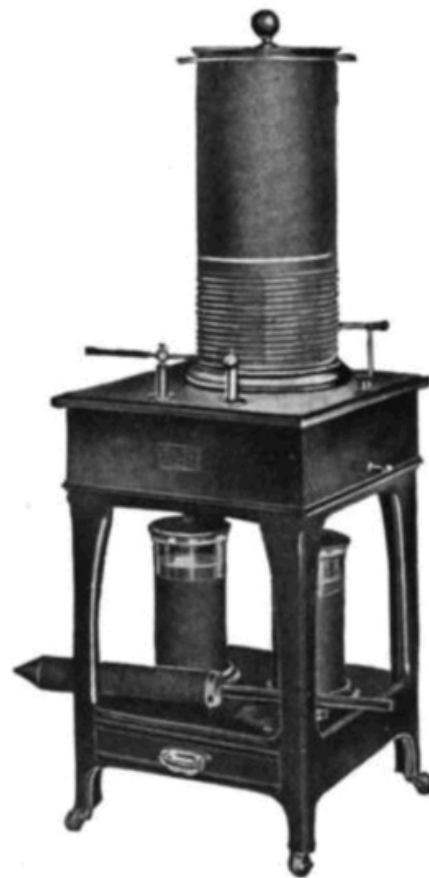
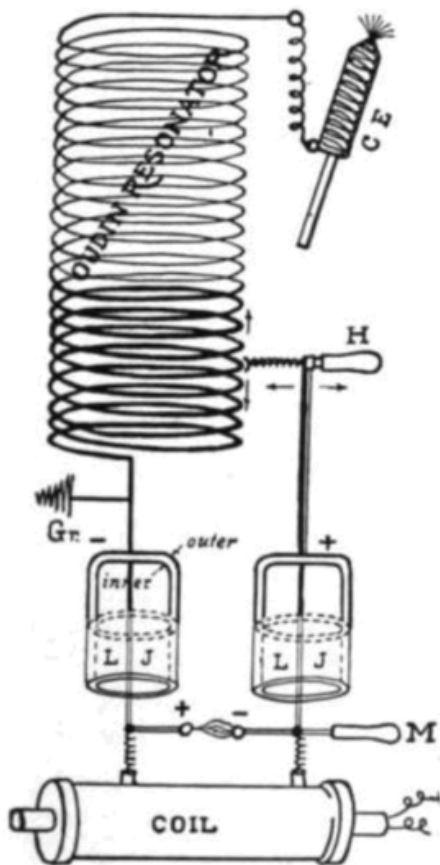
Tesla coil

The disruptive discharge Tesla coil is an early predecessor of the "ignition coil" in the ignition system as was invented in 1891. Tesla also gained U.S. Patent 609,250, "*Electrical Igniter for Gas Engines*", on August 16, 1898. The principles of the modern ignition coil used today is based on this design. A. Atwater Kent, in 1921, patented the modern form of the ignition coil.

Chapter-6

Oudin Coil, Polyphase Coil and Maxwell Coil

Oudin Coil



Oudin coil used for medical 'electrotherapy', 1907.

An **Oudin coil**, also called an **Oudin oscillator** or **Oudin resonator**, is a disruptive discharge coil wired as a transformer designed to produce high voltage arcs and discharges, similar to a Tesla coil. It was invented by French physician Paul Marie Oudin and physicist Jacques d'Arsonval around 1899.

The device is a high frequency current generator which uses the principles of resonant electrical circuits. It produces an antinode of high potential. The high-voltage, self-regenerative resonant transformer has the bottom ends of the primary and secondary coils connected together and to ground.

Oudin coils generate high voltages at high frequency, but produce lower currents than other disruptive discharge coils (such as the later version of the Tesla coil). The Oudin coil is modified for greater safety.

Polyphase Coil

Polyphase coils are electrical coils (phases) connected together in a polyphase system such as a generator or motor. In modern systems, the number of phases is usually three or a multiple of three. Each phase carries a sinusoidal alternating current whose phase is delayed relative to one of its neighbours and advanced relative to its other neighbour. The phase currents are separated in time evenly within each period of the alternating current. For example, in a three-phase system, the phases are separated from each other by one-third of the period.

Coil construction

Like all coils used in electrical machinery, polyphase coils (made from insulated conducting wire) are wound around ferromagnetic armatures with radial projections and maximum core-surface exposure to the magnetic field.

The windings are physically separated around the circumference of an electrical machine. The result of such an arrangement is a rotating magnetic field that is used to convert electrical power to rotary mechanical work, or vice versa.

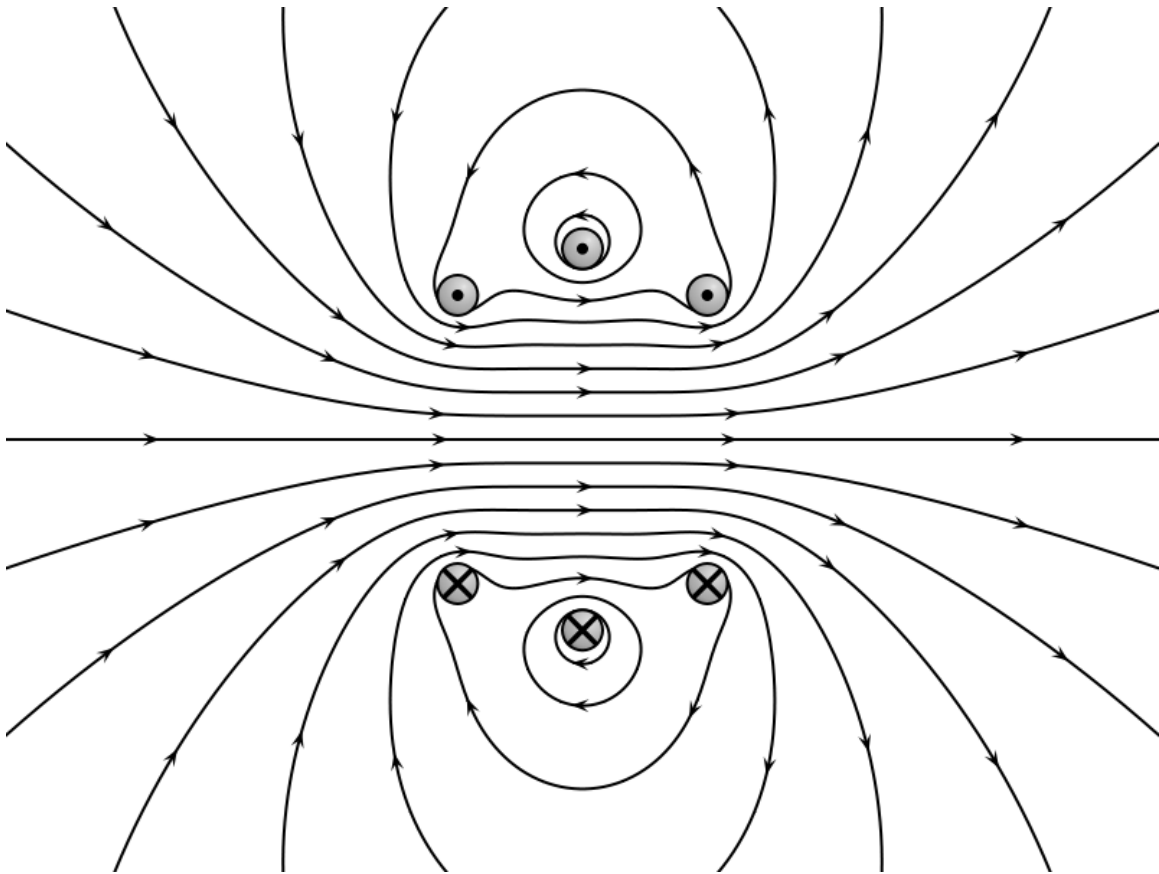
Polyphase motors and generators

Compared to single-phase motors and generators, polyphase motors are simpler, because they do not require external circuitry (using capacitors and inductors) to produce a starting torque. Polyphase machines can deliver constant power over each period of the alternating current, eliminating the pulsations found in a single-phase machine as the current passes through zero amplitude.

History

The use of polyphase coils in electrical power systems was pioneered by the engineers Nikola Tesla, Galileo Ferraris, and Michail Dolivo-Dobrovolsky.

Maxwell Coil



Magnetic field around a Maxwell coil

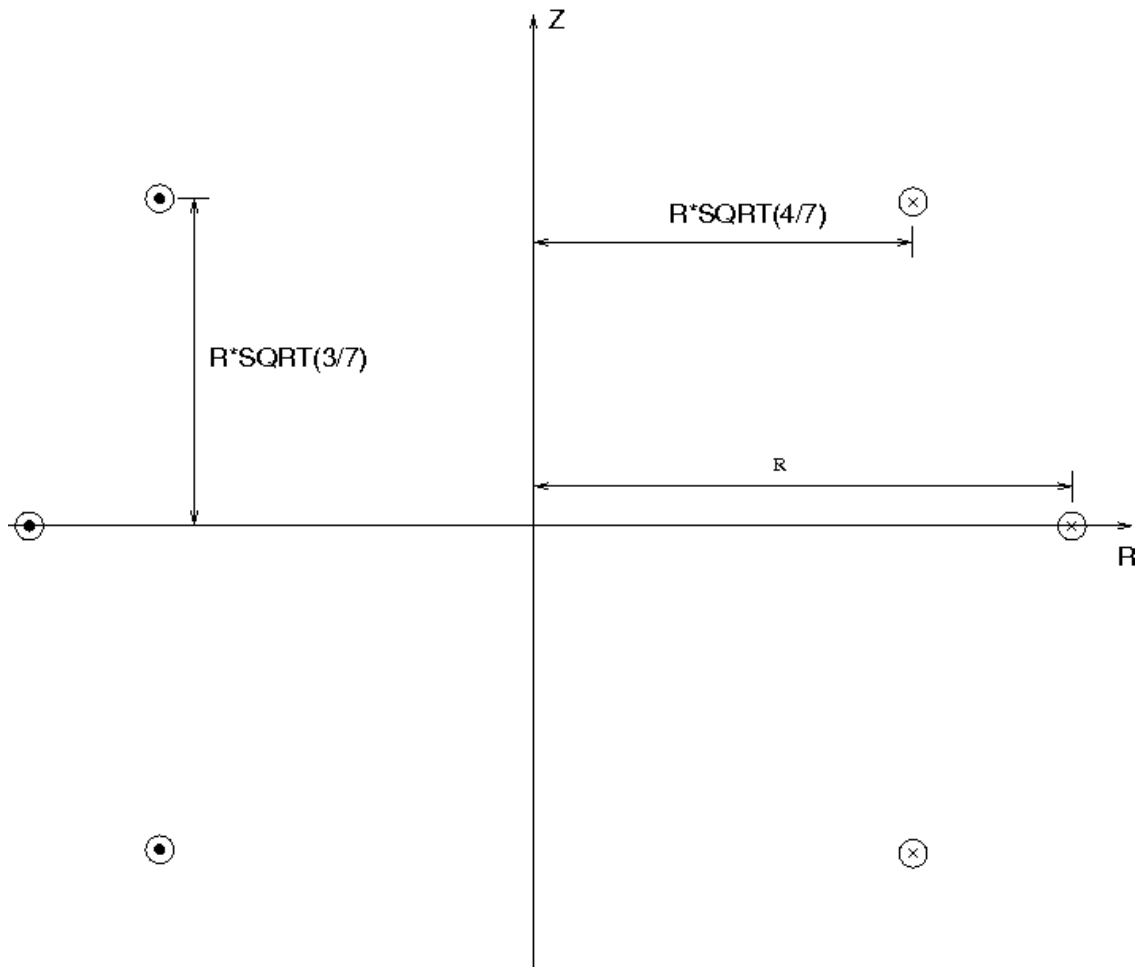
A **Maxwell coil** is a device for producing a large volume of almost constant (or constant-gradient) magnetic field.

Description

A constant-field Maxwell coil set consists of three coils oriented on the surface of a virtual sphere. According to Maxwell's original 1873 design each of the outer coils

should be of radius $\sqrt{\frac{4}{7}}R$ and distance $\sqrt{\frac{3}{7}}R$ from the plane of the central coil of radius $\frac{49}{64}R$.

The number of ampere-turns of each of the smaller coils should equal exactly $\frac{49}{64}$ of the middle coil. This arrangement removes variations in magnetic field, up to its 6th-order derivative with respect to position, near the centre of the virtual sphere.



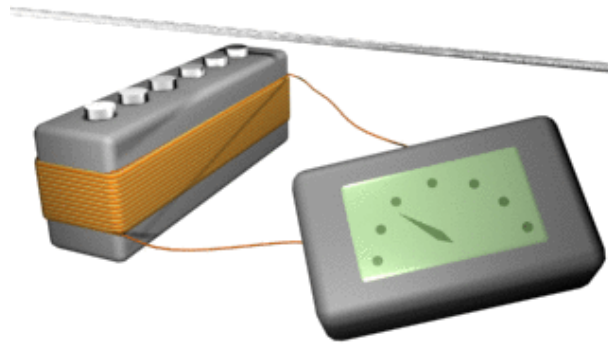
A gradient-field Maxwell coil is essentially the same geometry of the 3-coil configuration above, with the central coil removed to leave only the smaller two coils. If the current in one of the coils is reversed, a uniform-gradient magnetic field is produced near the centre of the two coils.

Chapter-7

Single Coil



This image shows three single coil pickups on a Stratocaster guitar. Left to right: bridge, middle and neck pickups.



String effect on a single coil (electric guitar). The coil is connected to a multimeter that indicates the voltage changes when the string moves. This signal is normally sent to the amplifier.

A **single coil pickup** is a type of magnetic transducer, or pickup, for the electric guitar and the electric bass. It electromagnetically converts the vibration of the strings to an electric signal. Single coil pickups are one of the two most popular designs, along with dual-coil or "humbucking" pickups.

Beauchamp was backed in his efforts by Adolph Rickenbacker, an engineer and wealthy owner of a successful tool and die business. Beauchamp eventually produced the first successful single coil pickup. The pickup consisted of two massive "U" shaped magnets and one coil and was known as the "horseshoe pickup". The two horseshoe-shaped magnets surrounded the strings that passed over a single core plate (or blade) in the center of the coil.

Beauchamp outfitted the pickup in a custom built lap slide guitar. The production model based on this prototype became the Hawaiian Electro lap steel guitar, nicknamed the "Frying Pan" for its round, flat body.

In 1931 Beauchamp founded the Ro-Pat-In Company with Rickenbacker and his associates. Ro-Pat-In eventually became The Electro String Instrument Corporation and subsequently the Rickenbacker International Corporation. The company introduced its first "Electro-String Instruments" to the public in 1932.

Gibson

The Gibson Guitar Corporation introduced the "bar pickup" in 1935 for its new line of Hawaiian lap steel guitars. The pickup's basic construction is that of a metal blade inserted through the coil as a shared pole piece for all the strings. A pair of large flat magnets were fastened below the coil assembly.

In 1936 Gibson introduced the ES-150, its first electric Spanish styled guitar. The ES-150 was outfitted with the bar pickup. Jazz guitar innovator, Charlie Christian, began playing an ES-150 in the late 1930s with the Benny Goodman Orchestra. This caused the popularity of the electrified guitar to soar. Due to Christian's close association with the ES-150 it began being referred to as the "Charlie Christian Model" and Gibson's now famous bar pickup as the "Charlie Christian pickup" or "CC unit".

Sound

The sound of a single coil pickup can range from the strong, fat midrange sound of the Gibson P-90 to the bright and clear Fender Telecaster single-coil tone.

Common designs

Gibson P-90

The P-90 is a single-coil pickup designed by the Gibson Guitar Corporation. These pickups have a large, flat coil with adjustable steel screws as pole pieces, and a pair of flat alnico bar magnets lying under the coil bobbin. The adjustable pole pieces pick up the magnetism from the magnets. Moving the screw closer or further away from the magnet determines signal strength, thus tone as well. There are two variations of P-90 pickup that differ mainly by mounting options:



Gibson P-90 soap bar

- **Soap bar** casing has true rectangular shape and the mounting screws are contained within the coil perimeter, positioned between the pole pieces, between strings 2-3 and 4-5, thus creating irregular and somewhat unusual pattern. Occasionally, they are mistaken for pole pieces; thus, the P-90 is sometimes erroneously said to have eight pole pieces. The "soap bar" nickname most probably comes from its predominantly rectangular shape and proportions resembling a bar of soap, and the fact that the first P-90s on the original Gibson Les Paul Model of 1952 were white.



P90 dog ear

- **Dog ear** is a casing type with extensions at both sides of pickup that somewhat resemble dog's ears. These are extensions of the predominantly rectangular cover that encompass the outlying mounting screws. Dog-ear P-90 pickups were commonly mounted on Gibson's hollowbody guitars like the ES-330 and occasionally on solid body models like the Les Paul Junior. The same pickups were also available on Epiphone models (since Gibson was building Epiphone guitars in the 1950s) and the design is best remembered for its appearance on the hollow body Epiphone Casino of the mid to late 1960s.

The sound of a P-90 is somewhat brighter and more transparent than Gibson's later humbucker pickup, and every bit as crisp and snappy as Fender's single-coil pickups despite its high output and big sound.

Despite its tonal qualities the P-90 fell out of favor with Gibson in the early 1950s as a consequence of guitar players complaining about the amount of hum (noise) it put out. Gibson employee Seth Lover solved the hum problem by designing a hum-canceling pickup known as a humbucker, it was supposed to sound like a P-90 but in fact has quite a different sound. It nevertheless became Gibson's mainstay pickup from that point on. The P-90 likely did not become as popular for that reason, although many guitarists still prefer the tone of the P-90.

The hum problem proved extremely difficult to solve and despite numerous attempts by Gibson with their P-100, and the larger aftermarket pickup manufacturers with their stacked and sidewinders noiseless designs, hum-canceling P-90 pickups lost most of their favored tonal characteristics and generally did not gain acceptance among guitar players.

Telecaster design



Two pickups on a Telecaster

The Fender Telecaster features two single coils. The neck pickup produces a mellower sound, while the bridge pickup produces an extremely twangy, sharp tone with exaggerated treble response, because the bridge pickup is mounted on a steel plate. These design elements allow musicians to emulate steel guitar sounds, making it particularly appropriate for country music.

Pickups are selected with a three-position switch, and two wiring schemes exist:

- **Vintage:** 1) neck pickup with treble cutoff for a bassier sound; 2) neck pickup only; 3) bridge pickup only.
- **Modern:** 1) neck pickup only, with no treble cutoff; 2) neck and bridge; 3) bridge pickup only.

The Fender Esquire has a variation to the Vintage wiring scheme by using the scheme on a single pickup. This gives a treble cutoff in the first position, normal in the middle position, and a tone control cutoff in the third position.

Stratocaster design



Stratocaster pickups, viewed along the neck profile. Note that the poles are of different heights.

The traditional Stratocaster design guitar features three single coils. The guitarist can control which pickup or combination of pickups are selected with a lever switch. The pickup positions are usually referred to as the bridge, middle and neck pickups based on their proximity to those parts of the instrument.

Pickup position, number of coil winds, type of magnet wire, magnets and other factors shape the sound. A given pickup in the neck position will give louder, mellower and warmer sound, while an identical pickup in the bridge position will have lower output and produce a brighter, sharper sound. The reason the neck pickup has the most output is that the string's vibration has a higher amplitude at the neck position, being near the middle of the string length. Some manufacturers overwind the bridge pickup for more output to compensate for this difference.

The magnet poles have different heights. This is called a **magnet stagger** and is done to compensate for the different outputs of the string for two reasons. The first reason is that the fretboard has a radius (also called *camber*) of between 7 and 12 inches usually. Naturally the strings will follow the radius of the fretboard and so must the top surface of

the magnets, generally speaking. The second reason is that some strings have naturally higher output, the plain or non-wound G-string being the most significant and this calls for the corresponding magnet to be further compensated, resulting in an apparent odd looking stagger. Fender Strat pickups generally follow the traditional design and have the G string's magnet pole piece as tall as the D-string's, but this causes the G-string of modern string sets to be excessively loud and dominate all the other strings. This comes about because Stratocaster pickups were designed in the 1950s when string sets came with a wound G-string, but modern rock and blues players found it difficult to stretch or bend wound G-strings across the fretboard because of their inherently higher tension. In the 1970s, string manufacturers responded and introduced the now standard non-wound G-string which has lower tension and can be stretched more easily, but which produces much higher output. In order for the G-string to have the same output the corresponding magnet pole should have the greatest gap between the string and the magnet pole piece, thus different strings have magnets with differently compensated heights.

The first Stratocasters had a three-way pickup selector switch, selecting either the neck, middle or bridge pickup. Innovative guitarists found they could get an interesting sound by carefully positioning the selector switch lever between detented positions, where any two adjacent pickups would be on simultaneously. Some players wedged a plectrum between the pickguard and the selector switch to lock it in these positions. Later on, Fender introduced the now standard five-way selector switch, which uses additional detents between the original three positions to allow the combinations of any two adjacent pickups.

Modern Stratocasters have five-position pickup selector switch. Positions 1, 3 and 5 activate only one pickup (bridge, middle or neck respectively), while positions 2 and 4 activate a combination of two pickups (bridge and middle, or middle and neck, respectively). Some pickup sets have a reverse wound and reverse polarity middle pickup that when in combination with the normal bridge or neck pickups will cancel electromagnetic interference (noise/hum) which single coil pickups suffer badly from. The sonic effect of positions 2 and 4 is sometimes referred to as a "quack" or "notch positions", and some guitar notation includes directions to use these pickup combinations. One example is "Sultans of Swing" by Dire Straits which is played in position 2 (bridge and middle).

Noise problems

Fender Stratocaster and Telecaster pickups, being of the single-coil type, output a type of noise known as mains hum or 50Hz / 60Hz hum. Mains hum has its origin in wiring of a building and electrical apparatus/appliances such as transformers, electric motors and lighting. Hum is undesirable because it pollutes the musical notes being played on the instrument with its own sound of fixed unchanging frequency or pitch (usually 50 or 60 hertz) which is discordant with the musical sounds. To address this undesirable situation various attempts to eliminate mains hum signal from Fender single-coil pickups were made dating back to the early 1970s. DiMarzio, Seymour Duncan and EMG manufactured what are commonly known as stacked single coils which canceled mains

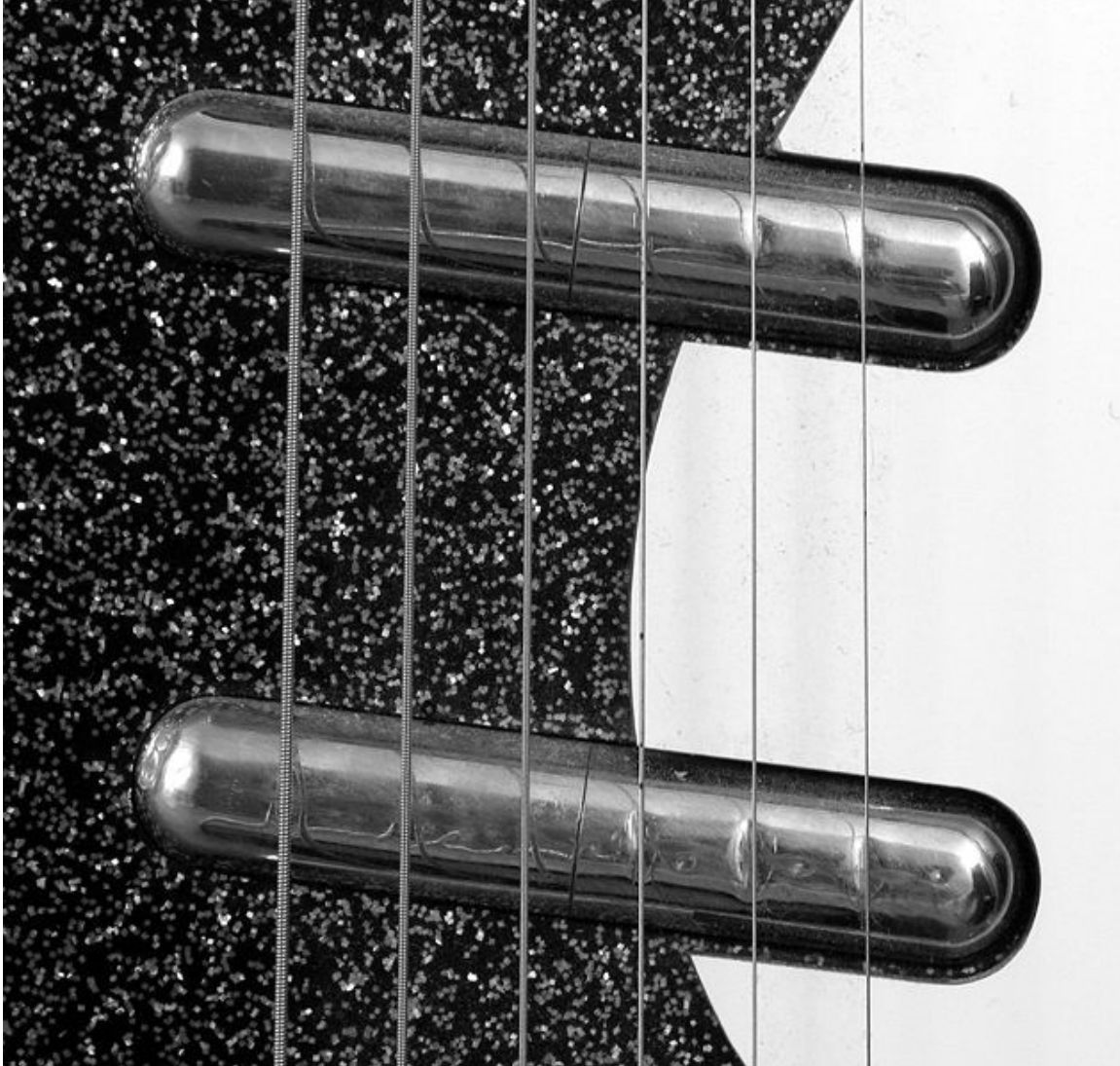
hum. Unfortunately these stacks also canceled string signal and had a detrimental effect on sound quality. EMG used active circuitry within the pickup to compensate for the losses caused by stacked coils by boosting and reshaping the damaged sound but this required an on-board battery with its attendant problems. The resultant sound was not authentic Fender trade mark sound but EMG pickups became popular for their own sound.

Actodyne General manufactured a low-noise design of single-coil pickup known as Lace Sensors, Don Lace being the inventor. The Lace Sensor pickup had a rubberized particle magnet and used ferrous shielding to reduce hum. Being the best at the time, Fender installed Lace Sensors on the Strat Plus model for many years as a solution to the mains hum problem. However the Lace Sensor was a stopgap solution because the sound was not authentic Fender trademark sound. Fender purists wanted the genuine sound of the original Fender pickups with Alnico rod magnets and Fender eventually discontinued Lace Sensors as their mainstay solution to mains hum circa 1998. Lace Sensors continue to be used by many guitar players regardless.

The search for an acceptable solution to mains hum gained new impetus around 1995 as guitar players became increasingly intolerant of degraded stacked single-coil sound. Fender was researching new techniques to solve the loss of tone around that time and eventually came out with their Vintage Noiseless design circa 1998.

Notable single-coil pickups

There are several well-known single-coil pickups that have a distinctive sound:



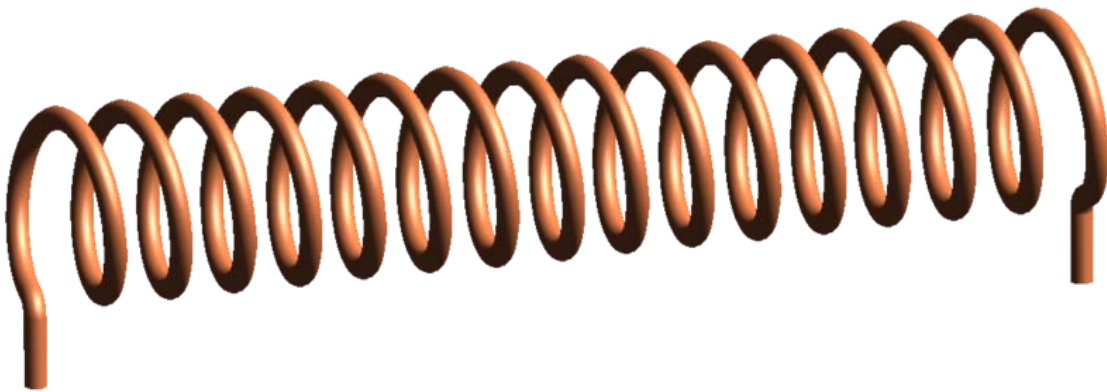
"Lipstick"-style single coil pickups on a Danelectro guitar

- Rickenbacker pickups (including the original 1930s "horseshoe" pickup as used in lap steel and solidbody upright basses, and later 6 string electric guitars, pedal steels, and electric bass guitars; also the "Toaster" and "Hi-Gain")
- Gibson bar pickup (1935) — later called the Charlie Christian pickup (1938)
- Gibson P-90 (1946)
- Fender Telecaster, Stratocaster, Jazzmaster, Jaguar, and other pickups
- Danelectro Lipstick
- Gretsch pickups (including the "HiLoTron")

- DeArmond pickups (found on various 50s and 60s guitars by various manufacturers including Gretsch, Guild, Epiphone, Martin, Kustom, Harmony, Regal, Premier, and others, but produced by the Rowe - DeArmond company of Toledo, Ohio; the trade name is now owned by Fender; single coil models including the 200 aka Dynasonic, 2K, and 2000, "mustache", various "gold foil" types, and many clip on, rail, or screw mount pickups designed for acoustic guitars and other instruments). The Fender "Tele-Sonic" featured large DeArmond single coils.
- Valco single coil pickups by Ralph Keller (1954) can be found in Airline, Supro, National, English Electronics, and a few Gretsch models of guitar from the 50's, 60's, and 70's. The majority of these pickups maintain the physical appearance of a larger, humbucking pickup. Early variations on the over-strings horseshoe pickup can be found on a number of similarly branded lapsteel guitars.
- Epiphone "New York" pickups
- Lace Sensor pickups (1987)

Chapter-8

Solenoid



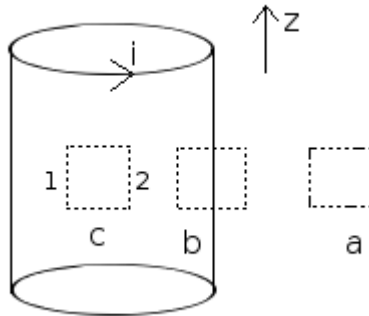
Solenoid

A **solenoid** is a coil wound into a tightly packed helix. In physics, the term **solenoid** refers to a long, thin loop of wire, often wrapped around a metallic core, which produces a magnetic field when an electric current is passed through it. Solenoids are important because they can create controlled magnetic fields and can be used as electromagnets. The term *solenoid* refers specifically to a magnet designed to produce a uniform magnetic field in a volume of space (where some experiment might be carried out).

In engineering, the term **solenoid** may also refer to a variety of transducer devices that convert energy into linear motion. The term is also often used to refer to a solenoid valve, which is an integrated device containing an electromechanical solenoid which actuates either a pneumatic or hydraulic valve, or a solenoid switch, which is a specific type of relay that internally uses an electromechanical solenoid to operate an electrical switch; for example, an automobile starter solenoid, or a linear solenoid, which is an electromechanical solenoid.

Magnetic field of a solenoid

Inside



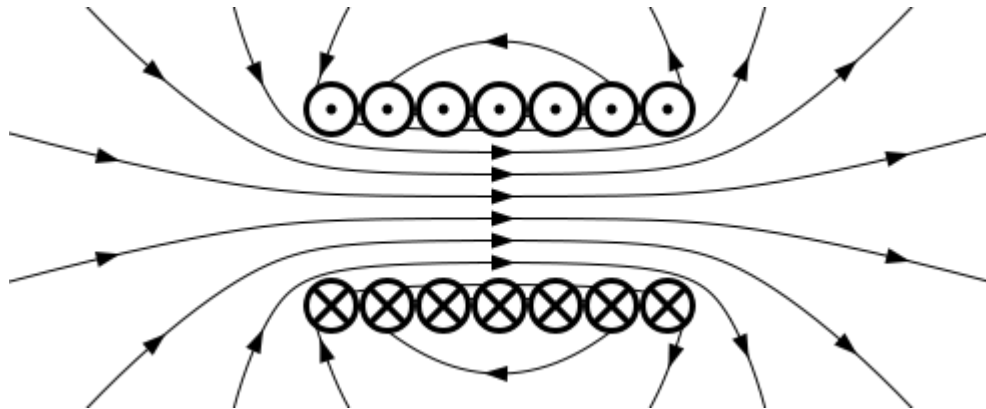
A solenoid with 3 Ampèrian loops: *a*, *b* and *c*.

In short: the magnetic field inside an infinitely long solenoid is homogeneous and its strength does not depend on the distance from the axis.

This is a derivation of the magnetic flux density around a solenoid that is long enough so that fringe effects can be ignored. In the diagram to the right, we immediately know that the flux density vector points in the positive z direction inside the solenoid, and in the negative z direction outside the solenoid. We see this by applying the right hand grip rule for the field around a wire. If we wrap our right hand around a wire with the thumb pointing in the direction of the current, the curl of the fingers shows how the field behaves. Since we are dealing with a long solenoid, all of the components of the magnetic field not pointing upwards cancel out by symmetry. Outside, a similar cancellation occurs, and the field is only pointing downwards.

Now consider the imaginary loop *c* that is located inside the solenoid. By Ampère's law, we know that the line integral of \mathbf{B} (the magnetic flux density vector) around this loop is zero, since it encloses no electrical currents (it can be also assumed that the circuital electric field passing through the loop is constant under such conditions: a constant or constantly changing current through the solenoid). We have shown above that the field is pointing upwards inside the solenoid, so the horizontal portions of loop *c* doesn't contribute anything to the integral. Thus the integral of the up side 1 is equal to the integral of the down side 2. Since we can arbitrarily change the dimensions of the loop and get the same result, the only physical explanation is that the integrands are actually equal, that is, the magnetic field inside the solenoid is radially uniform. Note, though, that nothing prohibits it from varying longitudinally, which in fact it does.

Outside



Magnetic field created by a solenoid (cross-sectional view) described using field lines.

A similar argument can be applied to the loop *a* to conclude that the field outside the solenoid is radially uniform or constant. This last result, which holds strictly true only near the centre of the solenoid where the field lines are parallel to its length, is important inasmuch as it shows that the flux density outside is practically zero since the radii of the field outside the solenoid will tend to infinity.

An intuitive argument can also be used to show that the flux density outside the solenoid is actually zero. Magnetic field lines only exist as loops, they cannot diverge from or converge to a point like electric field lines can. The magnetic field lines follow the longitudinal path of the solenoid inside, so they must go in the opposite direction outside of the solenoid so that the lines can form a loop. However, the volume outside the solenoid is much greater than the volume inside, so the density of magnetic field lines outside is greatly reduced. Now recall that the field outside is constant. In order for the total number of field lines to be conserved, the field outside must go to zero as the solenoid gets longer.

Quantitative description

Now we can consider the imaginary loop *b*. Take the line integral of \mathbf{B} around the loop, with the length of the loop *l*. The horizontal components vanish, and the field outside is practically zero, so Ampère's Law gives us:

$$Bl = \mu_0 Ni$$

where μ_0 is the magnetic constant, *N* the number of turns, *i* the current. From this we get:

$$B = \mu_0 \frac{Ni}{l}.$$

This equation is for a solenoid with no core. The inclusion of a ferromagnetic core, such as iron, increases the magnitude of the magnetic flux density in the solenoid. This is expressed by the formula

$$B = \mu_0 \mu_r \frac{Ni}{l} = \mu \frac{Ni}{l}$$

where μ_r is the relative permeability and μ ($\mu_0 \mu_r$) the permeability of the material that the core is made of.

Inductance of a solenoid

As shown above, the magnetic flux density B within the coil is practically constant and is given by

$$B = \mu_0 \frac{Ni}{l}$$

where μ_0 is the magnetic constant, N the number of turns, i the current and l the length of the coil. Ignoring end effects, the total magnetic flux through the coil is obtained by multiplying the flux density B by the cross-section area A :

$$\Phi = \mu_0 \frac{NiA}{l},$$

When this is combined with the definition of inductance,

$$L = \frac{N\Phi}{i}$$

it follows that the inductance of a solenoid is given by:

$$L = \mu_0 \frac{N^2 A}{l}.$$

A table of inductance for short solenoids of various diameter to length ratios has been calculated by Dellinger, Whitmore, and Ould.

This, and the inductance of more complicated shapes, can be derived from Maxwell's equations. For rigid air-core coils, inductance is a function of coil geometry and number of turns, and is independent of current.

Similar analysis applies to a solenoid with a magnetic core, but only if the length of the coil is much greater than the product of the relative permeability of the magnetic core and the diameter. That limits the simple analysis to low-permeability cores, or extremely long

thin solenoids. The presence of a core can be taken into account in the above equations by replacing the magnetic constant μ_0 with μ or $\mu_0\mu_r$, where μ represents permeability and μ_r relative permeability. Note that since the permeability of ferromagnetic materials changes with applied magnetic flux, the inductance of a coil with a ferromagnetic core will generally vary with current.

Applications

Electromechanical solenoids

28. The Commercial Solenoid.—The solenoid is used in practice for tripping circuit breakers (Par. 237), for operating contactors in automatic motor starters (Par. 219), for operating voltage regulating devices (Par. 207), for arc lamp feeds (Chap. XIII, Vol. II), for operating valves, and for numerous other purposes. In practically all instances a soft iron (or steel) plunger

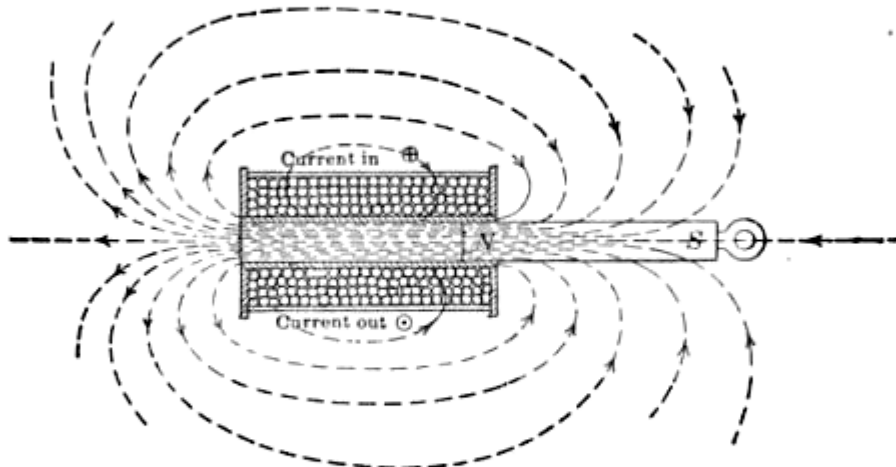


FIG. 30.—Simple solenoid and plunger.

er or armature is necessary to obtain the tractive pull required of the solenoid. The operation of a solenoid and plunger is indicated in Fig. 30. The flux due to the solenoid produces magnetic poles on the plunger. The pole nearer the plunger will be of such sign that it will be urged along the lines of force, (see Par. 11) and in such a direction as to be drawn within the solenoid.

A 1920 explanation of a commercial solenoid used as an electromechanical actuator

Electromechanical solenoids consist of an electromagnetically inductive coil, wound around a movable steel or iron slug (termed the armature). The coil is shaped such that the armature can be moved in and out of the center, altering the coil's inductance and thereby becoming an electromagnet. The armature is used to provide a mechanical force to some mechanism (such as controlling a pneumatic valve). Although typically weak over anything but very short distances, solenoids may be controlled directly by a controller circuit, and thus have very low reaction times.

The force applied to the armature is proportional to the change in inductance of the coil with respect to the change in position of the armature, and the current flowing through the coil. The force applied to the armature will always move the armature in a direction that increases the coil's inductance.

Electromechanical solenoids are commonly seen in electronic paintball markers, pinball machines, dot matrix printers and fuel injectors.

Rotary solenoid

The rotary solenoid is an electromechanical device used to rotate a ratcheting mechanism when power is applied. These were used in the 1950s for rotary snap-switch automation in electromechanical controls. Repeated actuation of the rotary solenoid advances the snap-switch forward one position. Two rotary actuators on opposite ends of the rotary snap-switch shaft, can advance or reverse the switch position.

The rotary solenoid has a similar appearance to a linear solenoid, except that the core is mounted in the center of a large flat disk, with two or three inclined grooves cut into the underside of the disk. These grooves align with slots on the solenoid body, with ball bearings in the grooves.

When the solenoid is activated, the core is drawn into the coil, and the disk rotates on the ball bearings in the grooves as it moves towards the coil body. When power is removed, a spring on the disk rotates it back to its starting position, also pulling the core out of the coil.

The rotary solenoid was invented in 1944 by George H. Leland, of Dayton, Ohio, to provide a more reliable and shock/vibration tolerant release mechanism for air-dropped bombs. Previously used linear (axial) solenoids were prone to inadvertent releases. U.S. Patent number 2,496,880 describes the electromagnet and inclined raceways that are the basis of the invention. Leland's engineer, Earl W. Kerman, was instrumental in developing a compatible bomb release shackle that incorporated the rotary solenoid. Bomb shackles of this type are found in a B-29 aircraft fuselage on display at the National Museum of the USAF in Dayton, Ohio.

Rotary voice coil

This is a rotational version of a solenoid. Typically the fixed magnet is on the outside, and the coil part moves in an arc controlled by the current flow through the coils. Rotary voice coils are widely employed in devices such as disk drives.

Pneumatic solenoid valves

A pneumatic solenoid valve is a switch for routing air to any pneumatic device, usually an actuator, allowing a relatively small signal to control a large device. It is also the interface between electronic controllers and pneumatic systems.

Hydraulic solenoid valves

Hydraulic solenoid valves are in general similar to pneumatic solenoid valves except that they control the flow of hydraulic fluid (oil), often at around 3000 psi (210 bar, 21 MPa, 21 MN/m²). Hydraulic machinery uses solenoids to control the flow of oil to rams or actuators to (for instance) bend sheets of titanium in aerospace manufacturing. Solenoid-controlled valves are often used in irrigation systems, where a relatively weak solenoid opens and closes a small pilot valve, which in turn activates the main valve by applying fluid pressure to a piston or diaphragm that is mechanically coupled to the main valve. Solenoids are also in everyday household items such as washing machines to control the flow and amount of water into the drum.

Transmission solenoids control fluid flow through an automatic transmission and are typically installed in the transmission valve body.

Automobile starter solenoid

In a car or truck, the starter solenoid is part of an automobile starting system. The starter solenoid receives a large electric current from the car battery and a small electric current from the ignition switch. When the ignition switch is turned on (i.e. when the key is turned to start the car), the small electric current forces the starter solenoid to close a pair of heavy contacts, thus relaying the large electric current to the starter motor.

Starter solenoids can also be built into the starter itself, often visible on the outside of the starter. If a starter solenoid receives insufficient power from the battery, it will fail to start the motor, and may produce a rapid 'clicking' or 'clacking' sound. This can be caused by a low or dead battery, by corroded or loose connections in the cable, or by a broken or damaged positive (red) cable from the battery. Any of these will result in some power to the solenoid, but not enough to hold the heavy contacts closed, so the starter motor itself never spins, and the engine does not start.

Chapter-9

Transformer



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

A **transformer** is a static device that transfers electrical energy from one circuit to another through inductively coupled conductors—the transformer's coils. A varying current in the first or *primary* winding creates a varying magnetic flux in the

transformer's core and thus a varying magnetic field through the *secondary* winding. This varying magnetic field induces a varying electromotive force (EMF) or "voltage" in the secondary winding. This effect is called mutual induction.

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

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

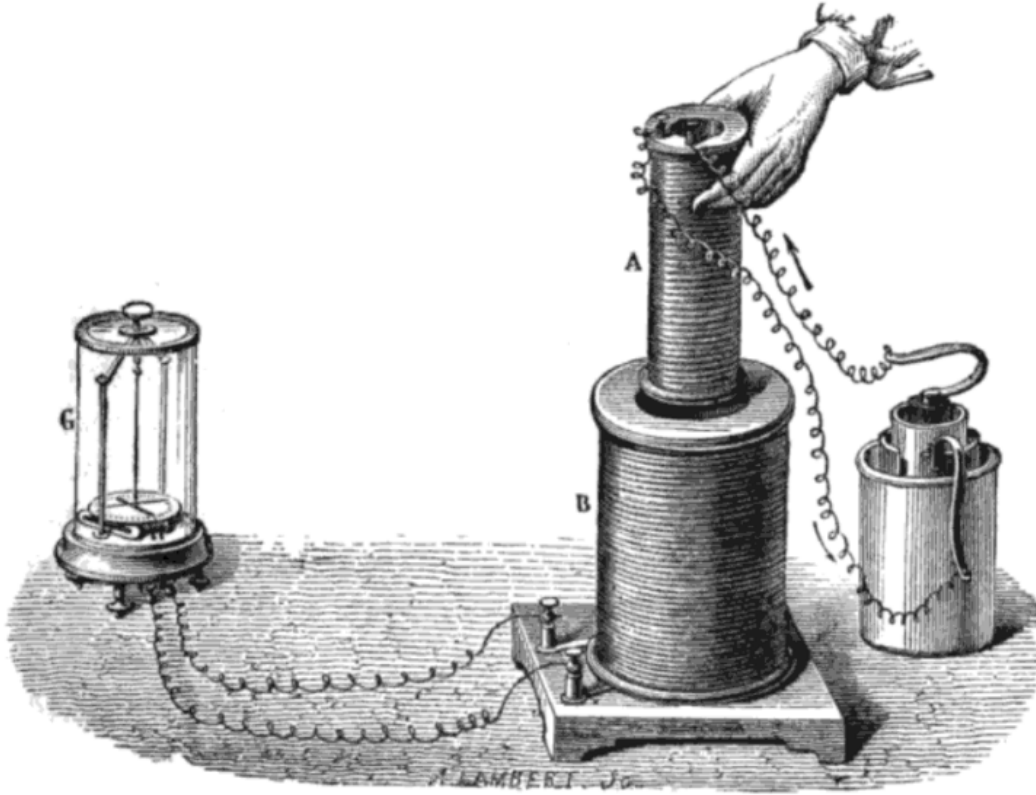
By appropriate selection of the ratio of turns, a transformer thus allows an alternating current (AC) voltage to be "stepped up" by making N_s greater than N_p , or "stepped down" by making N_s less than N_p .

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

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

History

Discovery



Faraday's experiment with induction between coils of wire

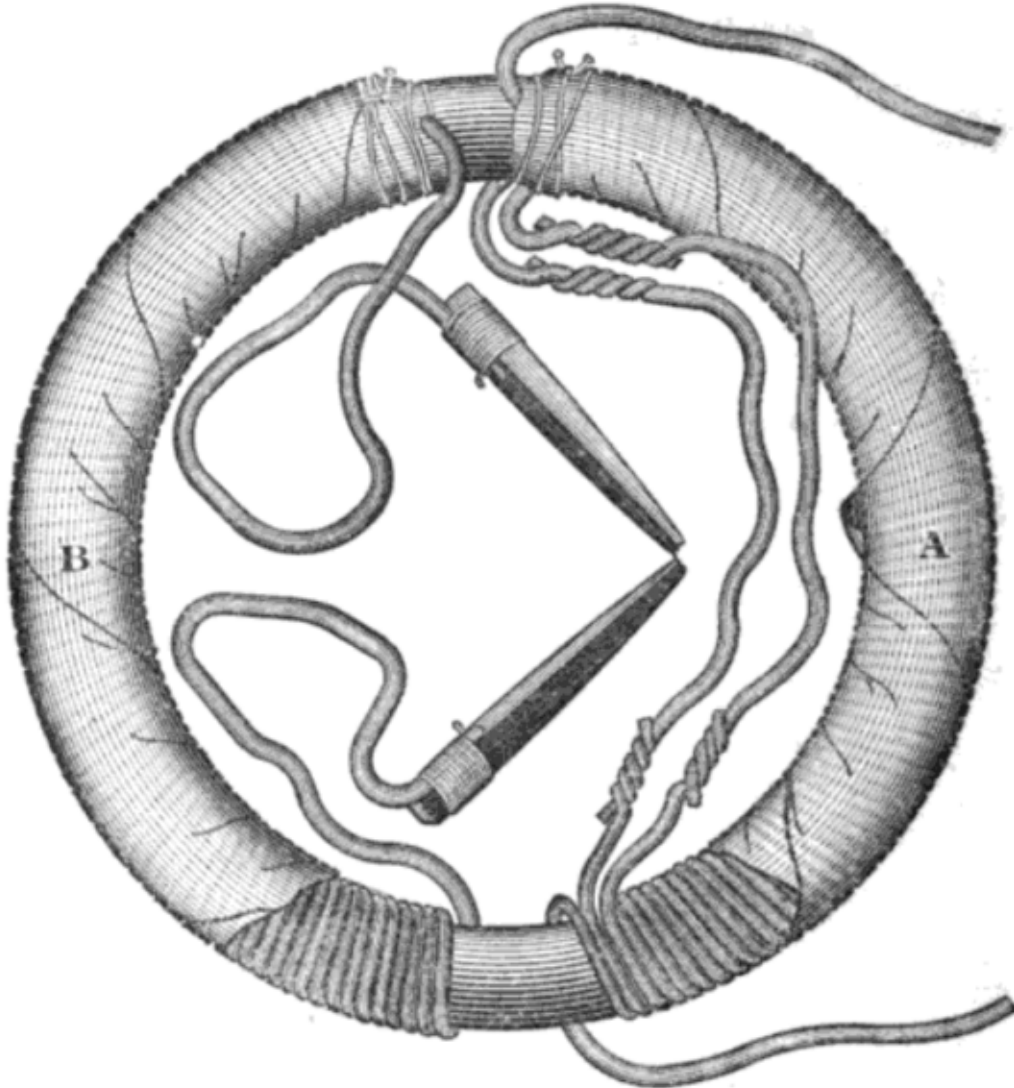
The phenomenon of electromagnetic induction was discovered independently by Michael Faraday and Joseph Henry in 1831. However, Faraday was the first to publish the results of his experiments and thus receive credit for the discovery. The relationship between electromotive force (EMF) or "voltage" and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

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

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

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

Induction coils



Faraday's ring transformer

The first type of transformer to see wide use was the induction coil, invented by Rev. Nicholas Callan of Maynooth College, Ireland in 1836. He was one of the first researchers to realize that the more turns the secondary winding has in relation to the primary winding, the larger is the increase in EMF. Induction coils evolved from scientists' and inventors' efforts to get higher voltages from batteries. Since batteries produce direct current (DC) rather than alternating current (AC), induction coils relied

upon vibrating electrical contacts that regularly interrupted the current in the primary to create the flux changes necessary for induction. Between the 1830s and the 1870s, efforts to build better induction coils, mostly by trial and error, slowly revealed the basic principles of transformers.

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

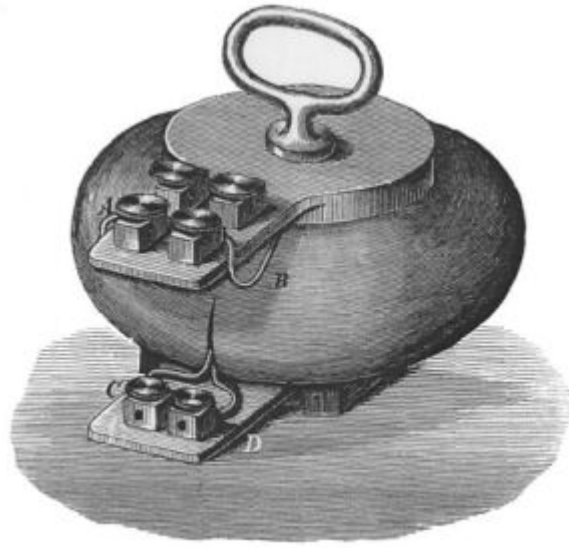
In 1878, the Ganz Company in Hungary began manufacturing equipment for electric lighting and, by 1883, had installed over fifty systems in Austria-Hungary. Their systems used alternating current exclusively and included those comprising both arc and incandescent lamps, along with generators and other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

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

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

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

Closed-core transformers and the introduction of parallel connection

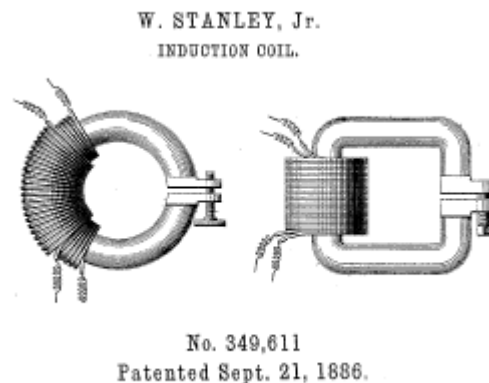


Drawing of Ganz Company's 1885 prototype. Capacity: 1400 VA, frequency: 40 Hz, voltage ratio: 120/72 V



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

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



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

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

straight iron plates laid in to create a closed magnetic circuit. Westinghouse applied for a patent for the new design in December 1886; it was granted in July 1887.

Other early transformers

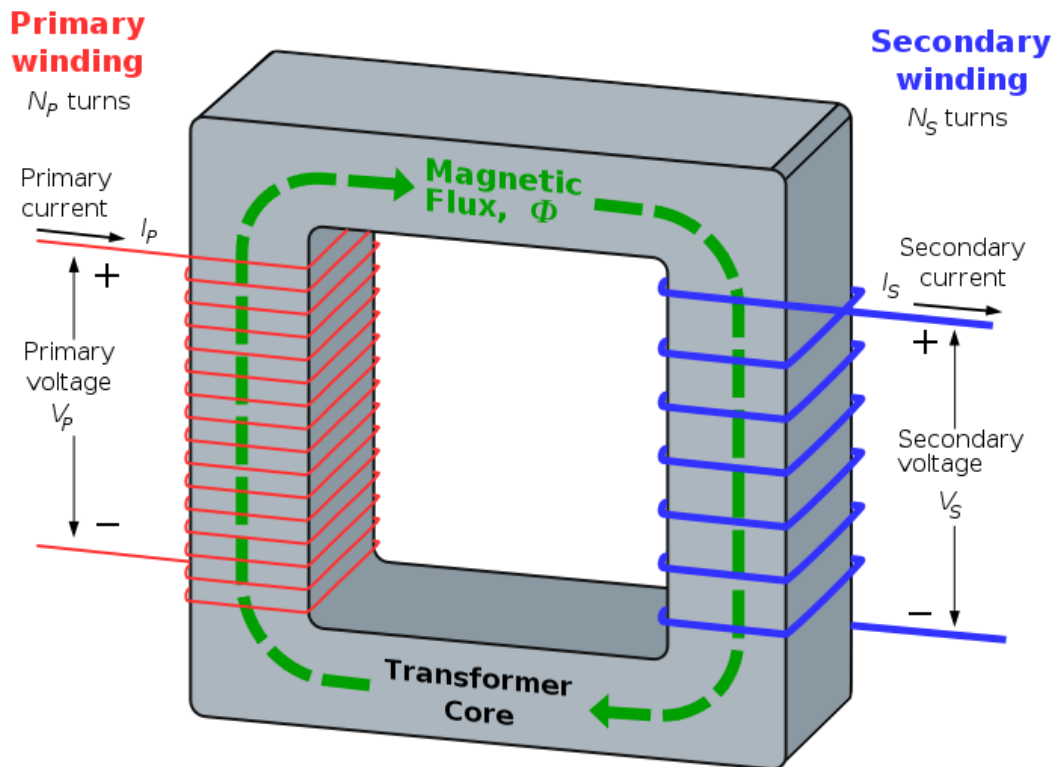
In 1889, Russian-born engineer Mikhail Dolivo-Dobrovolsky developed the first three-phase transformer at the Allgemeine Elektrizitäts-Gesellschaft ("General Electricity Company") in Germany.

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

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

Basic principles

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



An ideal transformer

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

Induction law

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

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

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

both the primary and secondary coils in an ideal transformer, the instantaneous voltage across the primary winding equals

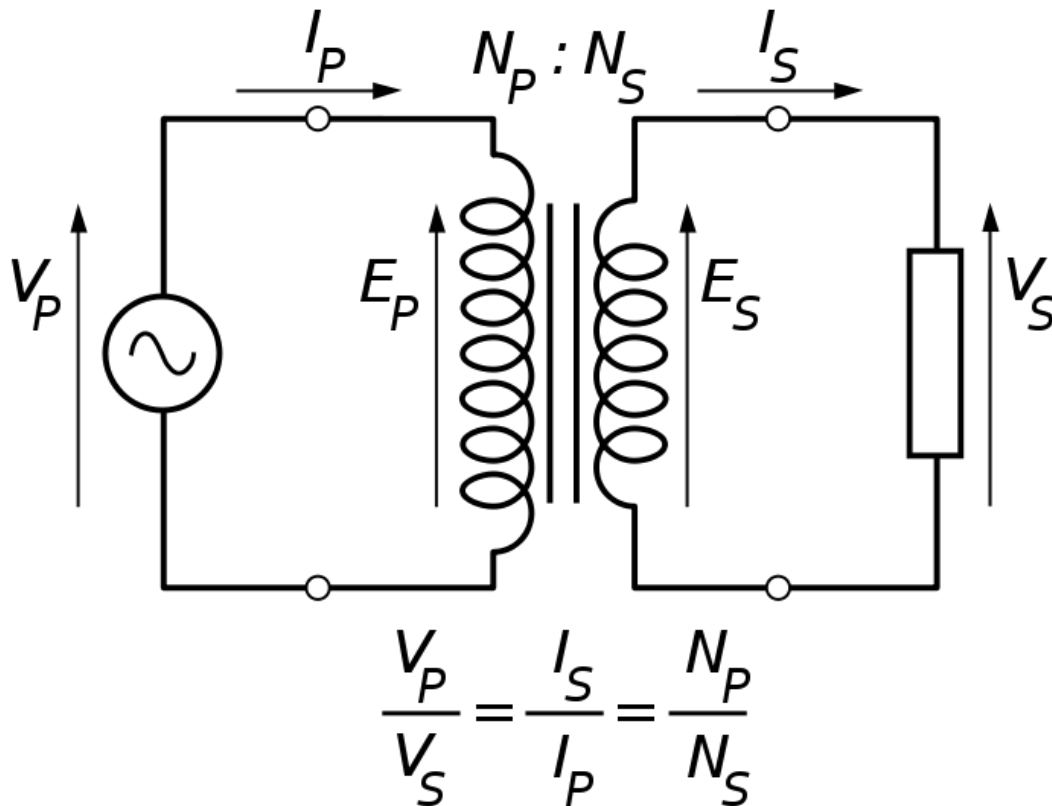
$$V_P = N_P \frac{d\Phi}{dt}.$$

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

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

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

Ideal power equation



The ideal transformer as a circuit element

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

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

giving the ideal transformer equation

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

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

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

Detailed operation

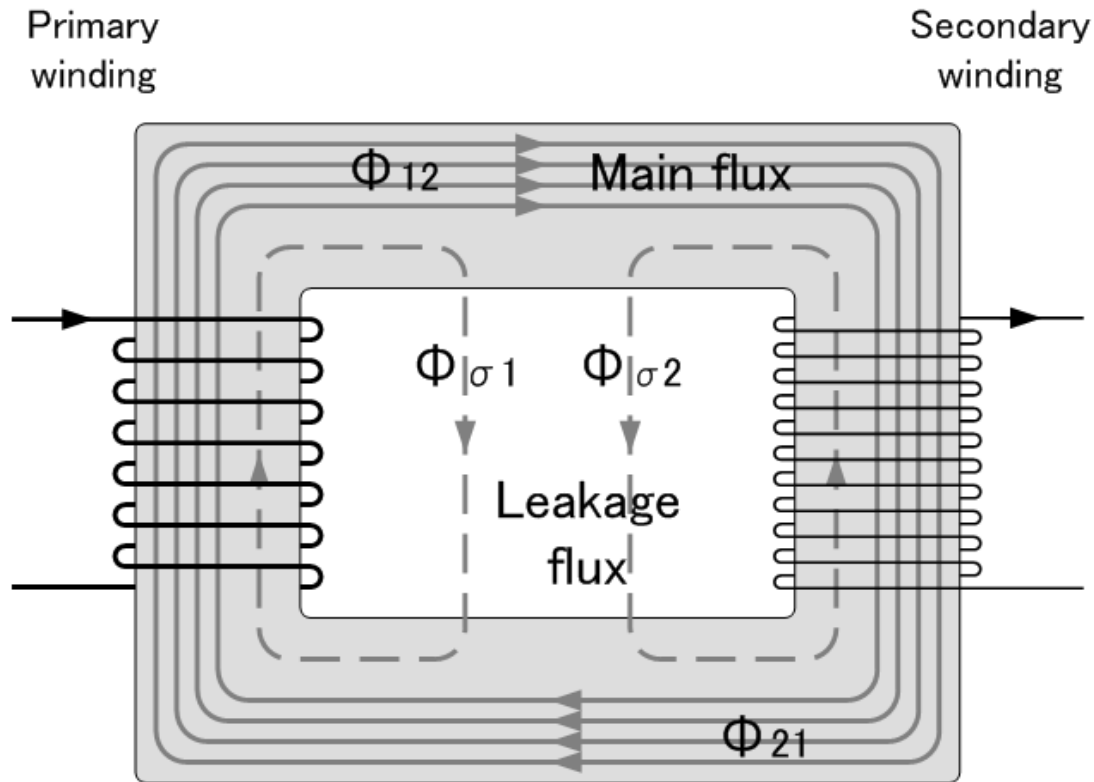
The simplified description above neglects several practical factors, in particular the primary current required to establish a magnetic field in the core, and the contribution to the field due to current in the secondary circuit.

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

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

Practical considerations

Leakage flux



Leakage flux of a transformer

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

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

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

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

Effect of frequency

Transformer universal EMF equation

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

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

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

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

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

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

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

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

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

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

Energy losses

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

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

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

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

Winding resistance

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

Hysteresis losses

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

Eddy currents

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

Magnetostriction

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

Mechanical losses

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

Stray losses

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

Dot convention

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

Equivalent circuit

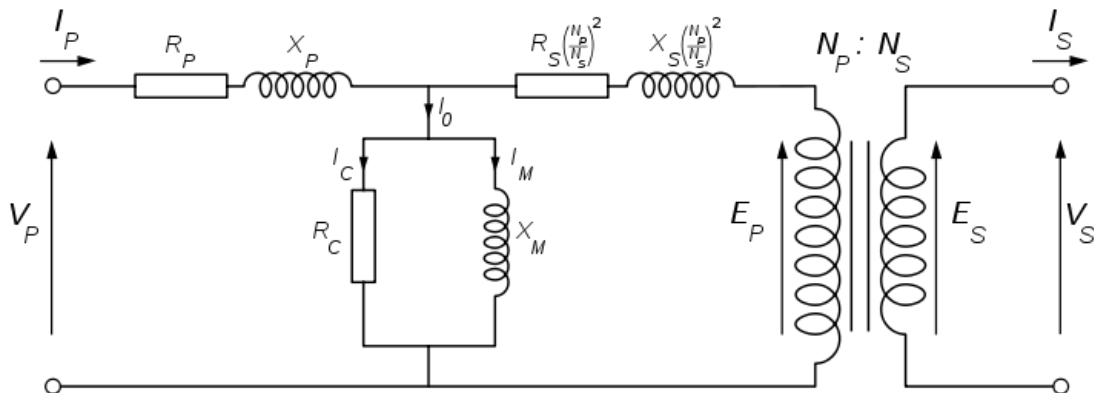
The physical limitations of the practical transformer may be brought together as an equivalent circuit model (shown below) built around an ideal lossless transformer. Power loss in the windings is current-dependent and is represented as in-series resistances R_p and R_s . Flux leakage results in a fraction of the applied voltage dropped without

contributing to the mutual coupling, and thus can be modeled as reactances of each leakage inductance X_p and X_s in series with the perfectly coupled region.

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

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

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



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

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

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

Types

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

Autotransformer



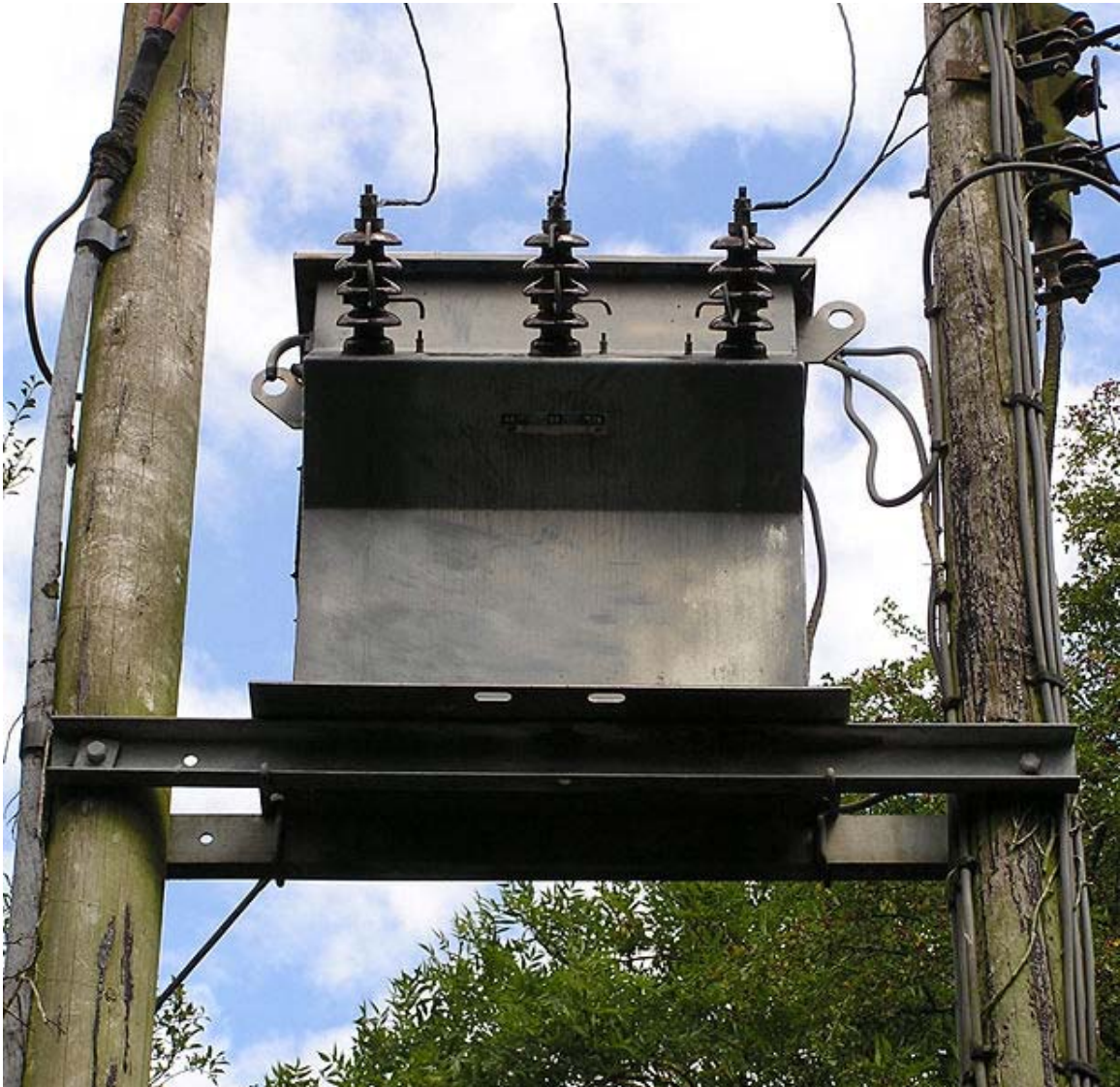
A variable autotransformer

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

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

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

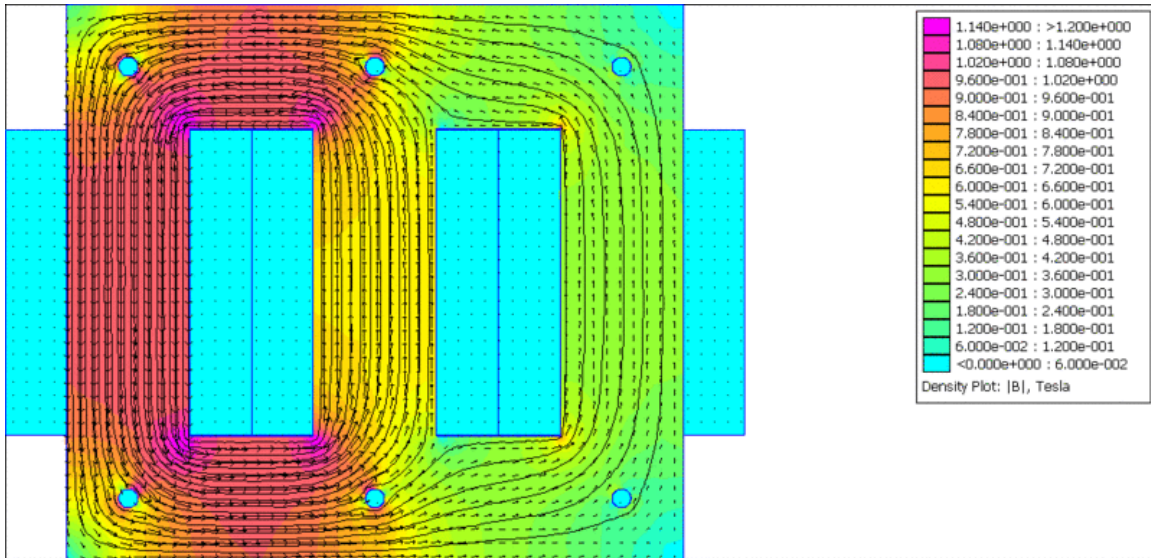
Polyphase transformers



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

For three-phase supplies, a bank of three individual single-phase transformers can be used, or all three phases can be incorporated as a single three-phase transformer. In this

case, the magnetic circuits are connected together, the core thus containing a three-phase flow of flux. A number of winding configurations are possible, giving rise to different attributes and phase shifts. One particular polyphase configuration is the zigzag transformer, used for grounding and in the suppression of harmonic currents.



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

Leakage transformers



Leakage transformer

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

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

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

Resonant transformers

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

Audio transformers

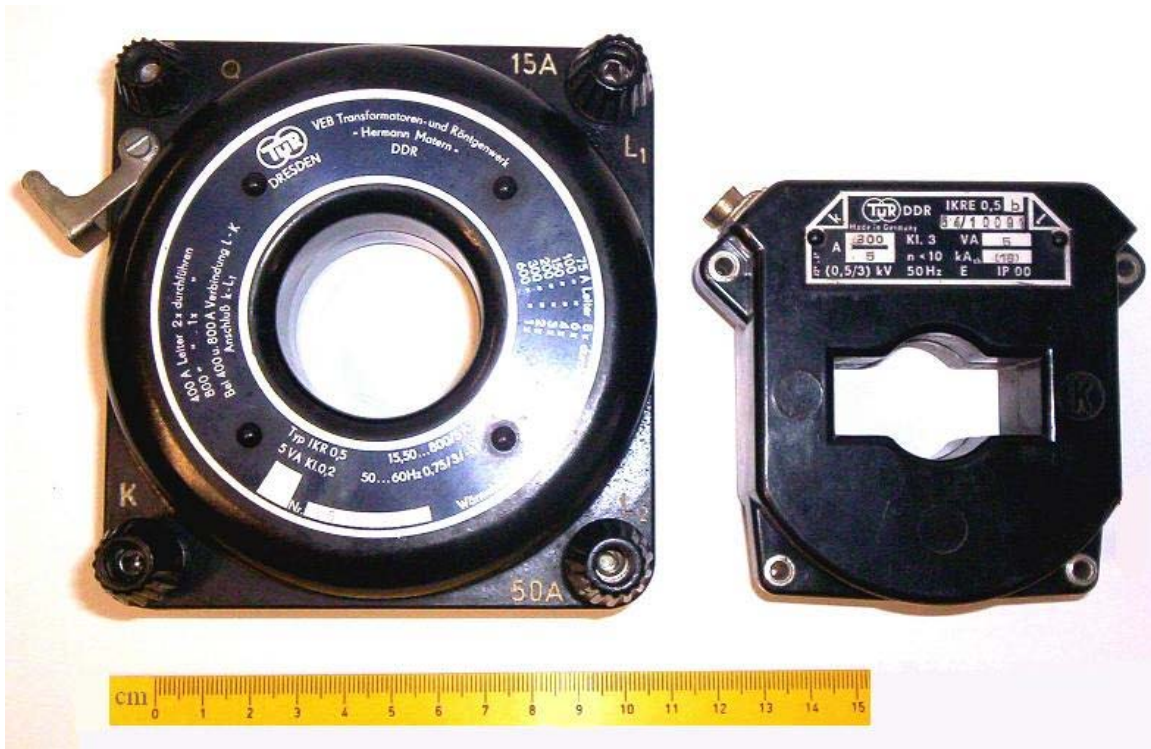
Audio transformers are those specifically designed for use in audio circuits. They can be used to block radio frequency interference or the DC component of an audio signal, to split or combine audio signals, or to provide impedance matching between high and low impedance circuits, such as between a high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

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

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

Instrument transformers

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



Current transformers, designed for placing around conductors

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

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

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

Classification

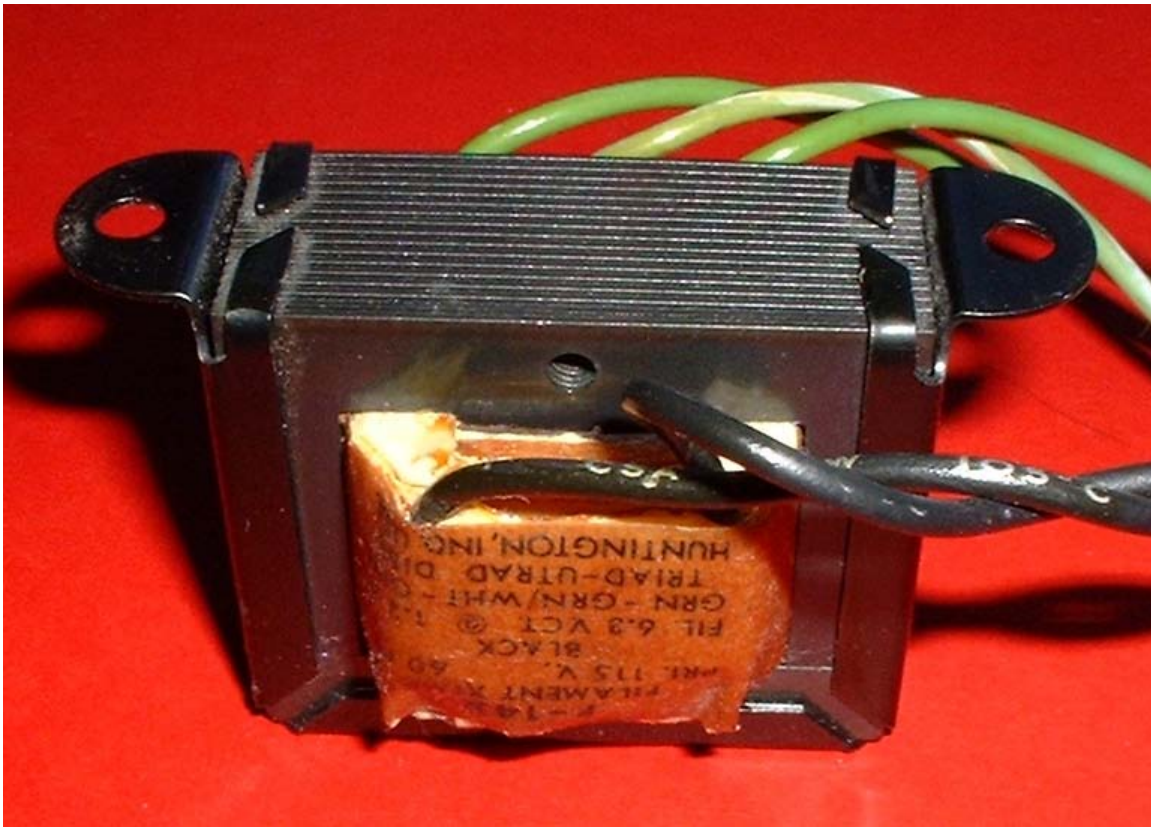
Transformers can be classified in many different ways; an incomplete list is:

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

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

Construction

Cores



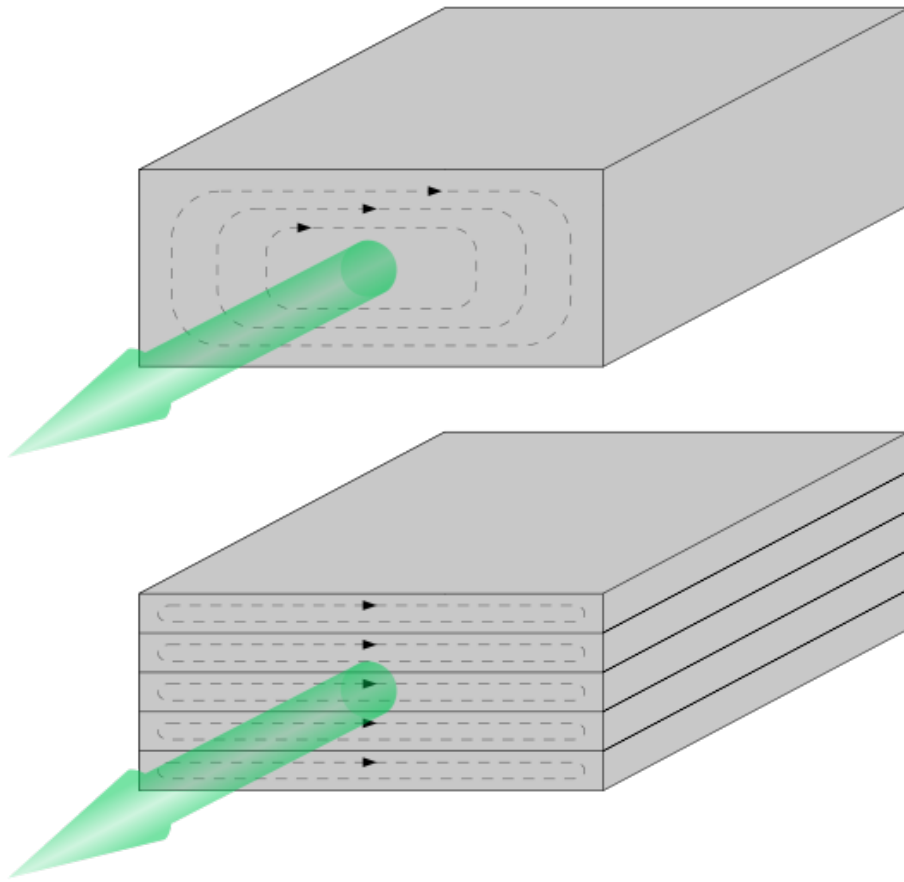
Laminated core transformer showing edge of laminations at top of photo

Laminated steel cores

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

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

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



Laminating the core greatly reduces eddy-current losses

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

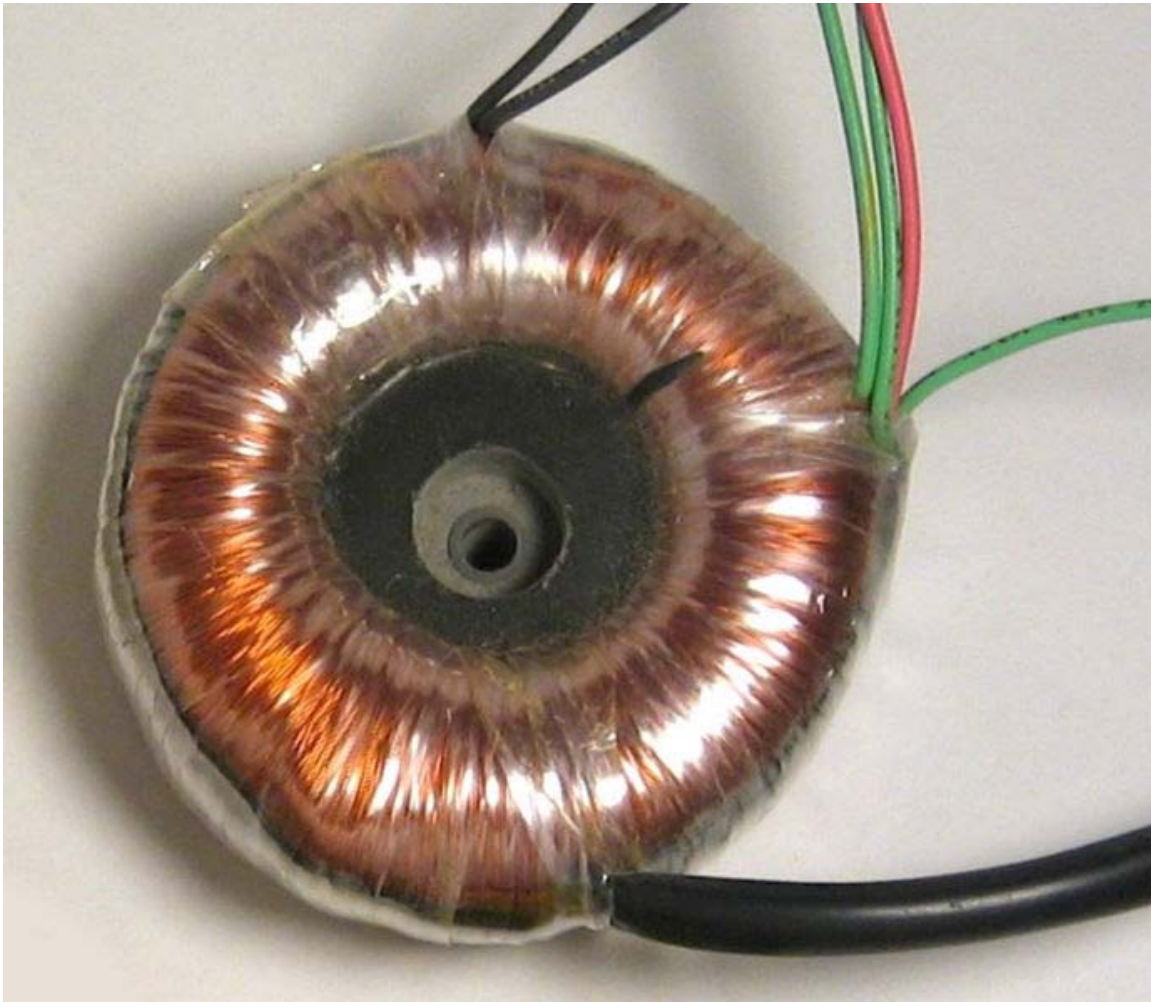
A steel core's remanence means that it retains a static magnetic field when power is removed. When power is then reapplied, the residual field will cause a high inrush current until the effect of the remaining magnetism is reduced, usually after a few cycles of the applied alternating current. Overcurrent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

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

Solid cores

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

Toroidal cores



Small toroidal core transformer

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

Toroidal transformers are more efficient than the cheaper laminated E-I types for a similar power level. Other advantages compared to E-I types, include smaller size (about half), lower weight (about half), less mechanical hum (making them superior in audio

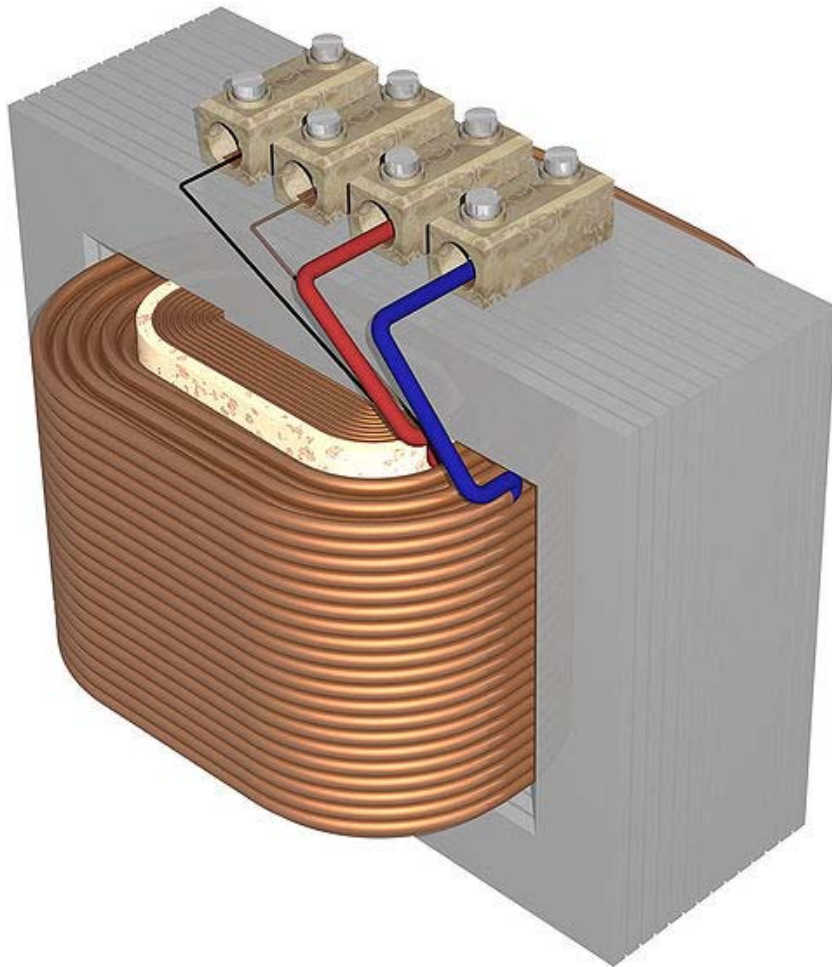
amplifiers), lower exterior magnetic field (about one tenth), low off-load losses (making them more efficient in standby circuits), single-bolt mounting, and greater choice of shapes. The main disadvantages are higher cost and limited power capacity. Because of the lack of a residual gap in the magnetic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

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

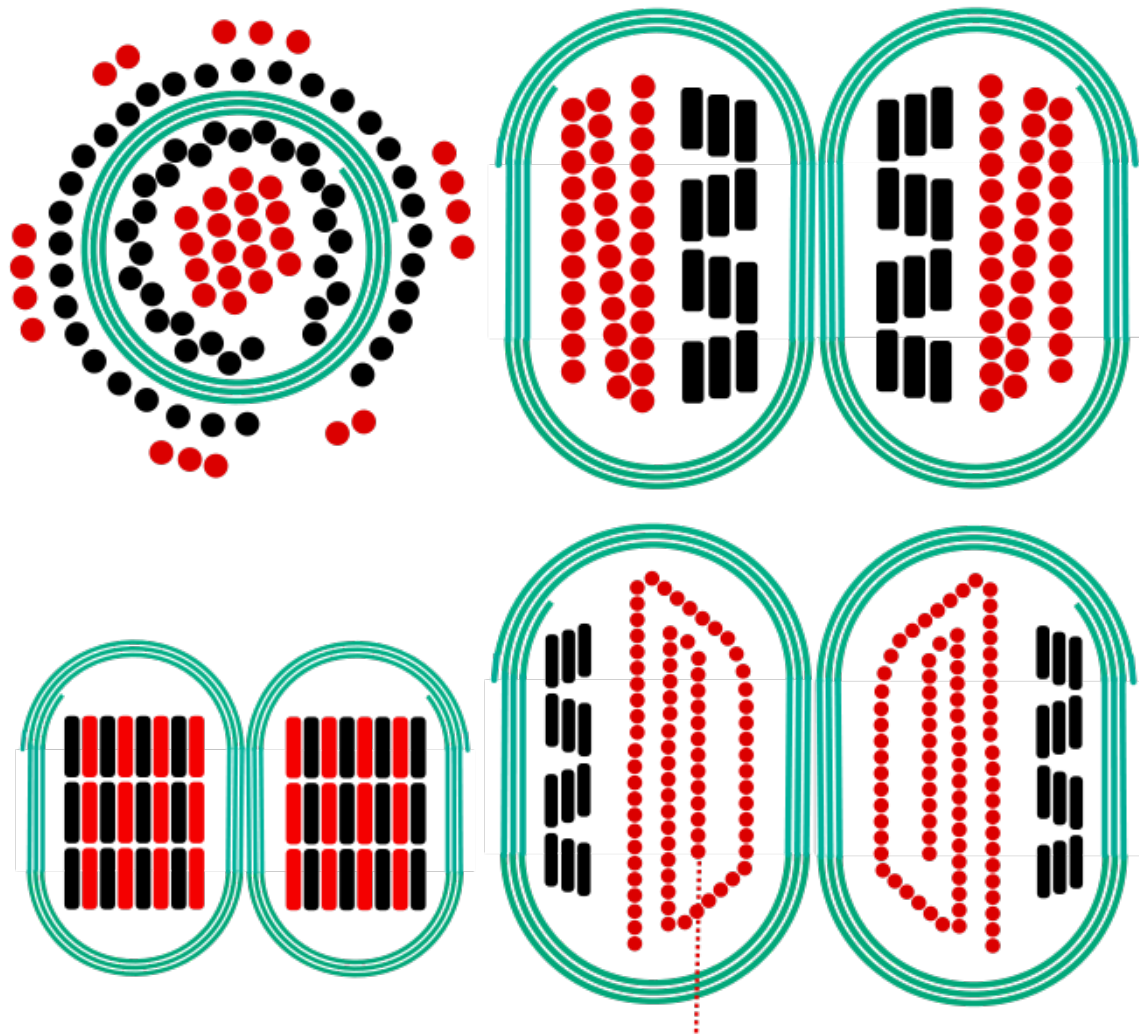
Air cores

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

Windings



Windings are usually arranged concentrically to minimize flux leakage.



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

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

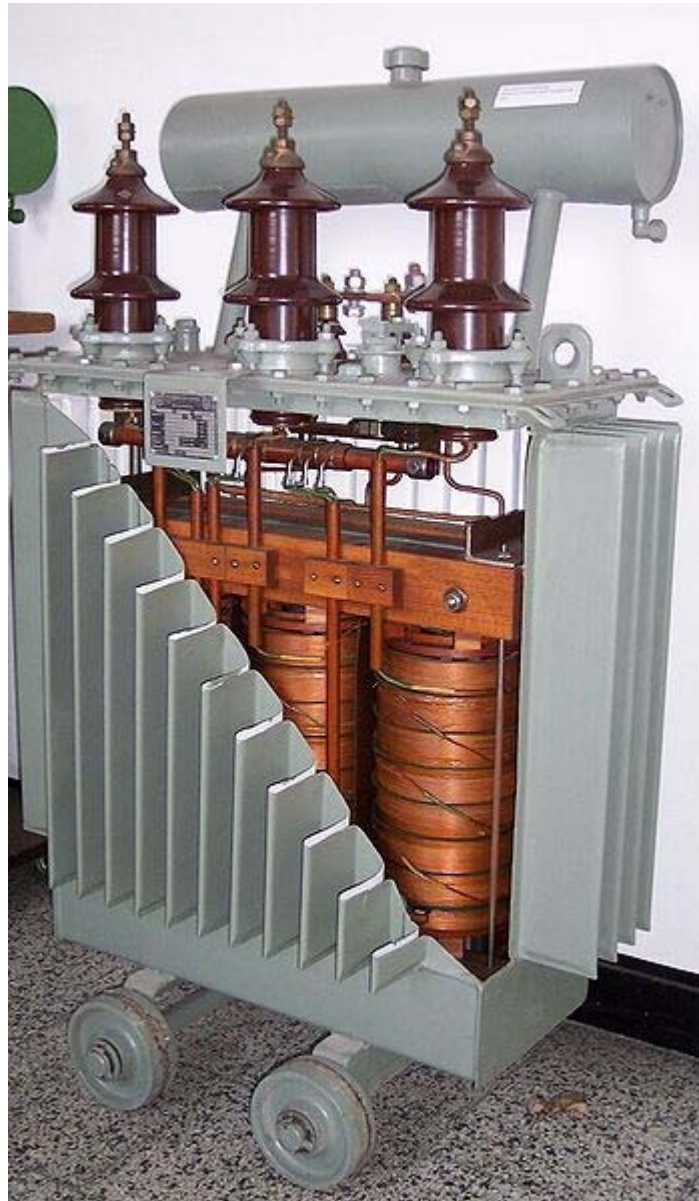
High-frequency transformers operating in the tens to hundreds of kilohertz often have windings made of braided Litz wire to minimize the skin-effect and proximity effect losses. Large power transformers use multiple-stranded conductors as well, since even at low power frequencies non-uniform distribution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

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

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

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

Coolant



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

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

preferred for indoor applications even at capacity ratings where oil-cooled construction would be more economical, because their cost is offset by the reduced building construction cost.

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

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

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

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

Insulation drying

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

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

Terminals

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

Applications



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

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


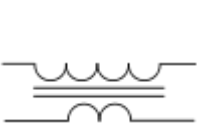

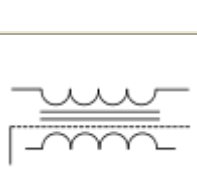
Transformers are also used extensively in electronic products to step down the supply voltage to a level suitable for the low voltage circuits they contain. The transformer also electrically isolates the end user from contact with the supply voltage.

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

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

Chapter-10

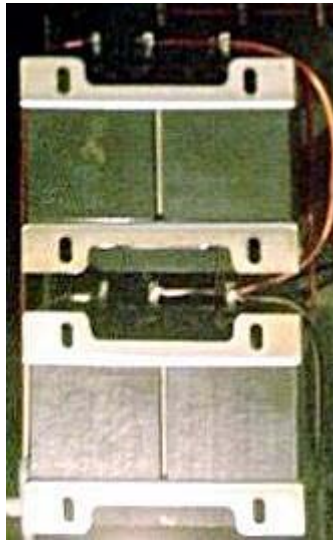
Transformer Types

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

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

Power transformers

Laminated core



Laminated Core Transformer

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

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

Toroidal



Toroidal Transformer

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

Toroidal transformers compared to EI core transformers:

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

Autotransformer

An autotransformer has only a single winding, which is tapped at some point along the winding. AC or pulsed voltage is applied across a portion of the winding, and a higher (or lower) voltage is produced across another portion of the same winding. The higher voltage will be connected to the ends of the winding, and the lower voltage from one end to a tap. For example, a transformer with a tap at the center of the winding can be used with 230 V across the entire winding, and 115 volts between one end and the tap. It can be connected to a 230 V supply to drive 115 V equipment, or reversed to drive 230 V equipment from 115 V. Since the current in the windings is lower, the transformer is smaller, lighter cheaper and more efficient. For voltage ratios not exceeding about 3:1, an

autotransformer is cheaper, lighter, smaller and more efficient than an isolating (two-winding) transformer of the same rating. Large three-phase autotransformers are used in electric power distribution systems, for example, to interconnect 33 kV and 66 kV sub-transmission networks.

Variac

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

Induction regulator

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

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

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

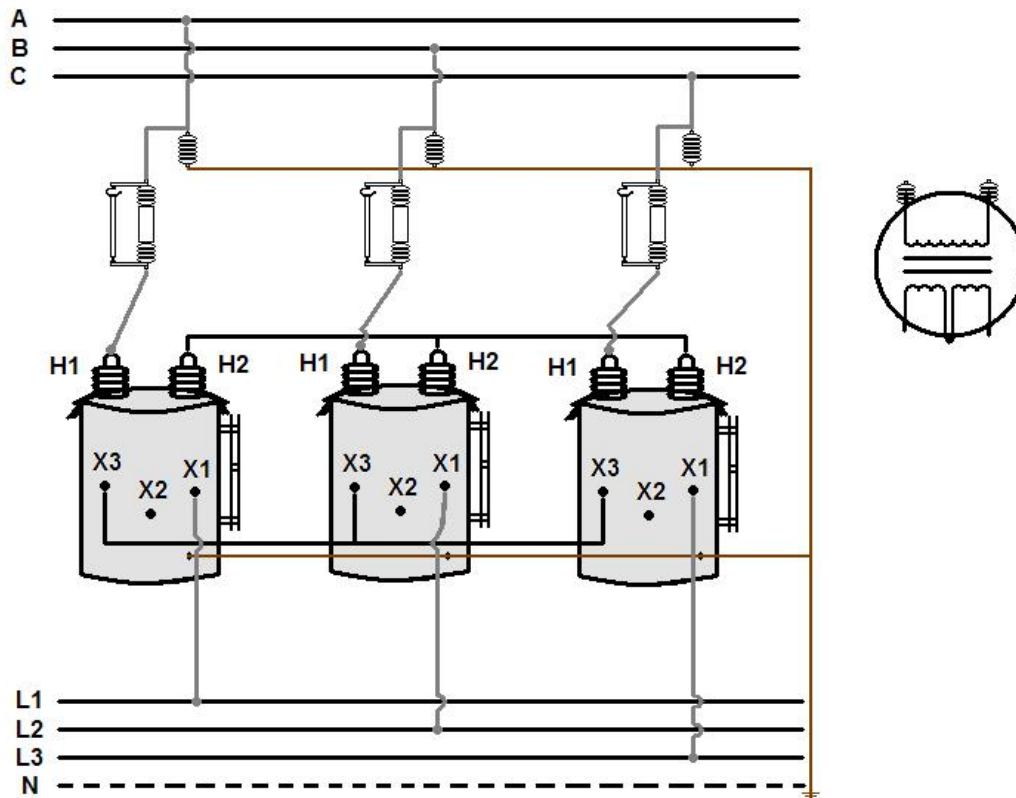
Hence, such regulators find widespread use in high-voltage laboratories.

Stray field transformer

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

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

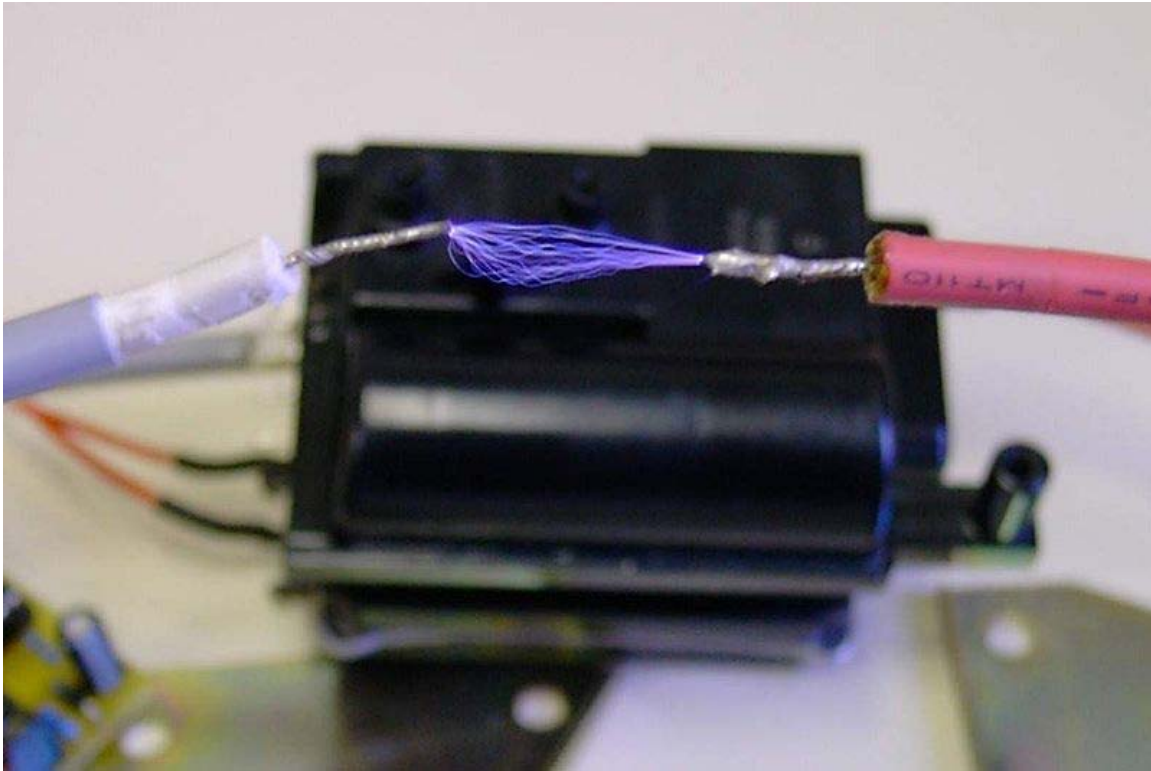
Polyphase transformers



Example of Y Y Connection

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

Resonant transformers



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

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

Examples:

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

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

Constant voltage transformer

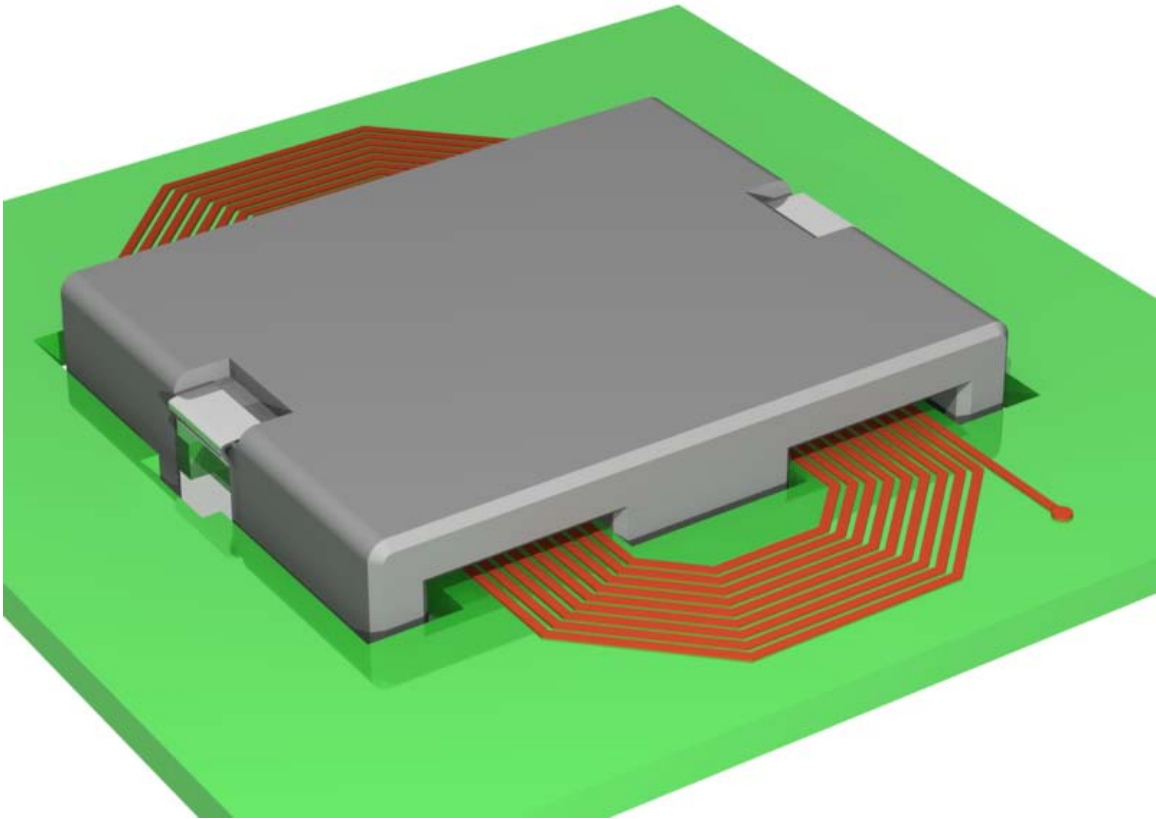
By arranging particular magnetic properties of a transformer core, and installing a ferro-resonant tank circuit (a capacitor and an additional winding), a transformer can be arranged to automatically keep the secondary winding voltage relatively constant for varying primary supply without additional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

Ferrite core

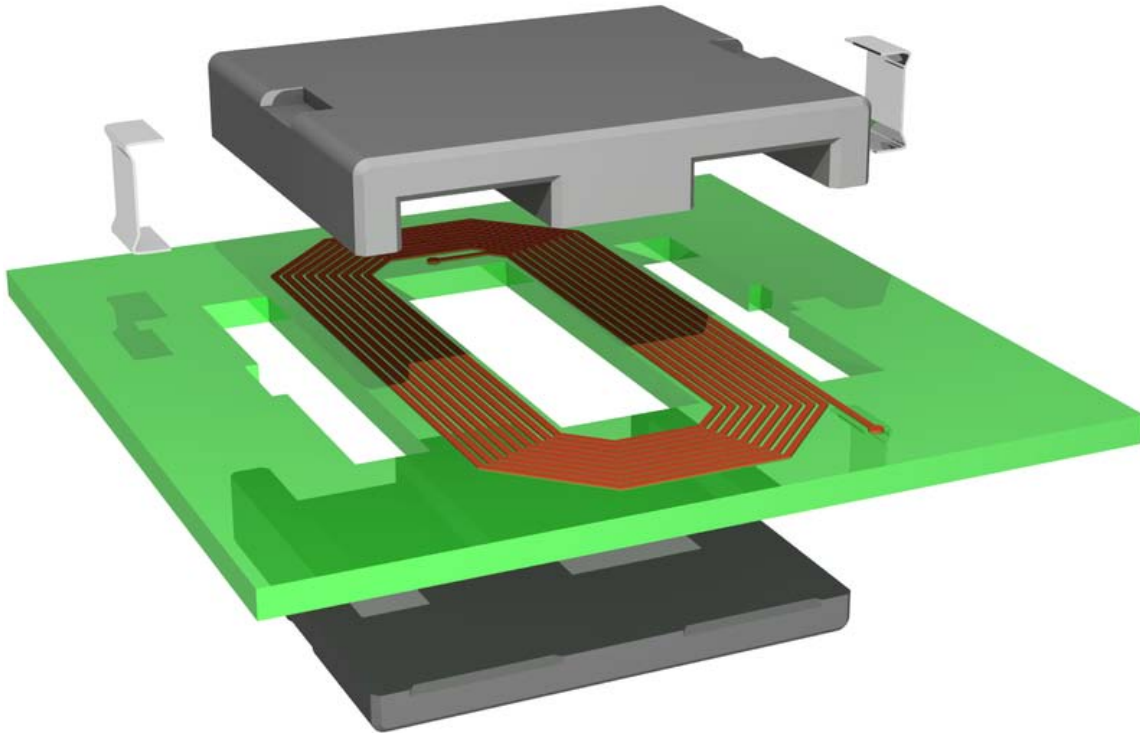
Ferrite core power transformers are widely used in switched-mode power supplies (SMPSs). The powder core enables high-frequency operation, and hence much smaller size-to-power ratio than laminated-iron transformers.

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

Planar transformer



A planar transformer



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

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

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

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

Oil cooled transformer

For large transformers used in power distribution or electrical substations, the core and coils of the transformer are immersed in oil which cools and insulates. Oil circulates through ducts in the coil and around the coil and core assembly, moved by convection. The oil is cooled by the outside of the tank in small ratings, and in larger ratings an air-

cooled radiator is used. Where a higher rating is required, or where the transformer is used in a building or underground, oil pumps are used to circulate the oil and an oil-to-water heat exchanger may also be used. Formerly, indoor transformers required to be fire-resistant used PCB liquids; since these are now banned, substitute fire-resistant liquids such as silicone oils are instead used.

Cast resin transformers

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

Isolating Transformer

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

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

Instrument transformers

Current transformers



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

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

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

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

Voltage transformers

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

The transformer winding high-voltage connection points are typically labeled as H_1 , H_2 (sometimes H_0 if it is internally grounded) and X_1 , X_2 and sometimes an X_3 tap may be present. Sometimes a second isolated winding (Y_1 , Y_2 , Y_3) may also be available on the same voltage transformer. The high side (primary) may be connected phase to ground or phase to phase. The low side (secondary) is usually phase to ground.

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

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

Pulse transformers

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

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

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

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

RF transformers

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

Air-core transformers

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

Ferrite-core transformers

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

Transmission-line transformers

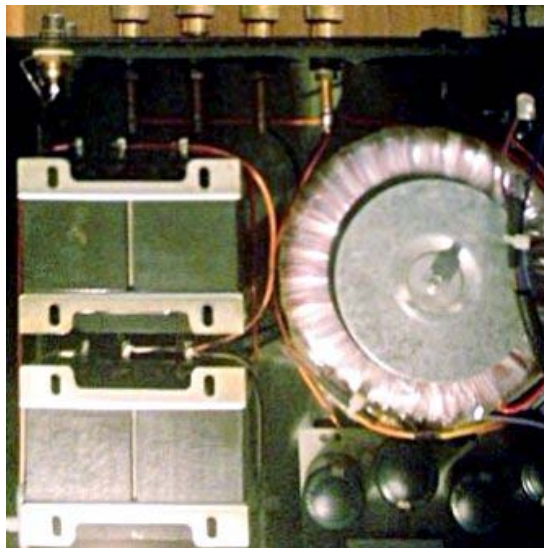
For radio frequency use, transformers are sometimes made from configurations of transmission line, sometimes bifilar or coaxial cable, wound around ferrite or other types of core. This style of transformer gives an extremely wide bandwidth but only a limited number of ratios (such as 1:9, 1:4 or 1:2)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

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

Baluns

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

Audio transformers



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

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

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

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

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

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

Loudspeaker transformers

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

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

Output transformer

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

Small signal transformers

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

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

Interstage and coupling transformers

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

Homemade and obsolete transformers

Transformer kits

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

Firm clamping of laminations and varnish help to avoid buzz.

100% homemade

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

- picture
- device in use

Hedgehog

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

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

Variocouplers

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

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

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

Not transformers

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

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

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

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

Chapter-11

Current Transformer

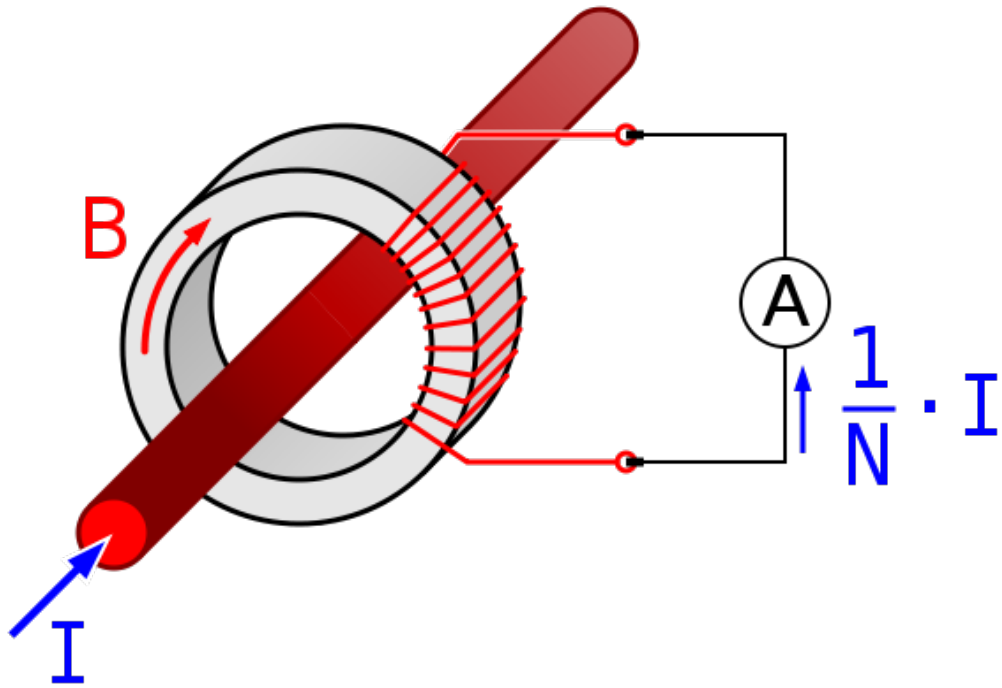


A CT for operation on a 110 kV grid

In electrical engineering, a **current transformer (CT)** is used for measurement of electric currents. Current transformers, together with **voltage transformers (VT) (potential transformers (PT))**, are known as **instrument transformers**. When current in a circuit is too high to directly apply to measuring instruments, a current transformer produces a reduced current accurately proportional to the current in the circuit, which can

be conveniently connected to measuring and recording instruments. A current transformer also isolates the measuring instruments from what may be very high voltage in the monitored circuit. Current transformers are commonly used in metering and protective relays in the electrical power industry.

Design





SF₆ 110 kV current transformer TGFM series, Russia



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

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

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

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

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

Usage

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

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

Safety precautions

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

Accuracy

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

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

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

Burden

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

ampere secondaries which will produce less voltage drop between a CT and its metering devices (used for remote measurement).

Knee-point voltage

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

Rating factor

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

Special designs

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

Chapter-12

Transformer Oil and Transformer Oil Testing

Transformer oil

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

Explanation

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

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

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

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

Oil transformer

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

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

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

Transformer Oil Testing

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

1. Dissolved gas analysis
2. Furan analysis
3. PCB analysis
4. General electrical & physical tests:
 - Color & Appearance
 - Breakdown Voltage
 - Water Content
 - Acidity (Neutralization Value)
 - Dielectric Dissipation Factor
 - Resistivity
 - Sediments & Sludge
 - Interfacial Tension
 - Flash Point
 - Pour Point
 - Density
 - Kinematic Viscosity

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

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

On-site transformer oil testing

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

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

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

Transformer oil testing

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

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



Voltage breakdown during transformer oil testing

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

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

Transformer oil testing procedure

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

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

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

On-site transformer oil testing

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

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

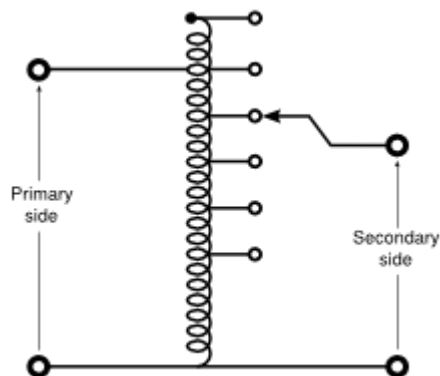
Chapter-13

Autotransformer

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

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

Operation



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

An **autotransformer** has a single winding with two end terminals, and one or more terminals at intermediate tap points. The primary voltage is applied across two of the terminals, and the secondary voltage taken from two terminals, almost always having one terminal in common with the primary voltage. The primary and secondary circuits therefore have a number of windings turns in common. Since the volts-per-turn is the

same in both windings, each develops a voltage in proportion to its number of turns. In an autotransformer part of the current flows directly from the input to the output, and only part is transferred inductively, allowing a smaller, lighter, cheaper core to be used as well as requiring only a single winding.

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

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

Limitations

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

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

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

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

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

Applications

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

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

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

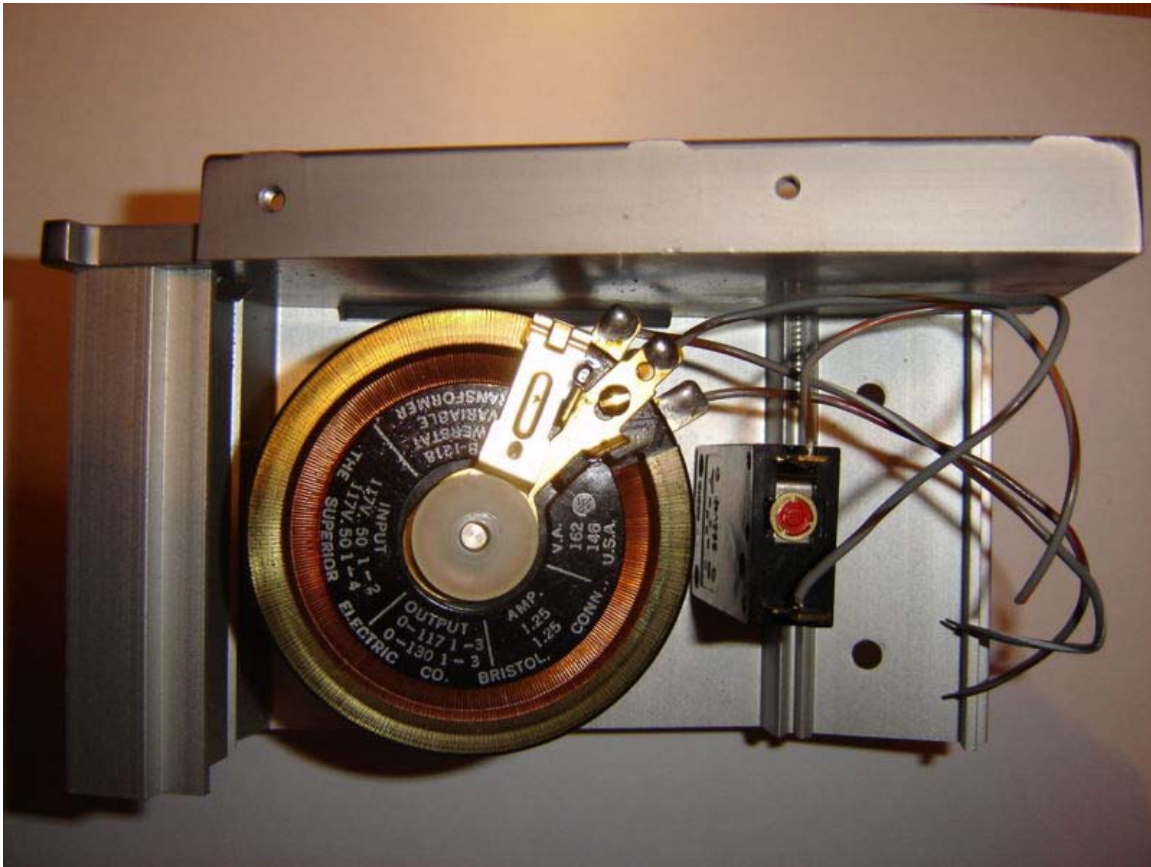
In audio applications, tapped autotransformers are used to adapt speakers to constant-voltage audio distribution systems, and for impedance matching such as between a low-impedance microphone and a high-impedance amplifier input.

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

Variable autotransformers



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



Variable Transformer - part of Tektronix 576 Curve Tracer

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

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

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

From 1934 to 2002, **Variac** was a U.S. trademark of General Radio for a variable autotransformer intended to conveniently vary the output voltage for a steady AC input

voltage. In 2004, Instrument Service Equipment applied for and obtained the *Variac* trademark for the same type of product.

Chapter-14

Tesla Coil

Tesla coil



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

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

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

The early Tesla coil transformer design employs a medium- to high-voltage power source, one or more high voltage capacitor(s), and a spark gap to excite a multiple-layer primary inductor with periodic bursts of high frequency current. The multiple-layer Tesla coil transformer secondary is excited by resonant inductive coupling, the primary and secondary circuits both being *tuned* so they resonate at the same frequency (typically,

between 25 kHz and 2 MHz). The later and higher-power coil design has a single-layer primary and secondary. These Tesla coils are often used by hobbyists and at venues such as science museums to produce long sparks.

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

History

Tesla's coil

The "American Electrician" gives a description of an early Tesla coil wherein a glass battery jar, 15 x 20 cm (6 x 8 in) is wound with 60 to 80 turns of AWG No. 18 B & S magnet wire (0.823 mm²). Into this is slipped a primary consisting of eight to ten turns of AWG No. 6 B & S wire (13.3 mm²) and the whole combination immersed in a vessel containing linseed or mineral oil. (Norrie, pg. 34-35)

Tesla Coil Theory

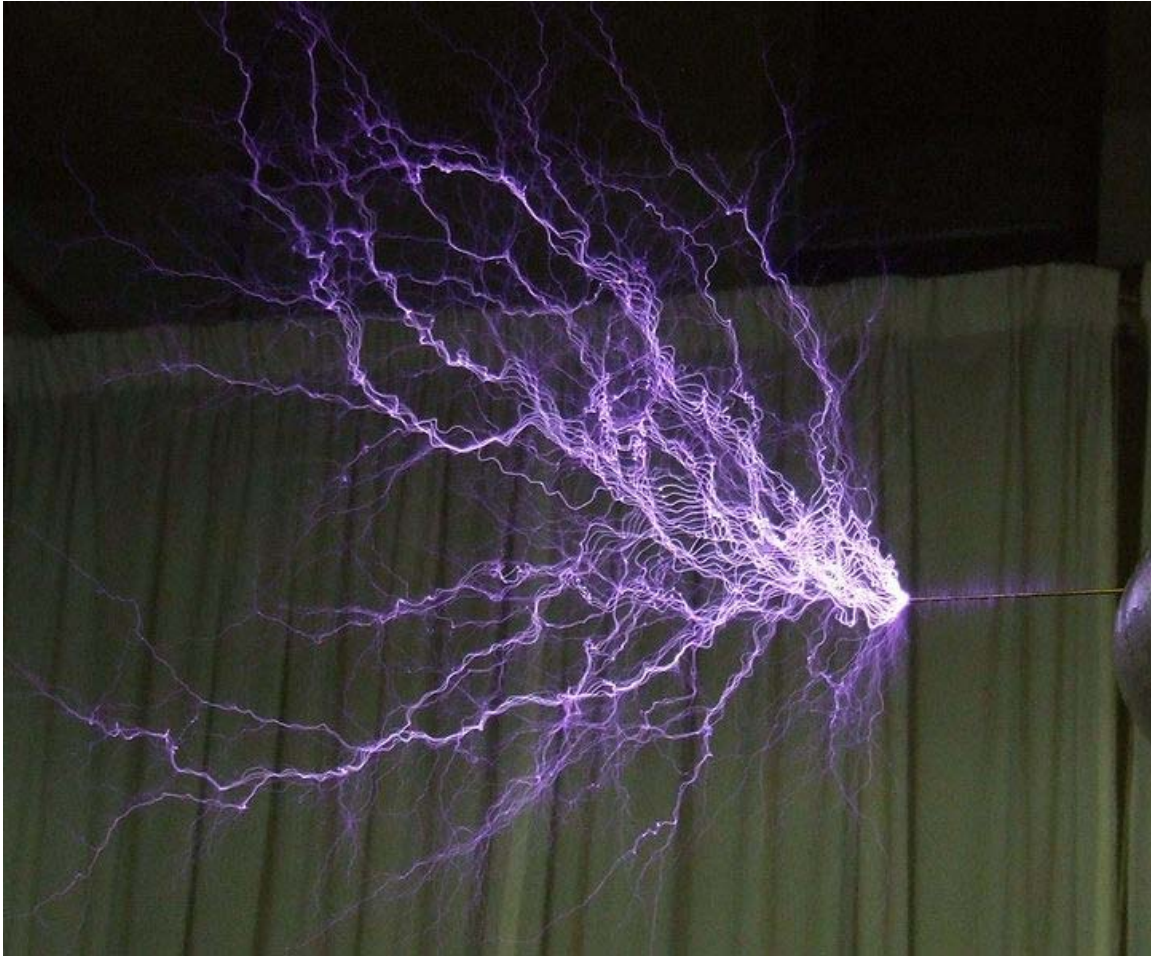
A Tesla coil transformer operates in a significantly different fashion than a conventional (i.e., iron core) transformer. In a conventional transformer, the windings are very tightly coupled, and voltage gain is determined by the ratio of the numbers of turns in the windings. This works well at normal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

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

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

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

Modern day Tesla coils



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

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

electric fields over large distances to prevent high electrical stresses in the first place, thereby allowing operation in free air.

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

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

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

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

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



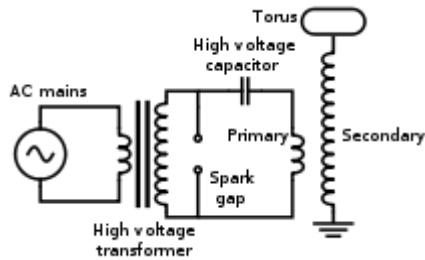
Demonstration of the Nevada Lightning Laboratory 1:12 scale prototype twin Tesla Coil at Maker Faire 2008.

In a *dual resonant solid-state Tesla coil (DRSSTC)*, the electronic switching of the solid-state Tesla coil is combined with the resonant primary circuit of a spark-gap Tesla coil. The resonant primary circuit is formed by connecting a capacitor in series with the primary winding of the coil, so that the combination forms a series tank circuit with a resonant frequency near that of the secondary circuit. Because of the additional resonant circuit, one manual and one adaptive tuning adjustment are necessary. Also, an interrupter is usually used to reduce the duty cycle of the switching bridge, in order to improve peak power capabilities; similarly, IGBTs are more popular in this application

than bipolar transistors or MOSFETs, due to their superior power handling characteristics. Performance of a DRSSTC can be comparable to a medium power spark gap Tesla coil, and efficiency (as measured by spark length versus input power) can be significantly greater than a spark gap Tesla coil operating at the same input power.

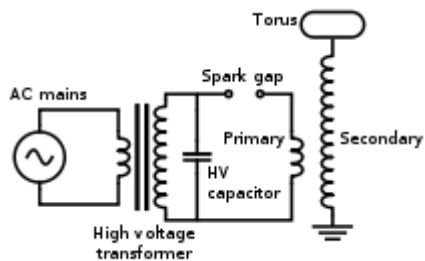
Applications

Transmission



Typical Tesla Coil Schematic

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



Alternate Tesla Coil Configuration

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

High voltage production

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

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

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

Tuning precautions

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

Air discharges



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

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

When the spark gap fires, the charged capacitor discharges into the primary winding, causing the primary circuit to oscillate. The oscillating primary current creates a magnetic field that couples to the secondary winding, transferring energy into the secondary side of

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

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

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

Wireless transmission and reception

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

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



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

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

A Tesla coil can receive electromagnetic impulses from atmospheric electricity and radiant energy, besides normal wireless transmissions. Radiant energy throws off with great velocity minute particles which are strongly electrified and other rays falling on the insulated-conductor connected to a condenser (*i.e.*, a capacitor) can cause the condenser to indefinitely charge electrically. The helical resonator can be "shock excited" due to radiant energy disturbances not only at the fundamental wave at one-quarter wave-length but also is excited at its harmonics. Hertzian methods can be used to excite the Tesla coil

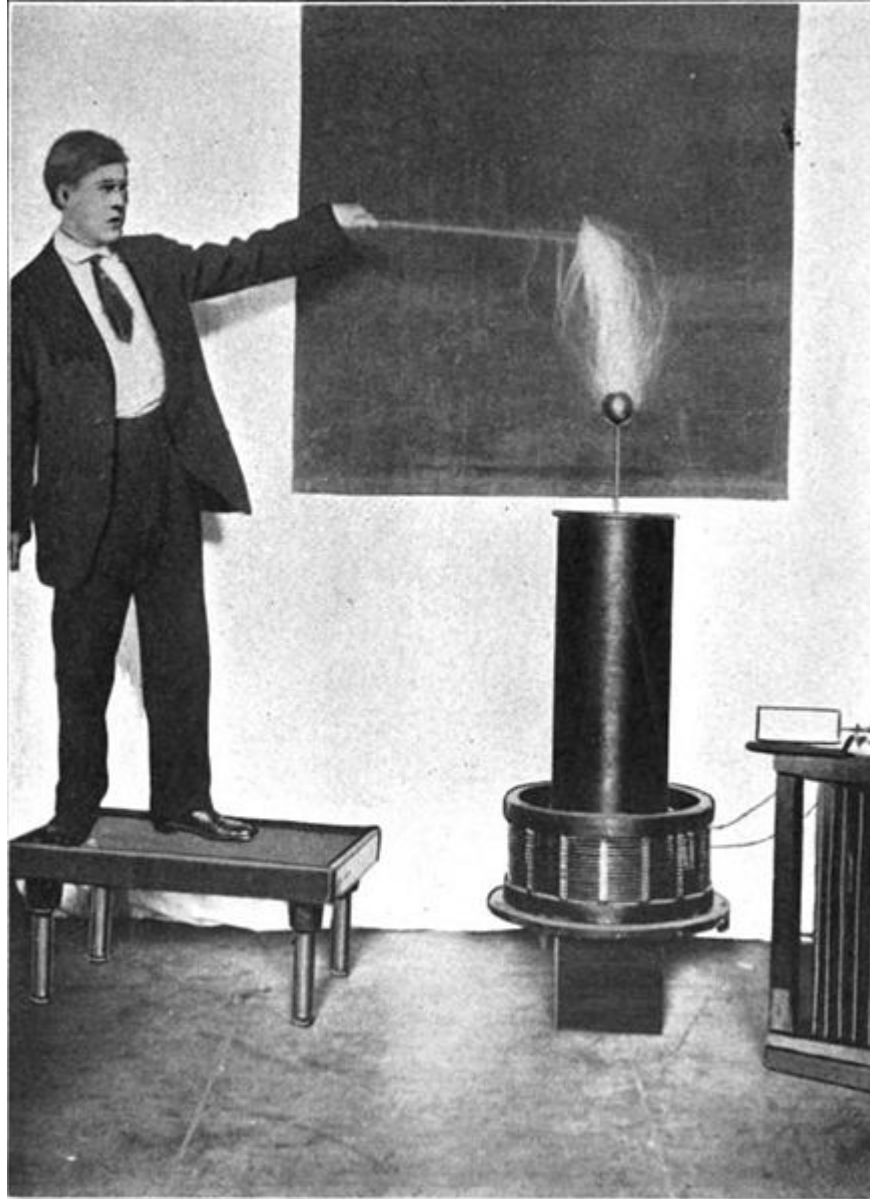
receiver with limitations that result in great disadvantages for utilization, though. The methods of ground conduction and the various induction methods can also be used to excite the Tesla coil receiver, but are again at a disadvantages for utilization. The charging-circuit can be adapted to be energized by the action of various other disturbances and effects at a distance. Arbitrary and intermittent oscillations that are propagated via conduction to the receiving resonator will charge the receiver's capacitor and utilize the potential energy to greater effect. Various radiations can be used to charge and discharge conductors, with the radiations considered electromagnetic vibrations of various wavelengths and ionizing potential. The Tesla receiver utilizes the effects or disturbances to charge a storage device with energy from an external source (natural or man-made) and controls the charging of said device by the actions of the effects or disturbances (during succeeding intervals of time determined by means of such effects and disturbances corresponding in succession and duration of the effects and disturbances). The stored energy can also be used to operate the receiving device. The accumulated energy can, for example, operate a transformer by discharging through a primary circuit at predetermined times which, from the secondary currents, operate the receiving device.

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

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

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

High frequency electrical safety



Student conducting Tesla coil streamers through his body, 1909

The 'skin effect'

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

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

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

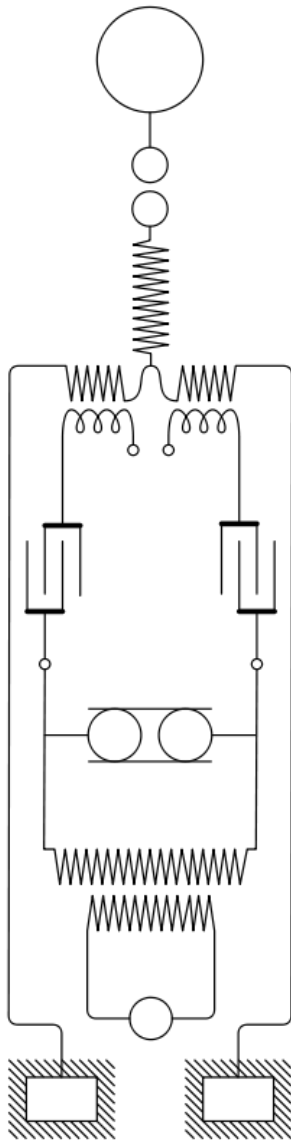
The most serious dangers associated with Tesla coil operation are associated with the primary circuit. It is the primary circuit that is capable of delivering a sufficient current at a significant voltage to stop the heart of a careless experimenter. Because these components are not the source of the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

Further, great care should be taken when working on the primary section of a coil even when it has been disconnected from its power source for some time. The tank capacitors

can remain charged for days with enough energy to deliver a fatal shock. Proper designs should always include 'bleeder resistors' to bleed off stored charge from the capacitors. In addition, a safety shorting operation should be performed on each capacitor before any internal work is performed.

Instances and devices

Magnifier Configurations



Classically driven configuration.



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

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

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

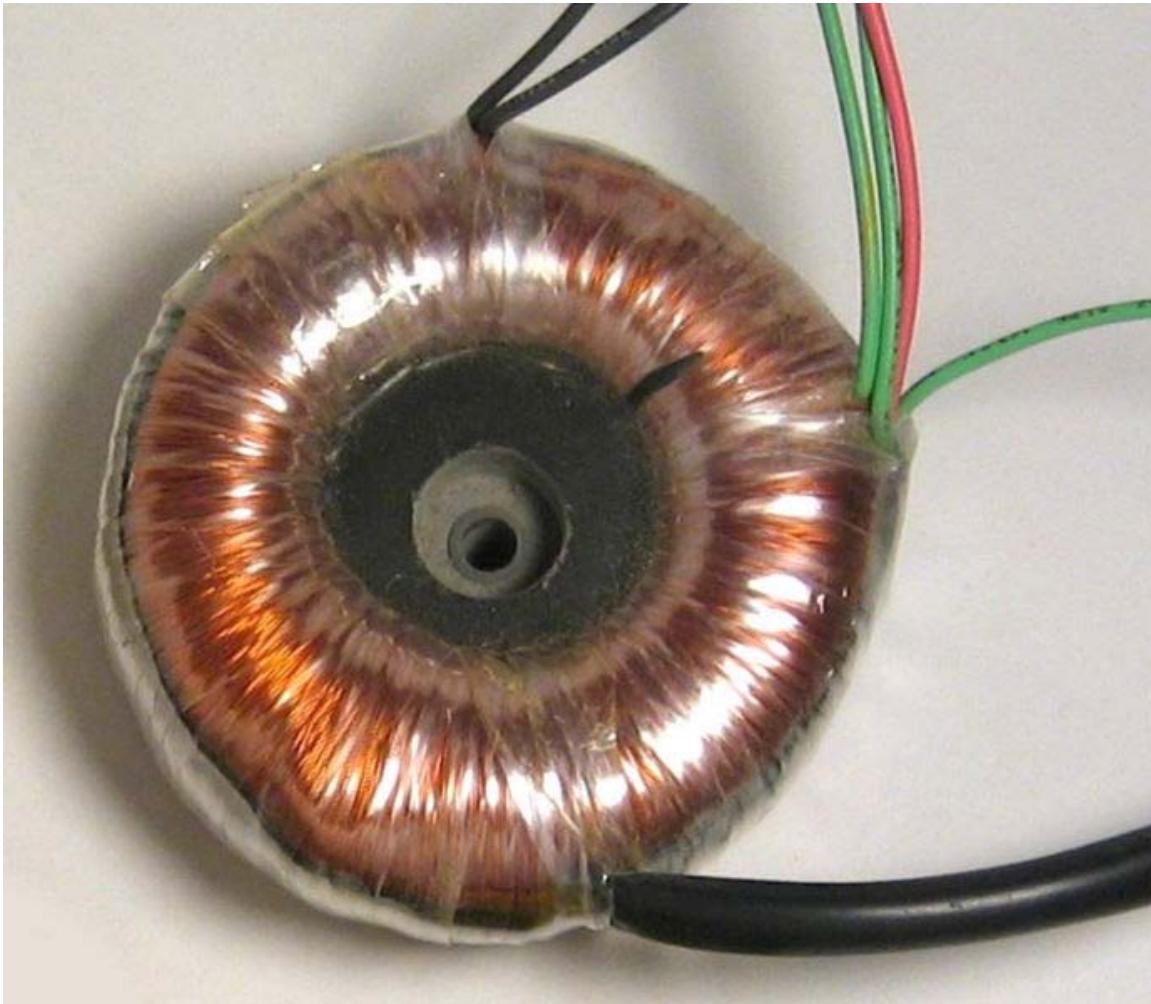
Scientists working with a glass vacuum line (e.g. chemists working with volatile substances in the gas phase, inside a system of glass tubes, taps and bulbs) test for the presence of tiny pin-holes in the apparatus (especially a newly blown piece of glassware) using a Tesla coil. When the system is evacuated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

Chapter-15

Toroidal Inductors and Transformers



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



A small toroidal transformer.

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

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

Total B Field Confinement by Toroidal Inductors

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

Sufficient conditions for total internal confinement of the B field

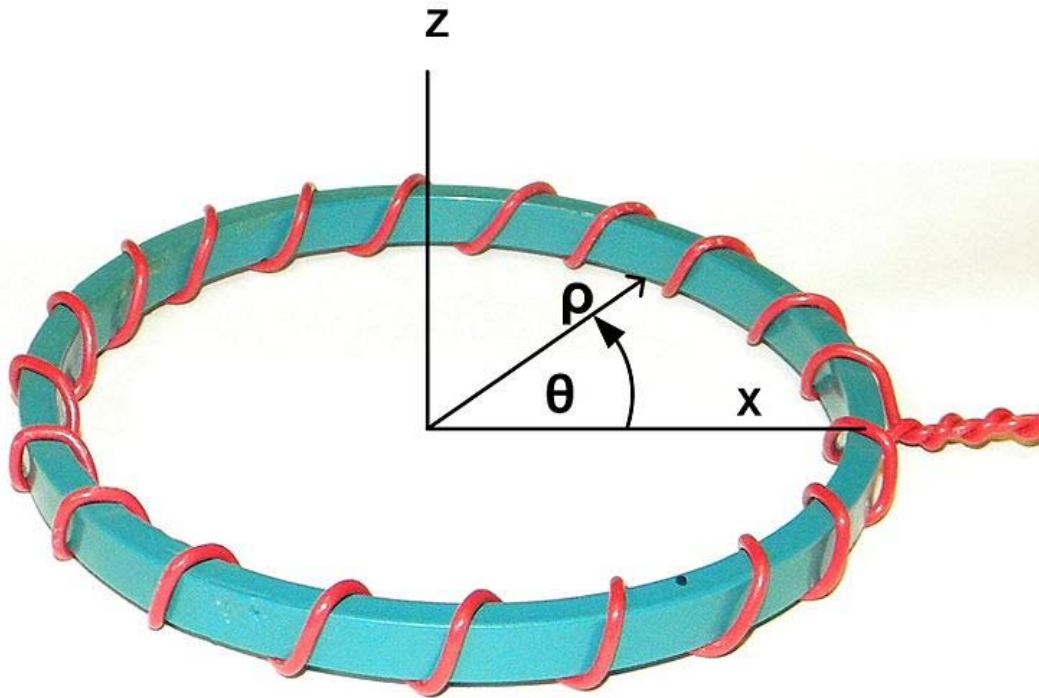


Fig. 1. Coordinate system. The Z axis is the nominal axis of symmetry. The X axis chosen arbitrarily to line up with the starting point of the winding. ρ is called the radial direction. θ is called the circumferential direction.

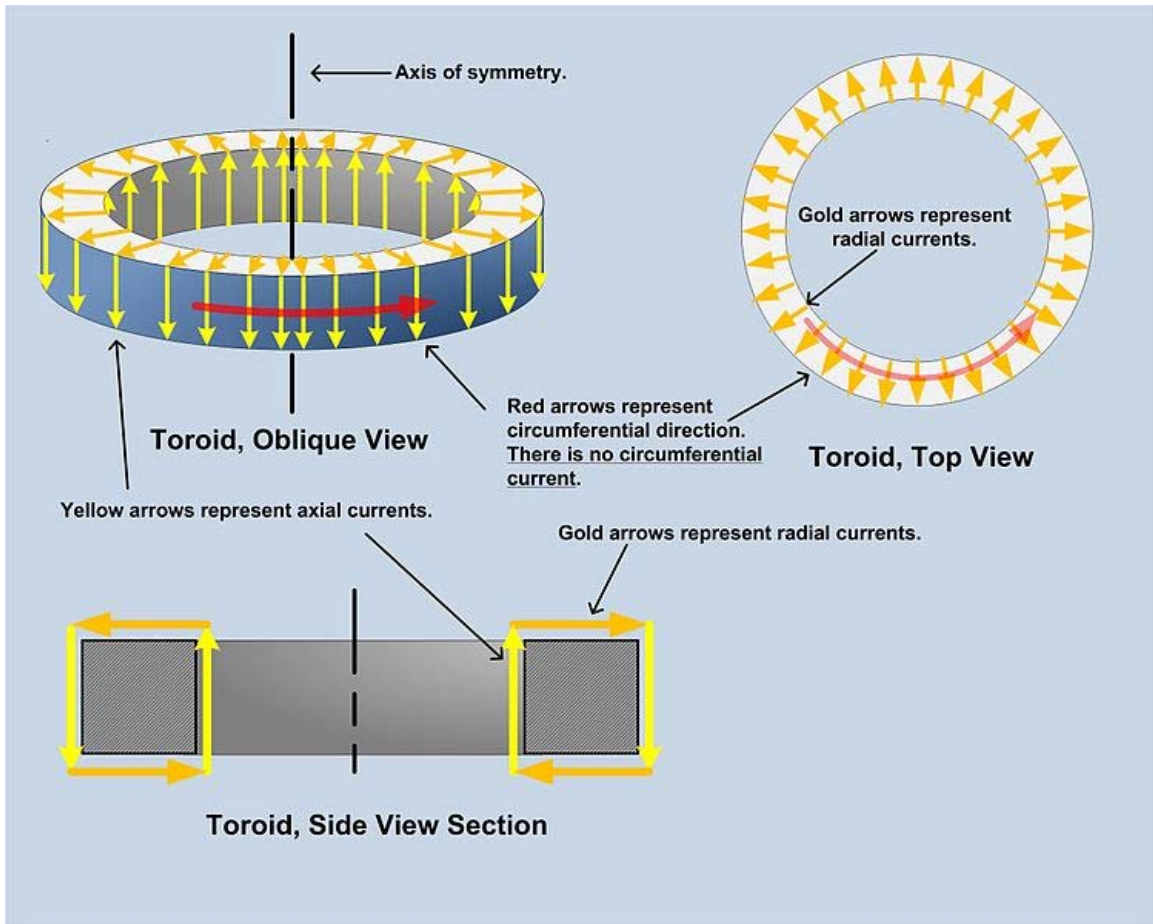


Fig. 2. An axially symmetric toroidal inductor with no circumferential current.

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

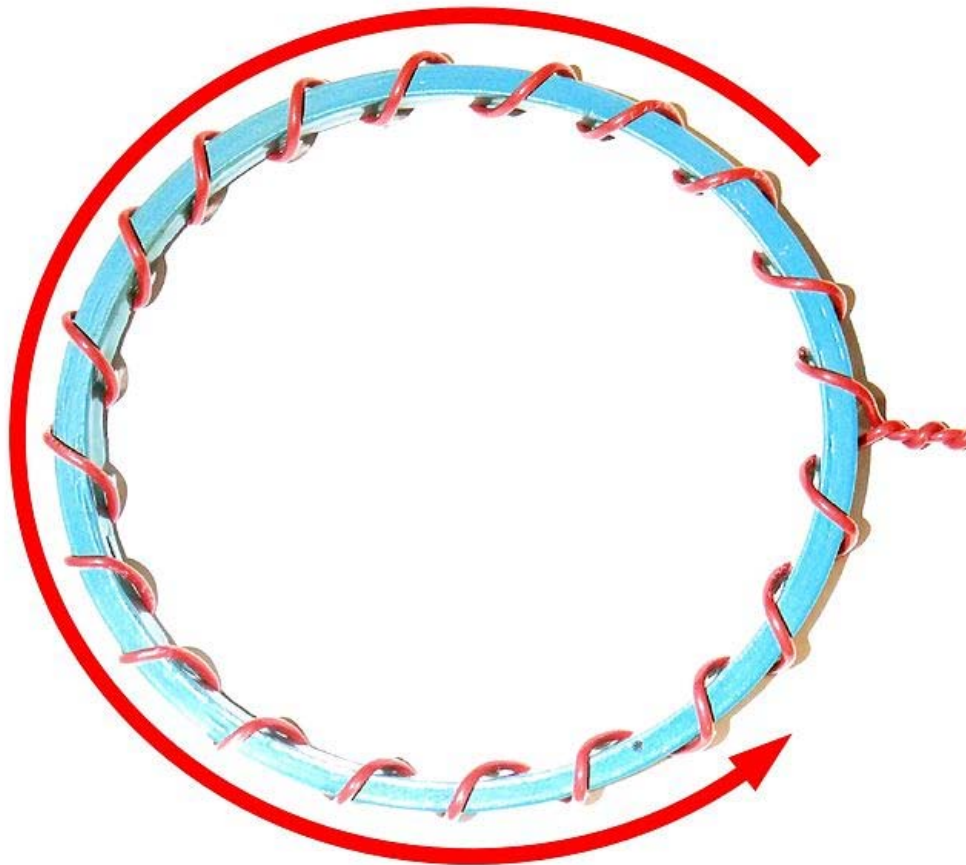


Fig. 3. Toroidal inductor with circumferential current

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

Figures 4-6 show different ways to neutralize the circumferential current. Figure 4 is the simplest and has the advantage that the return wire can be added after the inductor is bought or built.

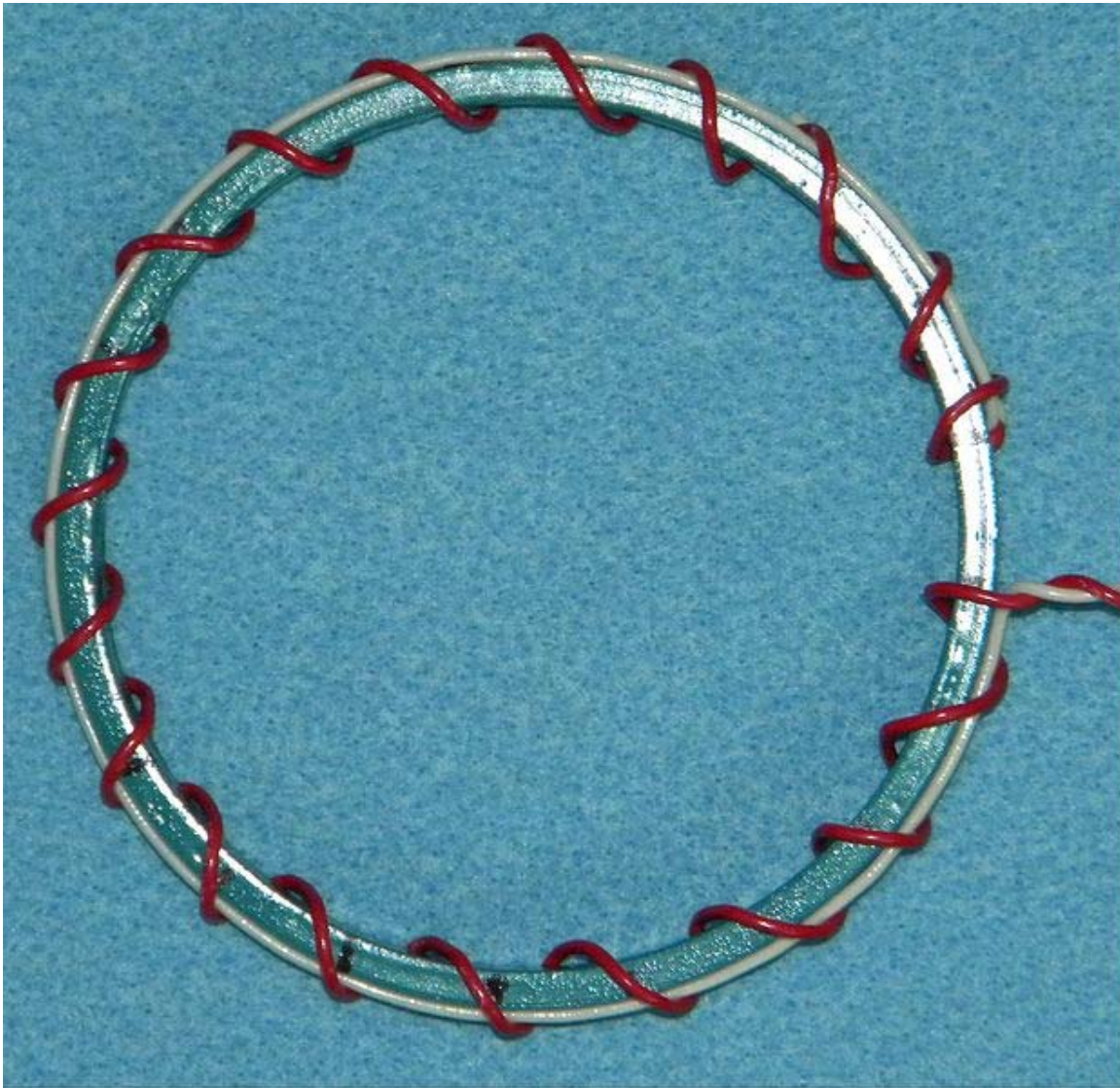


Fig. 4. Circumferential current countered with a return wire. The wire is white and runs between the outer rim of the inductor and the outer portion of the winding.



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



Fig. 6. Circumferential current countered with a split return winding.

E Field in the Plane of the Toroid

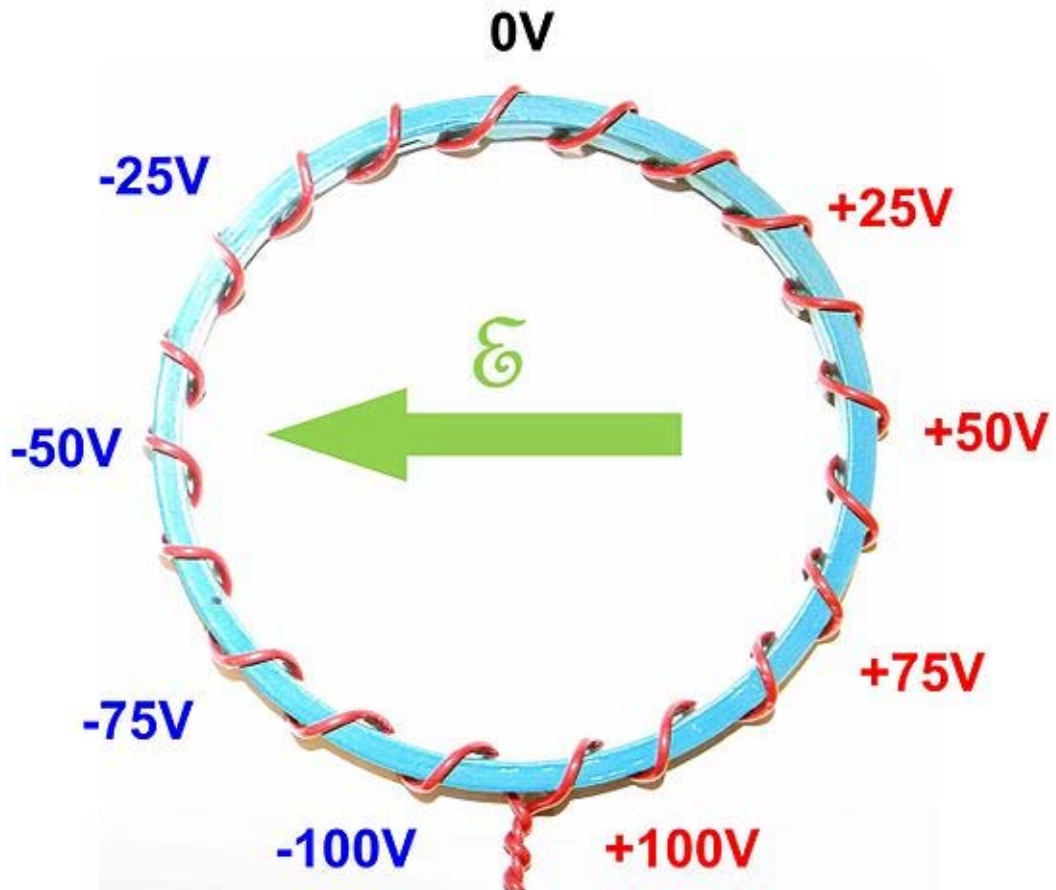


Fig. 7. Simple toroid and the E-field produced. +/- 100 Volt excitation assumed.

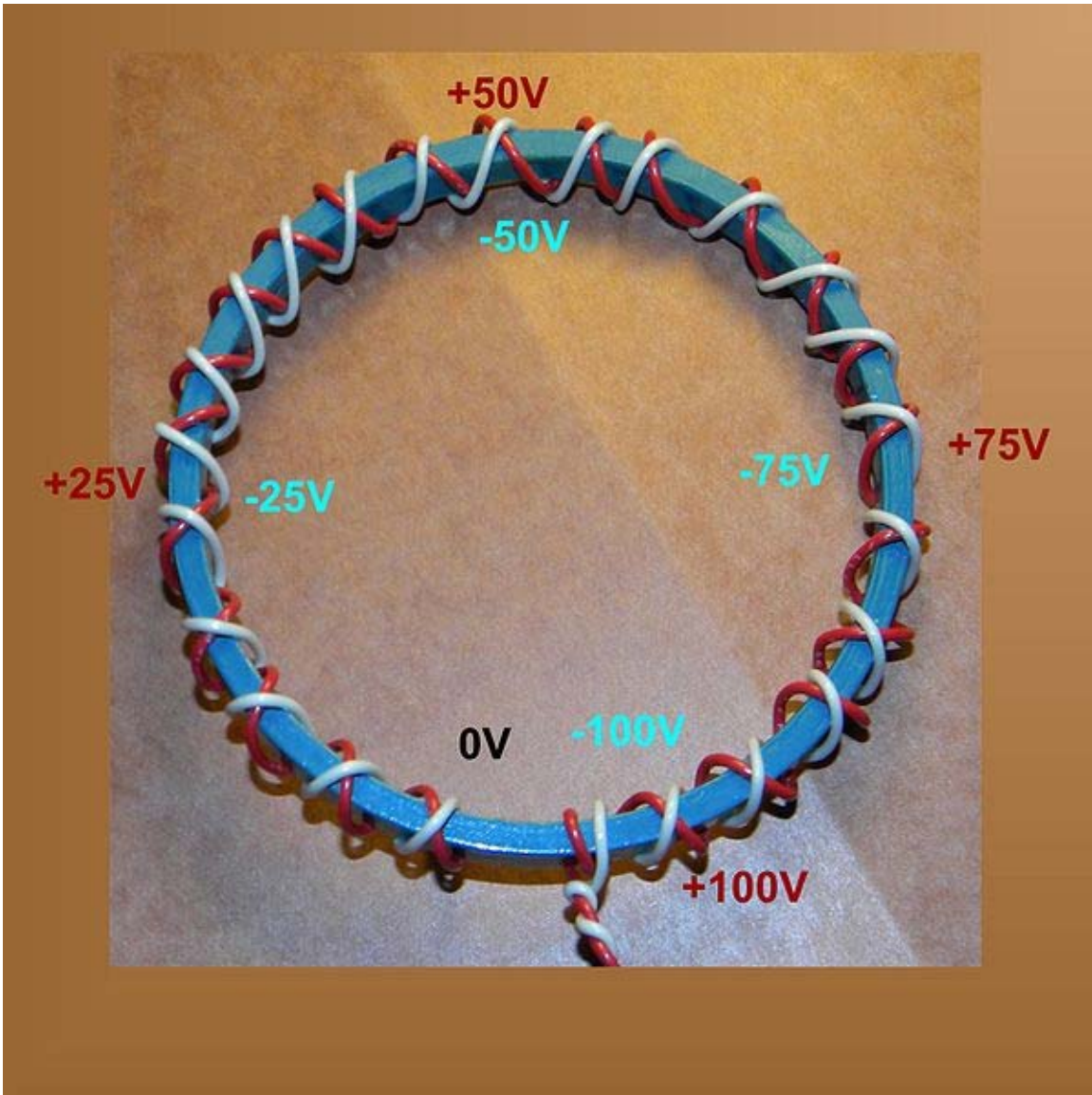
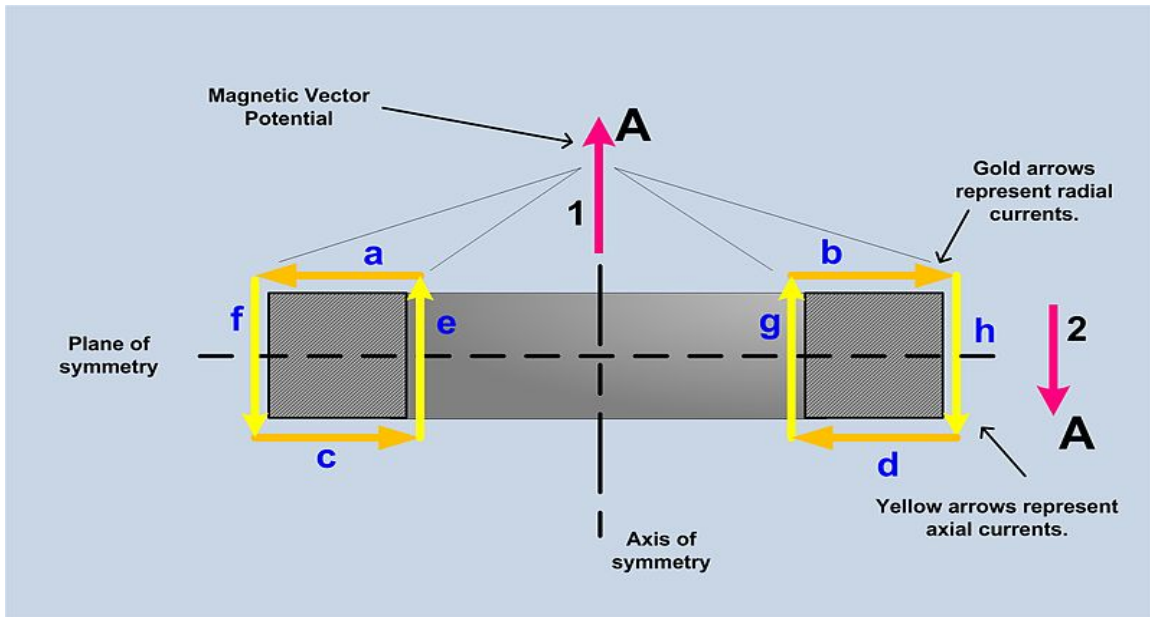


Fig. 8. Voltage distribution with return winding. +/- 100 Volt excitation assumed.

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

Torroidal Inductor/Transformer and Magnetic Vector Potential



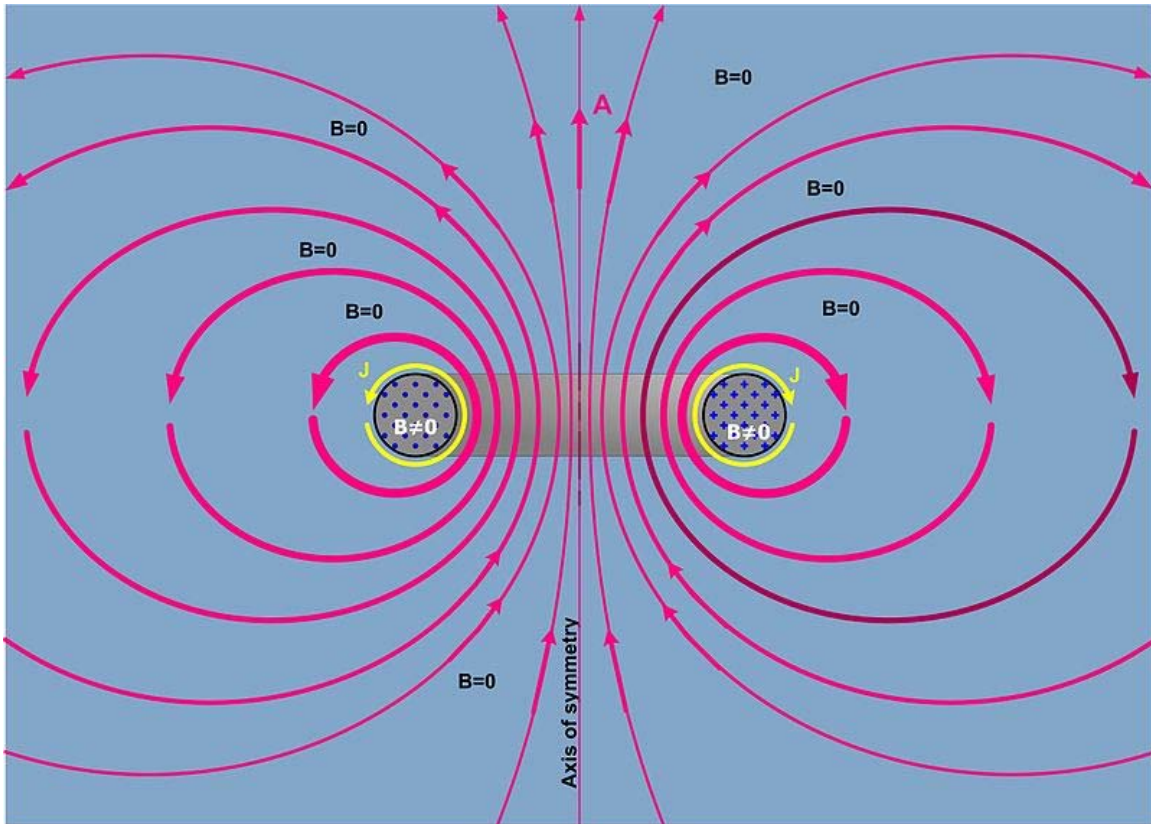
Showing the development of the magnetic vector potential around a symmetric torroidal inductor.

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

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

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

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



Representing the magnetic vector potential (\mathbf{A}), magnetic flux (\mathbf{B}), and current density (\mathbf{j}) fields around a toroidal inductor of circular cross section. Thicker lines indicate field lines of higher average intensity. Circles in cross section of the core represent \mathbf{B} flux coming out of the picture. Plus signs on the other cross section of the core represent \mathbf{B} flux going into the picture. $\text{Div } \mathbf{A} = 0$ has been assumed.

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

Toroidal Transformer Action in the Presence of Total \mathbf{B} field Confinement

The \mathbf{E} and \mathbf{B} fields can be computed from the \mathbf{A} and ϕ (scalar electric potential) fields

$\mathbf{B} = \nabla \times \mathbf{A}$. and : $\mathbf{E} = -\nabla\phi - \frac{\partial\mathbf{A}}{\partial t}$ and so even if the region outside the windings is devoid of \mathbf{B} field, it is filled with non-zero \mathbf{E} field.

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

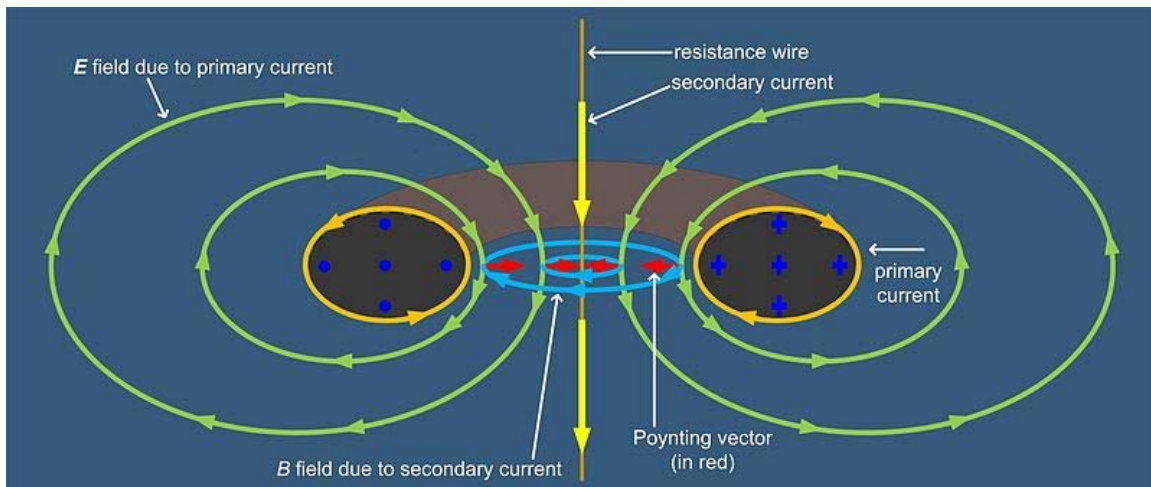
Stokes theorem applies, so that the path integral of \mathbf{A} is equal to the enclosed \mathbf{B} flux, just as the path integral \mathbf{B} is equal to a constant times the enclosed current

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

$$\text{EMF} = \oint_{\text{path}} \mathbf{E} \cdot d\mathbf{l} = - \oint_{\text{path}} \frac{\partial\mathbf{A}}{\partial t} \cdot d\mathbf{l} = - \frac{\partial}{\partial t} \oint_{\text{path}} \mathbf{A} \cdot d\mathbf{l} = - \frac{\partial}{\partial t} \int_{\text{surface}} \mathbf{B} \cdot d\mathbf{s}$$

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

Toroidal Transformer Poynting Vector Coupling from Primary to Secondary in the Presence of Total B field Confinement



In this figure, blue dots indicate where B flux from the primary current comes out of the picture and plus signs indicate where it goes into the picture.

Explanation of the Figure

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