



Power Supply & Transformers in Electrical Engineering

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First Edition, 2012

ISBN 978-81-323-0970-3

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Published by:

Academic Studio

4735/22 Prakashdeep Bldg,

Ansari Road, Darya Ganj,

Delhi - 110002

Email: info@wtbooks.com

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Chapter-1

Power Supply

A **power supply** is a device that supplies electrical energy to one or more electric loads. The term is most commonly applied to devices that convert one form of electrical energy to another, though it may also refer to devices that convert another form of energy (e.g., mechanical, chemical, solar) to electrical energy. A regulated power supply is one that controls the output voltage or current to a specific value; the controlled value is held nearly constant despite variations in either load current or the voltage supplied by the power supply's energy source.

Every power supply must obtain the energy it supplies to its load, as well as any energy it consumes while performing that task, from an energy source. Depending on its design, a power supply may obtain energy from:

- Electrical energy transmission systems. Common examples of this include power supplies that convert AC line voltage to DC voltage.
- Energy storage devices such as batteries and fuel cells.
- Electromechanical systems such as generators and alternators.
- Solar power.

A power supply may be implemented as a discrete, stand-alone device or as an integral device that is hardwired to its load. In the latter case, for example, low voltage DC power supplies are commonly integrated with their loads in devices such as computers and household electronics.

Constraints that commonly affect power supplies include:

- The amount of voltage and current they can supply.
- How long they can supply energy without needing some kind of refueling or recharging (applies to power supplies that employ portable energy sources).
- How stable their output voltage or current is under varying load conditions.
- Whether they provide continuous or pulsed energy.

Power supplies types

Power supplies for electronic devices can be broadly divided into linear and switching power supplies. The linear supply is usually a relatively simple design, but it becomes increasingly bulky and heavy for high-current equipment due to the need for large mains-frequency transformers and heat-sinked electronic regulation circuitry. Linear voltage regulators produce regulated output voltage by means of an active voltage divider that consumes energy, thus making efficiency low. A switched-mode supply of the same rating as a linear supply will be smaller, is usually more efficient, but will be more complex.

Battery

A battery is an alternative to a line-operated power supply; it is independent of the availability of mains electricity, suitable for portable equipment and use in locations without mains power. A battery consists of several electrochemical cells connected in series to provide the voltage desired. Batteries may be primary (able to supply current when constructed, discarded when drained) or secondary (rechargeable; can be charged, used, and recharged many times)

The primary cell first used was the carbon-zinc dry cell. It had a voltage of 1.5 volts; later battery types have been manufactured, when possible, to give the same voltage per cell. Carbon-zinc and related cells are still used, but the alkaline battery delivers more energy per unit weight and is widely used. The most commonly used battery voltages are 1.5 (1 cell) and 9V (6 cells).

Various technologies of rechargeable battery are used. Types most commonly used are NiMH, and lithium ion and variants.

DC power supply



A home-made linear power supply (used here to power amateur radio equipment)

An AC powered unregulated power supply usually uses a transformer to convert the voltage from the wall outlet (mains) to a different, nowadays usually lower, voltage. If it is used to produce DC, a rectifier is used to convert alternating voltage to a pulsating direct voltage, followed by a filter, comprising one or more capacitors, resistors, and sometimes inductors, to filter out (smooth) most of the pulsation. A small remaining unwanted alternating voltage component at mains or twice mains power frequency (depending upon whether half- or full-wave rectification is used)—ripple—is unavoidably superimposed on the direct output voltage.

For purposes such as charging batteries the ripple is not a problem, and the simplest unregulated mains-powered DC power supply circuit consists of a transformer driving a single diode in series with a resistor.

Before the introduction of solid-state electronics, equipment used valves (vacuum tubes) which required high voltages; power supplies used step-up transformers, rectifiers, and filters to generate one or more direct voltages of some hundreds of volts, and a low alternating voltage for filaments. Only the most advanced equipment used expensive and bulky regulated power supplies.

AC power supply

An AC power supply typically takes the voltage from a wall outlet (mains supply, often 230v in Europe) and lowers it to the desired voltage (eg 9vac). As well as lowering the voltage some filtering may take place. An example use for an AC power supply is powering certain guitar effects pedals (e.g. the Digitech Whammy pedal) although it is more common for effects pedals to require DC.

Linear regulated power supply

The voltage produced by an unregulated power supply will vary depending on the load and on variations in the AC supply voltage. For critical electronics applications a linear regulator may be used to set the voltage to a precise value, stabilized against fluctuations in input voltage and load. The regulator also greatly reduces the ripple and noise in the output direct current. Linear regulators often provide current limiting, protecting the power supply and attached circuit from overcurrent.

Adjustable linear power supplies are common laboratory and service shop test equipment, allowing the output voltage to be adjusted over a range. For example, a bench power supply used by circuit designers may be adjustable up to 30 volts and up to 5 amperes output. Some can be driven by an external signal, for example, for applications requiring a pulsed output.

AC/DC supply

In the past, mains electricity was supplied as DC in some regions, AC in others. Transformers cannot be used for DC, but a simple, cheap unregulated power supply could run directly from either AC or DC mains without using a transformer. The power supply consisted of a rectifier and a filter capacitor. When operating from DC, the rectifier was essentially a conductor, having no effect; it was included to allow operation from AC or DC without modification.

Switched-mode power supply



A computer's switched mode power supply unit.

A switched-mode power supply (SMPS) works on a different principle. AC input, usually at mains voltage, is rectified without the use of a mains transformer, to obtain a DC voltage. This voltage is then switched on and off at a high speed by electronic switching circuitry, which may then pass through a high-frequency, hence small, light, and cheap, transformer or inductor. The duty cycle of the output square wave increases as power output requirements increase. Switched-mode power supplies are always regulated. If the SMPS uses a properly-insulated high-frequency transformer, the output will be electrically isolated from the mains, essential for safety.

The input power slicing occurs at a very high speed (typically 10 kHz — 1 MHz). High frequency and high voltages in this first stage permit much smaller transformers and smoothing capacitors than in a power supply operating at mains frequency, as linear supplies do. After the transformer secondary, the AC is again rectified to DC. To keep output voltage constant, the power supply needs a sophisticated feedback controller to monitor current drawn by the load.

SMPSs often include safety features such as current limiting or a crowbar circuit to help protect the device and the user from harm. In the event that an abnormal high-current power draw is detected, the switched-mode supply can assume this is a direct short and

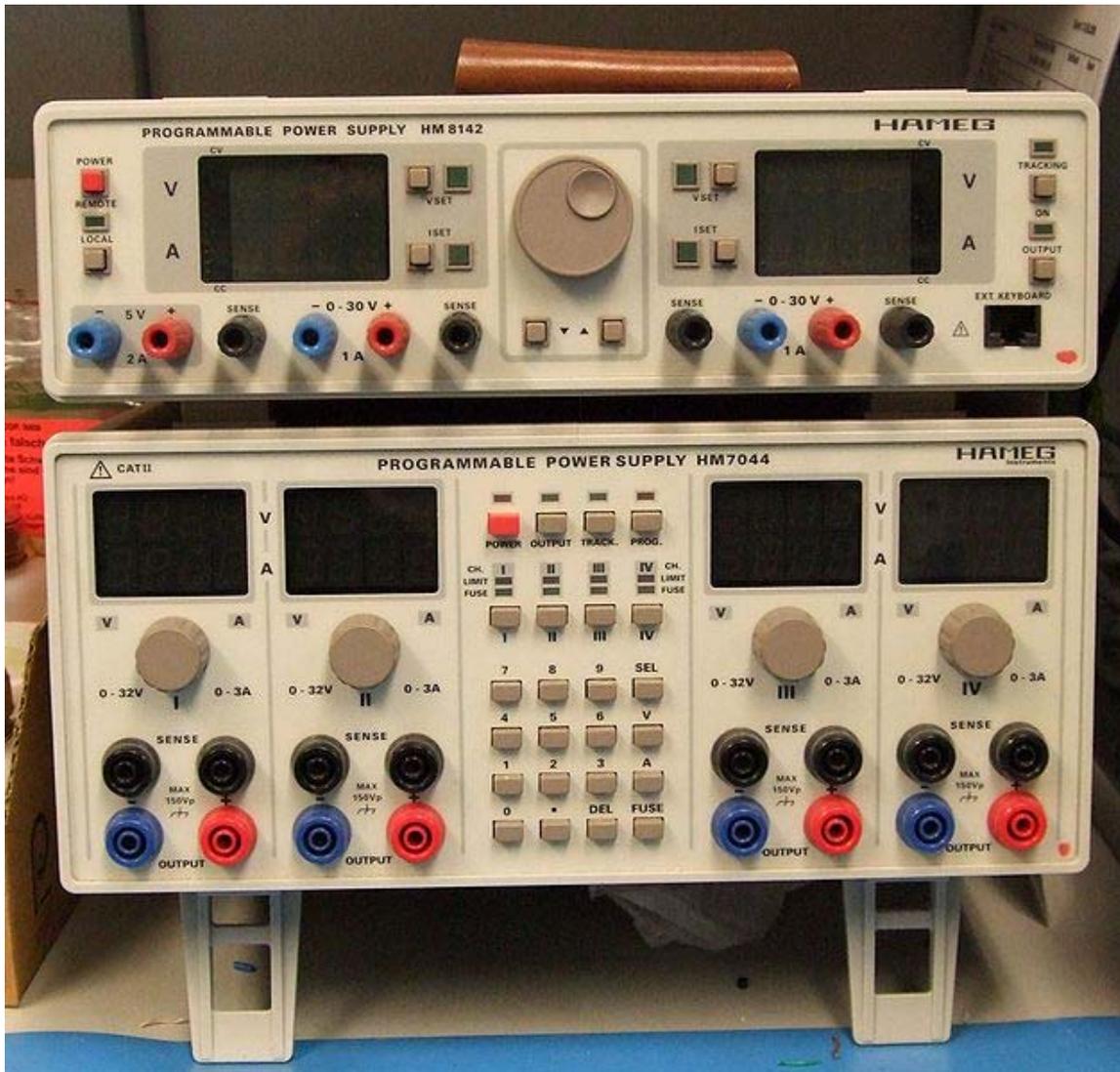
will shut itself down before damage is done. For decades PC power supplies have provided a *power good* signal to the motherboard whose absence prevents operation when abnormal supply voltages are present.

SMPSs have an absolute limit on their minimum current output. They are only able to output above a certain power level and cannot function below that point. In a no-load condition the frequency of the power slicing circuit increases to great speed, causing the isolated transformer to act as a Tesla coil, causing damage due to the resulting very high voltage power spikes. Switched-mode supplies with protection circuits may briefly turn on but then shut down when no load has been detected. A very small low-power dummy load such as a ceramic power resistor or 10-watt light bulb can be attached to the supply to allow it to run with no primary load attached.

Power factor has become a recent issue of concern for computer manufacturers. Switched mode power supplies have traditionally been a source of power line harmonics and have a very poor power factor. Many computer power supplies built in the last few years now include power factor correction built right into the switched-mode supply, and may advertise the fact that they offer *1.0 power factor*.

By slicing up the sinusoidal AC wave into very small discrete pieces, a portion of unused alternating current stays in the power line as very small spikes of power that cannot be utilized by AC motors and results in waste heating of power line transformers. Hundreds of switched mode power supplies in a building can result in poor power quality for other customers surrounding that building, and high electric bills for the company if they are billed according to their power factor in addition to the actual power used. Filtering capacitor banks may be needed on the building power mains to suppress and absorb these negative power factor effects.

Programmable power supply



Programmable power supplies

Programmable power supplies allow for remote control of the output voltage through an analog input signal or a computer interface such as RS232 or GPIB. Variable properties include voltage, current, and frequency (for AC output units). These supplies are composed of a processor, voltage/current programming circuits, current shunt, and voltage/current read-back circuits. Additional features can include overcurrent, overvoltage, and short circuit protection, and temperature compensation. Programmable power supplies also come in a variety of forms including modular, board-mounted, wall-mounted, floor-mounted or bench top.

Programmable power supplies can furnish DC, AC, or AC with a DC offset. The AC output can be either single-phase or three-phase. Single-phase is generally used for low-voltage, while three-phase is more common for high-voltage power supplies.

Programmable power supplies are now used in many applications. Some examples include automated equipment testing, crystal growth monitoring, and differential thermal analysis.

Uninterruptible power supply

An uninterruptible power supply (UPS) takes its power from two or more sources simultaneously. It is usually powered directly from the AC mains, while simultaneously charging a storage battery. Should there be a dropout or failure of the mains, the battery instantly takes over so that the load never experiences an interruption. Such a scheme can supply power as long as the battery charge suffices, e.g., in a computer installation, giving the operator sufficient time to effect an orderly system shutdown without loss of data. Other UPS schemes may use an internal combustion engine or turbine to continuously supply power to a system in parallel with power coming from the AC. The engine-driven generators would normally be idling, but could come to full power in a matter of a few seconds in order to keep vital equipment running without interruption. Such a scheme might be found in hospitals or telephone central offices.

High-voltage power supply

High voltage refers to an output on the order of hundreds or thousands of volts. High-voltage supplies use a linear setup to produce an output voltage in this range.

Additional features available on high-voltage supplies can include the ability to reverse the output polarity along with the use of circuit breakers and special connectors intended to minimize arcing and accidental contact with human hands. Some supplies provide analog inputs (i.e. 0-10V) that can be used to control the output voltage, effectively turning them into high-voltage amplifiers albeit with very limited bandwidth.

Voltage multipliers

Voltage multipliers, as the name implies, are circuits designed to multiply the input voltage. The input voltage may be doubled (voltage doubler), tripled (voltage tripler), quadrupled (voltage quadrupler), etc. Voltage multipliers are also power converters. An AC input is converted to a higher DC output. These circuits allow high voltages to be obtained using a much lower voltage AC source.

Typically, voltage multipliers are composed of half-wave rectifiers, capacitors, and diodes. For example, a voltage tripler consists of three half-wave rectifiers, three capacitors, and three diodes. Full-wave rectifiers may be used in a different configuration to achieve even higher voltages. Also, both parallel and series configurations are available. For parallel multipliers, a higher voltage rating is required at each consecutive multiplication stage, but less capacitance is required. The voltage capability of the capacitor limits the maximum output voltage.

Voltage multipliers have many applications. For example, voltage multipliers can be found in everyday items like televisions and photocopiers. Even more applications can be found in the laboratory, such as cathode ray tubes, oscilloscopes, and photomultiplier tubes.

Power supply applications

Computer power supply

A modern computer power supply is a switch with on and off supply designed to convert 110-240 V AC power from the mains supply, to several output both positive (and historically negative) DC voltages in the range + 12V,-12V,+5V,+5VBs and +3.3V. The first generation of computers power supplies were linear devices, but as cost became a driving factor, and weight became important, switched mode supplies are almost universal.

The diverse collection of output voltages also have widely varying current draw requirements, which are difficult to all be supplied from the same switched-mode source. Consequently most modern computer power supplies actually consist of several different switched mode supplies, each producing just one voltage component and each able to vary its output based on component power requirements, and all are linked together to shut down as a group in the event of a fault condition.

Welding power supply

Arc welding uses electricity to melt the surfaces of the metals in order to join them together through coalescence. The electricity is provided by a *welding power supply*, and can either be AC or DC. Arc welding typically requires high currents typically between 100 and 350 amps. Some types of welding can use as few as 10 amps, while some applications of spot welding employ currents as high as 60,000 amps for an extremely short time. Older welding power supplies consisted of transformers or engines driving generators. More recent supplies use semiconductors and microprocessors reducing their size and weight.

AC adapter



Switched mode mobile phone charger

A linear or switched-mode power supply (or in some cases just a transformer) that is built into the top of a plug is known as a "plug pack", "plug-in adapter", "adapter block", "domestic mains adapter" or just "power adapter". Slang terms include "wall wart" and "power brick". They are even more diverse than their names; often with either the same kind of DC plug offering different voltage or polarity, or a different plug offering the same voltage. "Universal" adapters attempt to replace missing or damaged ones, using multiple plugs and selectors for different voltages and polarities. Replacement power supplies must match the voltage of, and supply at least as much current as, the original power supply.

The least expensive AC units consist solely of a small transformer, while DC adapters include a few additional diodes. Whether or not a load is connected to the power adapter, the transformer has a magnetic field continuously present and normally cannot be completely turned off unless unplugged.

Because they consume standby power, they are sometimes known as "electricity vampires" and may be plugged into a power strip to allow turning them off. Expensive switched-mode power supplies can cut off leaky electrolyte-capacitors, use powerless MOSFETs, and reduce their working frequency to get a gulp of energy once in a while to power, for example, a clock, which would otherwise need a battery.

Overload protection

Power supplies often include some type of overload protection that protects the power supply from load faults (e.g., short circuits) that might otherwise cause damage by overheating components or, in the worst case, electrical fire. Fuses and circuit breakers are two commonly used mechanisms for overload protection.

Fuses

A fuse is a piece of wire, often in a casing that improves its electrical characteristics. If too much current flows, the wire becomes hot and melts. This effectively disconnects the power supply from its load, and the equipment stops working until the problem that caused the overload is identified and the fuse is replaced.

There are various types of fuses used in power supplies.

- fast blow fuses cut the power as quick as they can
- slow blow fuses tolerate more short term overload
- wire link fuses are just an open piece of wire, and have poorer overload characteristics than glass and ceramic fuses

Some power supplies use a very thin wire link soldered in place as a fuse.

Circuit breakers

One benefit of using a circuit breaker as opposed to a fuse is that it can simply be reset instead of having to replace the blown fuse. A circuit breaker contains an element that heats, bends and triggers a spring which shuts the circuit down. Once the element cools, and the problem is identified the breaker can be reset and the power restored.

Thermal cutouts

Some PSUs use a thermal cutout buried in the transformer rather than a fuse. The advantage is it allows greater current to be drawn for limited time than the unit can supply continuously. Some such cutouts are self resetting, some are single use only.

Current limiting

Some supplies use current limiting instead of cutting off power if overloaded. The two types of current limiting used are electronic limiting and impedance limiting. The former is common on lab bench PSUs, the latter is common on supplies of less than 3 watts output.

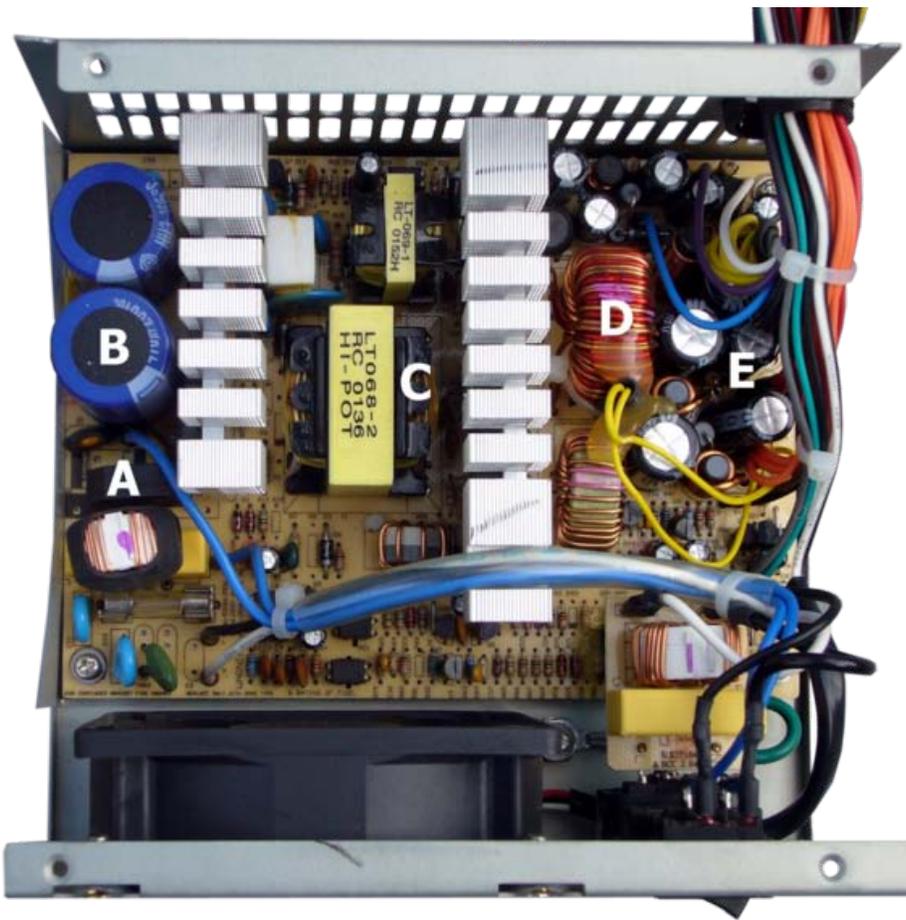
A foldback current limiter reduces the output current to much less than the maximum non-fault current.

Power conversion

The term "**power supply**" is sometimes restricted to those devices that *convert* some other form of energy into electricity (such as solar power and fuel cells and generators). A more accurate term for devices that convert one form of electric power into another form (such as transformers and linear regulators) is power converter. The most common conversion is from AC to DC.

Chapter-2

Switched-mode Power Supply



Interior view of an ATX SMPS: below
A: input EMI filtering; A: bridge rectifier;
B: input filter capacitors;
Between B and C: primary side heat sink;
C: transformer;
Between C and D: secondary side heat sink;

D: output filter coil;

E: output filter capacitors.

The coil and large yellow capacitor below E are additional input filtering components that are mounted directly on the power input connector and are not part of the main circuit board.



An adjustable switched-mode power supply for laboratory use

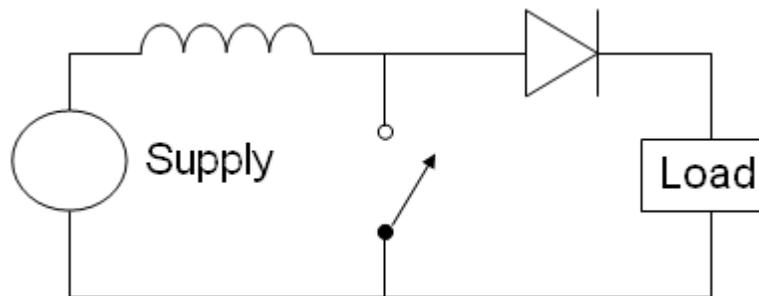
A **switched-mode power supply (switching-mode power supply, SMPS, or simply switcher)** is an electronic power supply that incorporates a switching regulator in order to be highly efficient in the conversion of electrical power. Like other types of power supplies, an SMPS transfers power from a source like the electrical power grid to a load (e.g., a personal computer) while converting voltage and current characteristics. An SMPS is usually employed to efficiently provide a regulated output voltage, typically at a level different from the input voltage.

Unlike a linear power supply, the pass transistor of a switching mode supply switches very quickly (typically between 50 kHz and 1 MHz) between full-on and full-off states, which minimizes wasted energy. Voltage regulation is provided by varying the ratio of on to off time. In contrast, a linear power supply must dissipate the excess voltage to regulate the output. This higher efficiency is the chief advantage of a switch-mode power supply.

Switching regulators are used as replacements for the linear regulators when higher efficiency, smaller size or lighter weight are required. They are, however, more complicated, their switching currents can cause electrical noise problems if not carefully suppressed, and simple designs may have a poor power factor.

Explanation

A linear regulator provides the desired output voltage by dissipating excess power in ohmic losses (e.g., in a resistor or in the collector–emitter region of a pass transistor in its active mode). A linear regulator regulates either output voltage or current by dissipating the excess electric power in the form of heat, and hence its maximum power efficiency is voltage-out/voltage-in since the volt difference is wasted. In contrast, a switched-mode power supply regulates either output voltage or current by switching ideal storage elements, like inductors and capacitors, into and out of different electrical configurations. Ideal switching elements (e.g., transistors operated outside of their active mode) have no resistance when "closed" and carry no current when "open", and so the converters can theoretically operate with 100% efficiency (i.e., all input power is delivered to the load; no power is wasted as dissipated heat).



The basic schematic of a boost converter.

For example, if a DC source, an inductor, a switch, and the corresponding electrical ground are placed in series and the switch is driven by a square wave, the peak-to-peak voltage of the waveform measured across the switch can exceed the input voltage from the DC source. This is because the inductor responds to changes in current by inducing its own voltage to counter the change in current, and this voltage adds to the source voltage while the switch is open. If a diode-and-capacitor combination is placed in parallel to the switch, the peak voltage can be stored in the capacitor, and the capacitor can be used as a DC source with an output voltage greater than the DC voltage driving the circuit. This boost converter acts like a step-up transformer for DC signals. A buck–boost converter works in a similar manner, but yields an output voltage which is opposite in polarity to the input voltage. Other buck circuits exist to boost the average output current with a reduction of voltage.

In an SMPS, the output current flow depends on the input power signal, the storage elements and circuit topologies used, and also on the pattern used (e.g., pulse-width modulation with an adjustable duty cycle) to drive the switching elements. Typically, the

spectral density of these switching waveforms has energy concentrated at relatively high frequencies. As such, switching transients, like ripple, introduced onto the output waveforms can be filtered with small LC filters.

Hydraulic analogy explains the basic principle.

Advantages and disadvantages

The main advantage of this method is greater efficiency because the switching transistor dissipates little power when it is outside of its active region (i.e., when the transistor acts like a switch and either has a negligible voltage drop across it or a negligible current through it). Other advantages include smaller size and lighter weight (from the elimination of low frequency transformers which have a high weight) and lower heat generation due to higher efficiency. Disadvantages include greater complexity, the generation of high-amplitude, high-frequency energy that the low-pass filter must block to avoid electromagnetic interference (EMI), and a ripple voltage at the switching frequency and the harmonic frequencies thereof.

Very low cost SMPSs may couple electrical switching noise back onto the mains power line, causing interference with A/V equipment connected to the same phase. Non-power-factor-corrected SMPSs also cause harmonic distortion.

Classification

SMPSs can be classified into four types according to the input and output waveforms:

- AC in, DC out: rectifier, off-line converter input stage
- DC in, DC out: voltage converter, or current converter, or DC to DC converter
- AC in, AC out: frequency changer, cycloconverter, transformer, phase converter
- DC in, AC out: inverter

SMPS and linear power supply comparison

There are two main types of regulated power supplies available: SMPS and linear. The following table compares linear regulated and unregulated AC-to-DC supplies with switching regulators in general:

Comparison of a linear power supply and a switched-mode power supply

	Linear power supply	Switching power supply	Notes
Size and weight	Heatsinks for high power linear regulators add size and weight. Transformers, if used, are large due to low	Smaller transformer (if used; else inductor) due to higher operating frequency (typically 50 kHz – 1 MHz). Size and weight of adequate RF shielding may be	A transformer's power handling capacity of given size and weight increases with frequency

	operating frequency (mains power frequency is at 50 or 60 Hz); otherwise can be compact due to low component count.	significant.	provided that hysteresis losses can be kept down. Therefore, higher operating frequency means either higher capacity or smaller transformer.
Output voltage	With transformer used, any voltages available; if transformerless, not exceeding input. If unregulated, voltage varies significantly with load.	Any voltages available, limited only by transistor breakdown voltages in many circuits. Voltage varies little with load.	A SMPS can usually cope with wider variation of input before the output voltage changes.
Efficiency, heat, and power dissipation	If regulated: efficiency largely depends on voltage difference between input and output; output voltage is regulated by dissipating excess power as heat resulting in a typical efficiency of 30–40%. If unregulated, transformer iron and copper losses may be the only significant sources of inefficiency.	Output is regulated using duty cycle control; the transistors are switched fully on or fully off, so very little resistive losses between input and the load. The only heat generated is in the non-ideal aspects of the components and quiescent current in the control circuitry.	Switching losses in the transistors (especially in the short part of each cycle when the device is partially on), on-resistance of the switching transistors, equivalent series resistance in the inductor and capacitors, and core losses in the inductor, and rectifier voltage drop contribute to a typical efficiency of 60–70%. However, by optimizing SMPS design (such as choosing the optimal switching frequency, avoiding saturation of inductors, and active

	<p>Unregulated may be simply a diode and capacitor; regulated has a voltage regulating IC or discrete circuit and a noise filtering capacitor; usually a simpler circuit (and simpler feedback loop stability criteria) than switch-mode circuits.</p>	<p>Consists of a controller IC, one or several power transistors and diodes as well as a power transformer, inductors, and filter capacitors. Some design complexities present (reducing noise/interference; extra limitations on maximum ratings of transistors at high switching speeds) not found in linear regulator circuits.</p>	<p>rectification), the amount of power loss and heat can be minimized; a good design can have an efficiency of 95%.</p> <p>In switch-mode mains (AC-to-DC) supplies, multiple voltages can be generated by one transformer core, but that can introduce design/use complications: for example it may place *minimum* output current restrictions on one output. For this SMPSs have to use duty cycle control. One of the outputs has to be chosen to feed the voltage regulation feedback loop (Usually 3.3 V or 5 V loads are more fussy about their supply voltages than the 12 V loads, so this drives the decision as to which feeds the feedback loop. The other outputs usually track the regulated one pretty well). Both need a careful selection of their transformers. Due to the high</p>
Complexity			

			operating frequencies in SMPSs, the stray inductance and capacitance of the printed circuit board traces become important.
Radio frequency interference	Mild high-frequency interference may be generated by AC rectifier diodes under heavy current loading, while most other supply types produce no high-frequency interference. Some mains hum induction into unshielded cables, problematical for low-signal audio.	EMI/RFI produced due to the current being switched on and off sharply. Therefore, EMI filters and RF shielding are needed to reduce the disruptive interference.	Long wires between the components may reduce the high frequency filter efficiency provided by the capacitors at the inlet and outlet. Stable switching frequency may be important.
Electronic noise at the output terminals	Unregulated PSUs may have a little AC ripple superimposed upon the DC component at twice mains frequency (100–120 Hz). Can cause audible mains hum in audio equipment or brightness ripples or banded distortions in analog security cameras.	Noisier due to the switching frequency of the SMPS. An unfiltered output may cause glitches in digital circuits or noise in audio circuits.	This can be suppressed with capacitors and other filtering circuitry in the output stage. With a switched mode PSU the switching frequency can be chosen to keep the noise out of the circuits working frequency band (e.g., for audio systems above the range of human hearing)
Electronic noise at the input terminals	Causes harmonic distortion to the input AC, but relatively little or no high frequency noise.	Very low cost SMPS may couple electrical switching noise back onto the mains power line, causing interference with A/V equipment connected to the same phase. Non power-factor-corrected SMPSs also	This can be prevented if a (properly earthed) EMI/RFI filter is connected between the input terminals and the bridge rectifier.

		cause harmonic distortion.	
Acoustic noise	Faint, usually inaudible mains hum, usually due to vibration of windings in the transformer and/or magnetostriction.	Usually inaudible to most humans, unless they have a fan or are unloaded/malfunctioning, or use a switching frequency within the audio range, or the laminations of the coil vibrate at a subharmonic of the operating frequency.	The operating frequency of an unloaded SMPS is sometimes in the audible human range, and may sound subjectively quite loud for people who have hyperacusis in the relevant frequency range.
Power factor	Low for a regulated supply because current is drawn from the mains at the peaks of the voltage sinusoid, unless a choke-input or resistor-input circuit follows the rectifier (now rare).	Ranging from very low to medium since a simple SMPS without PFC draws current spikes at the peaks of the AC sinusoid.	Active/passive power factor correction in the SMPS can offset this problem and are even required by some electric regulation authorities, particularly in Europe. The internal resistance of low-power transformers in linear power supplies usually limits the peak current each cycle and thus gives a better power factor than many switch-mode power supplies that directly rectify the mains with little series resistance.
Inrush current	Large current when mains-powered linear power supply equipment is switched on until magnetic flux of transformer stabilises and	Extremely large peak "in-rush" surge current limited only by the impedance of the input supply and any series resistance to the filter capacitors.	Empty filter capacitors initially draw large amounts of current as they charge up, with larger capacitors drawing

capacitors charge completely, unless a slow-start circuit is used.

larger amounts of peak current. Being many times above the normal operating current, this greatly stresses components subject to the surge, complicates fuse selection to avoid nuisance blowing and may cause problems with equipment employing overcurrent protection such as uninterruptible power supplies. Mitigated by use of a suitable soft-start circuit or series resistor.

Due to regulations concerning EMI/RFI radiation, many SMPS contain EMI/RFI filtering at the input stage before the bridge rectifier consisting of capacitors and inductors. Two capacitors are connected in series with the Live and Neutral rails with the Earth connection in between the two capacitors. This forms a capacitive divider that energises the

Supplies with transformers allow metalwork to be grounded, safely. Dangerous if primary/secondary insulation breaks down, unlikely with reasonable design. Transformerless mains-operated supply dangerous. In both linear and SM the mains, and possibly the output voltages, are hazardous and must be well-isolated.

Common rail of equipment (including casing) is energised to half mains voltage, but at high impedance, unless equipment is earthed/grounded or doesn't contain EMI/RFI filtering at the input terminals.

Risk of electric shock

Risk of equipment damage

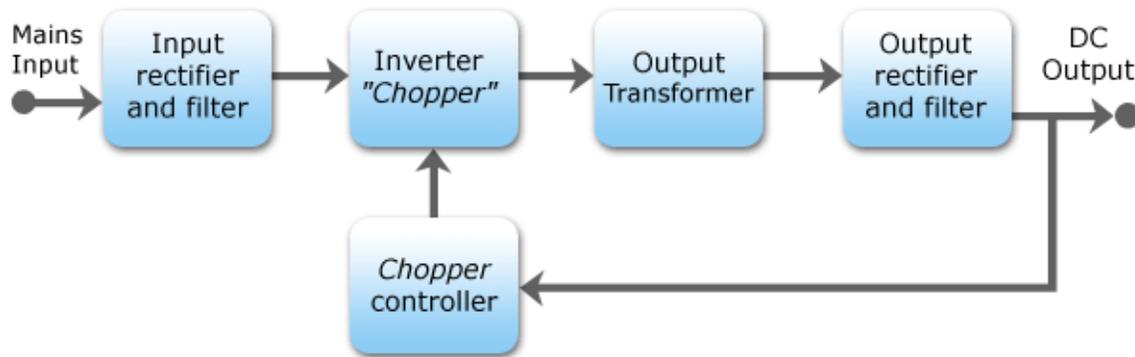
Very low, unless a short occurs between the primary and secondary windings or the regulator fails by shorting internally.

Can fail so as to make output voltage very high. Stress on capacitors may cause them to explode. Can in some cases destroy input stages in amplifiers if floating voltage exceeds transistor base-emitter breakdown voltage, causing the transistor's gain to drop and noise levels to increase. Mitigated by good failsafe design. Failure of a component in the SMPS itself can cause further damage to other PSU components; can be difficult to troubleshoot.

common rail at half mains voltage. Its high impedance current source can provide a tingling or a 'bite' to the operator or can be exploited to light an Earth Fault LED. However, this current may cause nuisance tripping on the most sensitive residual-current devices.

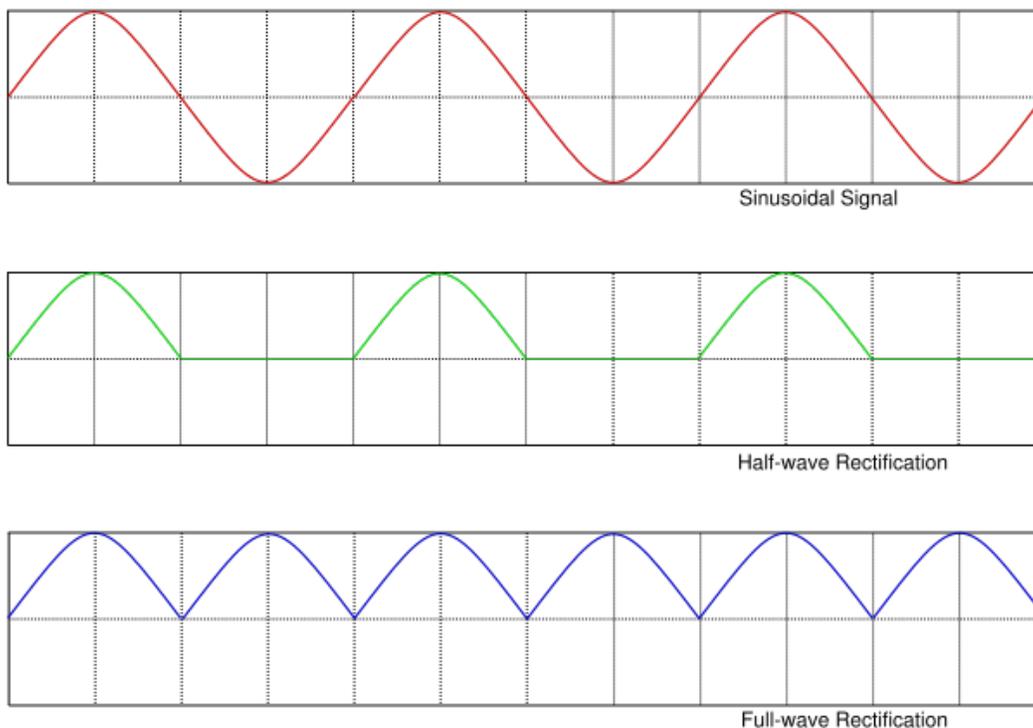
The floating voltage is caused by capacitors bridging the primary and secondary sides of the power supply. A connection to an earthed equipment will cause a momentary (and potentially destructive) spike in current at the connector as the voltage at the secondary side of the capacitor equalises to earth potential.

Theory of operation



Block diagram of a mains operated AC-DC SMPS with output voltage regulation

Input rectifier stage



AC, half-wave and full-wave rectified signals.

If the SMPS has an AC input, then the first stage is to convert the input to DC. This is called *rectification*. The rectifier circuit can be configured as a voltage doubler by the addition of a switch operated either manually or automatically. This is a feature of larger supplies to permit operation from nominally 120 V or 240 V supplies. The rectifier produces an unregulated DC voltage which is then sent to a large filter capacitor. The

current drawn from the mains supply by this rectifier circuit occurs in short pulses around the AC voltage peaks. These pulses have significant high frequency energy which reduces the power factor. Special control techniques can be employed by the following SMPS to force the average input current to follow the sinusoidal shape of the AC input voltage thus the designer should try correcting the power factor. An SMPS with a DC input does not require this stage. An SMPS designed for AC input can often be run from a DC supply (for 230 V AC this would be 330 V DC), as the DC passes through the rectifier stage unchanged. It's however advisable to consult the manual before trying this, though most supplies are quite capable of such operation even though nothing is mentioned in the documentation. However, this type of use may be harmful to the rectifier stage as it will only use half of diodes in the rectifier for the full load. This may result in overheating of these components, and cause them to fail prematurely.

If an input range switch is used, the rectifier stage is usually configured to operate as a voltage doubler when operating on the low voltage (~120 V AC) range and as a straight rectifier when operating on the high voltage (~240 V AC) range. If an input range switch is not used, then a full-wave rectifier is usually used and the downstream inverter stage is simply designed to be flexible enough to accept the wide range of DC voltages that will be produced by the rectifier stage. In higher-power SMPSs, some form of automatic range switching may be used.

Inverter stage

The inverter stage converts DC, whether directly from the input or from the rectifier stage described above, to AC by running it through a power oscillator, whose output transformer is very small with few windings at a frequency of tens or hundreds of kilohertz (kHz). The frequency is usually chosen to be above 20 kHz, to make it inaudible to humans. The output voltage is optically coupled to the input and thus very tightly controlled. The switching is implemented as a multistage (to achieve high gain) MOSFET amplifier. MOSFETs are a type of transistor with a low on-resistance and a high current-handling capacity.

Voltage converter and output rectifier

If the output is required to be isolated from the input, as is usually the case in mains power supplies, the inverted AC is used to drive the primary winding of a high-frequency transformer. This converts the voltage up or down to the required output level on its secondary winding. The output transformer in the block diagram serves this purpose.

If a DC output is required, the AC output from the transformer is rectified. For output voltages above ten volts or so, ordinary silicon diodes are commonly used. For lower voltages, Schottky diodes are commonly used as the rectifier elements; they have the advantages of faster recovery times than silicon diodes (allowing low-loss operation at higher frequencies) and a lower voltage drop when conducting. For even lower output voltages, MOSFETs may be used as synchronous rectifiers; compared to Schottky diodes, these have even lower conducting state voltage drops.

The rectified output is then smoothed by a filter consisting of inductors and capacitors. For higher switching frequencies, components with lower capacitance and inductance are needed.

Simpler, non-isolated power supplies contain an inductor instead of a transformer. This type includes *boost converters*, *buck converters*, and the *buck-boost converters*. These belong to the simplest class of single input, single output converters which use one inductor and one active switch. The buck converter reduces the input voltage in direct proportion to the ratio of conductive time to the total switching period, called the duty cycle. For example an ideal buck converter with a 10 V input operating at a 50% duty cycle will produce an average output voltage of 5 V. A feedback control loop is employed to regulate the output voltage by varying the duty cycle to compensate for variations in input voltage. The output voltage of a boost converter is always greater than the input voltage and the buck-boost output voltage is inverted but can be greater than, equal to, or less than the magnitude of its input voltage. There are many variations and extensions to this class of converters but these three form the basis of almost all isolated and non-isolated DC to DC converters. By adding a second inductor the Ćuk and SEPIC converters can be implemented, or, by adding additional active switches, various bridge converters can be realised.

Other types of SMPSs use a capacitor-diode voltage multiplier instead of inductors and transformers. These are mostly used for generating high voltages at low currents (*Cockcroft-Walton generator*). The low voltage variant is called charge pump.

Regulation

A feedback circuit monitors the output voltage and compares it with a reference voltage, which shown in the block diagram serves this purpose. Depending on design/safety requirements, the controller may contain an isolation mechanism (such as opto-couplers) to isolate it from the DC output. Switching supplies in computers, TVs and VCRs have these opto-couplers to tightly control the output voltage.

Open-loop regulators do not have a feedback circuit. Instead, they rely on feeding a constant voltage to the input of the transformer or inductor, and assume that the output will be correct. Regulated designs compensate for the impedance of the transformer or coil. Monopolar designs also compensate for the magnetic hysteresis of the core.

The feedback circuit needs power to run before it can generate power, so an additional non-switching power-supply for stand-by is added.

Transformer design

SMPS transformers run at high frequency. Most of the cost savings (and space savings) in off-line power supplies come from the fact that a high frequency transformer is much smaller than the 50/60 Hz transformers formerly used. There are additional design tradeoffs.

Transformer size

The higher the switching frequency, the lesser the amount of energy that needs to be stored intermediately during the time of a single switching cycle. Because this energy is stored in form of magnetic energy in the transformer core material (like ferrite), less of such material is needed.

However, higher frequency also means more energy lost during transitions of the switching semiconductor. Furthermore, much more attention to the physical layout of the circuit board is required, and the amount of electromagnetic interference will be more pronounced.

Core loss

There are several differences in the design of transformers for 50 Hz vs 500 kHz. Firstly a low frequency transformer usually transfers energy through its core (soft iron), while the (usually ferrite) core of a high frequency transformer limits leakage.

Copper loss

At low frequencies (such as the line frequency of 50 or 60 Hz), designers can usually ignore the skin effect. At line frequencies, the skin effect becomes important when the conductors have a diameter larger than about 0.3 inches (7.6 mm).

Switching power supplies must pay more attention to the skin effect because it is a source of power loss. At 500 kHz, the skin depth is about 0.003 inches (0.076 mm) – a dimension smaller than the typical wires used in a power supply.

The skin effect is exacerbated by the harmonics present in the switching waveforms. The appropriate skin depth is not just the depth at the fundamental, but also the skin depths at the harmonics.

Since the waveforms in a SMPS are generally high speed (PWM square waves), the wiring must be capable of supporting high harmonics of the base frequency due to skin effect.

In addition to the skin effect, there is also a proximity effect, which is another source of power loss.

Power factor

Simple off-line switched mode power supplies incorporate a simple full wave rectifier connected to a large energy storing capacitor. Such SMPSs draw current from the AC line in short pulses when the mains instantaneous voltage exceeds the voltage across this capacitor. During the remaining portion of the AC cycle the capacitor provides energy to the power supply.

As a result, the input current of such basic switched mode power supplies has high harmonic content and relatively low power factor. This creates extra load on utility lines, increases heating of the utility transformers and standard AC electric motors, and may cause stability problems in some applications such as in emergency generator systems or aircraft generators. Harmonics can be removed through the use of filter banks but the filtering is expensive, and the power utility may require a business with a very low power factor to purchase and install the filtering onsite.

Unlike displacement power factor created by linear inductive or capacitive loads, this distortion cannot be corrected by addition of a single linear component. Additional circuits are required to counteract the effect of the brief current pulses.

In 2001, the European Union put into effect the standard IEC/EN61000-3-2 to set limits on the harmonics of the AC input current up to the 40th harmonic for equipment above 75 W. The standard defines four classes of equipment depending on its type and current waveform. The most rigorous limits (class D) are established for personal computers, computer monitors, and TV receivers. In order to comply with these requirements modern switched-mode power supplies normally include an additional power factor correction (PFC) stage.

Putting a current regulated boost chopper stage after the off-line rectifier (to charge the storage capacitor) can correct the power factor, but increases the complexity (and any cost).

Types

Switched-mode power supplies can be classified according to the circuit topology. The most important distinction is between isolated converters and non-isolated ones.

Non-isolated topologies

Non-isolated converters are simplest, with the three basic types using a single inductor for energy storage. In the voltage relation column, D is the duty cycle of the converter, and can vary from 0 to 1. V_{in} is assumed to be greater than zero; if it is negative, negate V_{out} to match.

Type	Power [W]	Typical efficiency	Relative cost	Energy storage	Voltage relation	Features
Buck	0–1,000	80–90%	1.0	Single inductor	$0 \leq \text{Out} \leq \text{In}$, $V_2 = DV_1$	Current is continuous at output.
Boost	0–150	70%	1.0	Single inductor	$\text{Out} \geq \text{In}$, $V_2 = \frac{1}{1-D} V_1$	Current is continuous at input.
Buck-boost	0–150	78%	1.0	Single inductor	$\text{Out} \leq 0$, $V_2 = -\frac{D}{1-D} V_1$	Current is discontinuous at both input and output.

Split-pi (or, boost-buck)	0–2,000	96%	>2.0	Two inductors and three capacitors	Up or down	Bidirectional power control; in or out
Ćuk				Capacitor and two inductors	Any inverted, $V_2 = -\frac{D}{1-D} V_1$	Current is continuous at input <i>and</i> output
SEPIC				Capacitor and two inductors	Any, $V_2 = \frac{D}{1-D} V_1$	Current is continuous at input
Zeta				Capacitor and two inductors	Any, $V_2 = \frac{D}{1-D} V_1$	Current is continuous at output
Charge pump				Capacitors only		Low performance. Like a CW multiplier, the disadvantages of charge pumps for power conversion can be somewhat mitigated through proper component sizing and drive frequency, since output energy is proportional to capacitance and frequency.

When equipment is human-accessible, voltage and power limits of <42.5 V and 8.0 A limit apply for UL, CSA, VDE approval.

The buck, boost, and buck-boost topologies are all strongly related. Input, output and ground come together at one point. One of the three passes through an inductor on the way, while the other two pass through switches. One of the two switches must be active (e.g., a transistor), while the other can be a diode. Sometimes, the topology can be changed simply by re-labeling the connections. A 12 V input, 5 V output buck converter can be converted to a 7 V input, –5 V output buck-boost by grounding the *output* and taking the output from the *ground* pin.

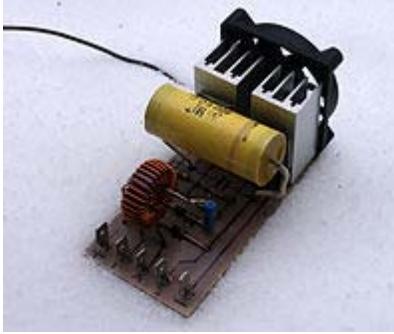
Likewise, SEPIC and Zeta converters are both minor rearrangements of the Ćuk converter.

Switchers become less efficient as duty cycles become extremely short. For large voltage changes, a transformer (isolated) topology may be better.

Isolated topologies

All isolated topologies include a transformer, and thus can produce an output of higher or lower voltage than the input by adjusting the turns ratio. For some topologies, multiple windings can be placed on the transformer to produce multiple output voltages. Some converters use the transformer for energy storage, while others use a separate inductor.

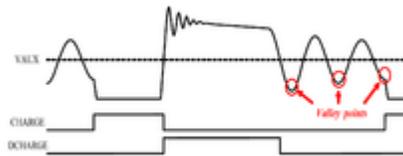
Type	Power [W]	Typical efficiency	Relative cost	Input range [V]	Energy storage	Features
Flyback	0–250	78%	1.0	5–600	Transformer	Isolated form of the buck-boost converter. ¹
Ringing choke converter (RCC)	0–150	78%	1.0	5–600	Transformer	Low-cost self-oscillating flyback variant.
Half-forward	0–250	75%	1.2	5–500	Inductor	
Forward ²	100–200	78%		60–200	Inductor	Isolated form of buck converter Single rail input, unregulated output, high efficiency, low EMI.
Resonant forward	0–60	87%	1.0	60–400	Inductor and capacitor	
Push-pull	100–1,000	72%	1.75	50–1,000	Inductor	
Half-bridge	0–2,000	72%	1.9	50–1,000	Inductor	
Full-bridge	400–5,000	69%	>2.0	50–1,000	Inductor	Very efficient use of transformer, used for highest powers.
Resonant, zero voltage switched	>1,000		>2.0			
Isolated Ćuk					Two capacitors and two inductors	



Zero voltage switched power supplies require only small heatsinks as little energy is lost as heat. This allows them to be small too; this ZVS can handle powers in excess of 1 kilowatt. Transformer is not shown.

- ^1 Flyback converter logarithmic control loop behaviour might be harder to control than other types.
- ^2 The forward converter has several variants, varying in how the transformer is "reset" to zero magnetic flux every cycle.

Quasi-resonant zero-current/zero-voltage switch



Quasi-resonant switching switches when the voltage is at a minimum and a valley is detected

A quasi-resonant zero-current/zero-voltage switch (ZCS/ZVS) where "each switch cycle delivers a quantized 'packet' of energy to the converter output, and switch turn-on and turn-off occurs at zero current and voltage, resulting in an essentially lossless switch." Quasi-resonant switching, also known as *valley switching*, reduces EMI in the power supply by two methods:

1. By switching the bipolar switch when the voltage is at a minimum (in the valley) to minimize the hard switching effect that causes EMI.
2. By switching when a valley is detected, rather than at a fixed frequency, introduces a natural frequency jitter that spreads the RF emissions spectrum and reduces overall EMI.

Efficiency and EMI

Higher input voltage and synchronous rectification mode makes the conversion process more efficient; the power consumption of the controller also has to be taken into account. Higher switch frequency allows component sizes to be shrunk, but can produce more

radio frequency (RF) interference. A resonant forward converter produces the lowest EMI of any SMPS approach because it uses a soft-switching resonant waveform compared with conventional hard switching.

Failure modes

Power supplies which use capacitors suffering from the capacitor plague may experience premature failure when the capacitance drops to 4% of the original value. This usually cause the switching semiconductor to fail in a conductive way. That may expose connected loads to the full input volt and current, and precipitate wild oscillations in output.

Failure of the switching transistor is common. Due to the large switching voltages this transistor must handle (around 325 V for a 230 V_{AC} mains supply), these transistors often short out, in turn immediately blowing the main internal power fuse.

Precautions

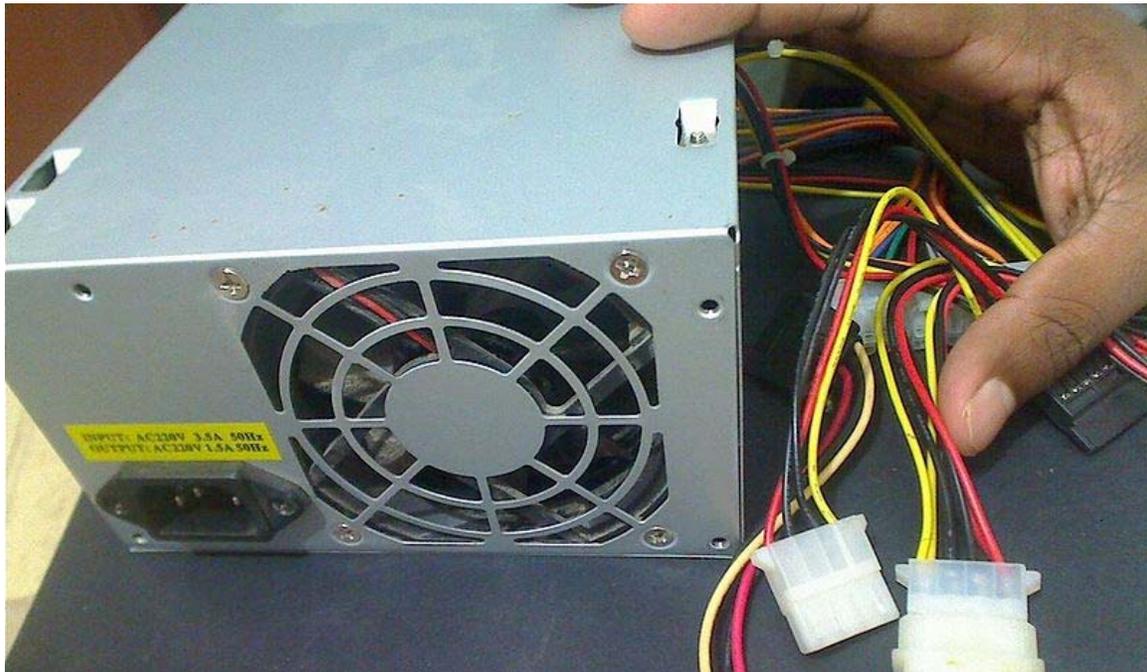
The main filter capacitor will often store up to 325 V long after the power cord has been removed from the wall. Not all power supplies contain a small "bleeder" resistor to slowly discharge this capacitor. Any contact with this capacitor may result in a severe electrical shock.

The primary and secondary side may be connected with an capacitor to reduce EMI and compensate for various capacitive couplings in the converter circuit, where the transformer is one. This may result in electric shock in some cases. The current flowing from line or neutral through a 2000 Ω resistor to any accessible part must according to IEC 60950 be less than 250 μ A for IT equipment.

Applications



Switched mode mobile phone charger



A 450 Watt SMPS for use in personal computers with the power input, fan, and output cords visible

Switched-mode power supply units (PSUs) in domestic products such as personal computers often have universal inputs, meaning that they can accept power from most

mains supplies throughout the world, with rated frequencies from 50 Hz to 60 Hz and voltages from 100 V to 240 V (although a manual voltage range switch may be required). In practice they will operate from a much wider frequency range and often from a DC supply as well.

In 2006, at an Intel Developers Forum, Google engineers proposed the use of a single 12 V supply inside PCs, due to the high efficiency of switch mode supplies directly on the PCB.

Most modern desktop and laptop computers also have a voltage regulator module—a DC–DC converter on the motherboard to step down the voltage from the power supply or the battery to the CPU core voltage, which is as low as 0.8 V for a low voltage CPU to 1.2–1.5 V for a desktop CPU as of 2007. Some motherboards have a setting in the BIOS that allows overclockers to set a new CPU core voltage; other motherboards support dynamic voltage scaling which constantly adjust the CPU core voltage. Most laptop computers also have a DC–AC converter to step up the voltage from the battery to drive a CCFL backlight in the flat-screen monitor, which typically requires around 1 kV_{RMS}.

Due to their high volumes mobile phone chargers have always been particularly cost sensitive. The first chargers were linear power supplies but they quickly moved to the cost effective ringing choke converter (RCC) SMPS topology, when new levels of efficiency were required. Recently the demand for even lower no load power requirements in the application has meant that flyback topology is being used more widely; primary side sensing flyback controllers are also helping to cut the bill of materials (BOM) by removing secondary-side sensing components such as optocouplers.

Where integration of capacitors for stabilization and batteries as a energy storage or hum and interference needs to be avoided in the power distribution, SMPS may be essential for efficient conversion of electric DC energy. For AC applications where frequency and voltage can't be produced by the primary source an SMPS may be essential as well. Applications may be found in the automobile industry where ordinary trucks uses nominal 24 V_{DC} but may need 12 V_{DC}. Ordinary cars use nominal 12 V_{DC} and may need to convert this to drive equipment. In industrial settings, DC supply is sometimes chosen to avoid hum and interference and ease the integration of capacitors and batteries used to buffer the voltage that makes SMPS essential.

Terminology

The term switchmode was widely used until Motorola claimed ownership of (but did not register) the trademark SWITCHMODE, for products aimed at the switching-mode power supply market, and started to enforce their trademark. *Switching-mode power supply*, *switching power supply*, and *switching regulator* refer to this type of power supply.

Chapter-3

AC Adapter



AC adapter plugged into Australian wall socket

The **AC adapter**, **AC/DC adapter** or **AC/DC converter** is a type of external power supply, often enclosed in what looks like an over-sized AC plug. Other names include **plug pack**, **plug-in adapter**, **adapter block**, **domestic mains adapter**, **line power**

adapter, or **power adapter**. Informal terms include **wall wart**, **wall cube** and **power brick**. AC adapters are typically used with electrical devices that do not contain their own internal power supply. The internal circuitry of an external power supply is very similar to the design that would be used for a built-in or internal supply, but there are several advantages of separating the power supply from the main body of the electronic device, as explained below.

Modes of operation



An AC adapter disassembled to reveal a simple unregulated DC supply circuit.

Originally, AC adapters were linear power supplies, containing a transformer to convert the mains electricity voltage to a lower voltage, a rectifier to convert it to pulsating DC, and a filter to smooth the pulsating waveform to DC, with residual ripple variations small enough not to affect the device being powered. Size and weight of the device was largely determined by the transformer, which in turn was determined by the power output and mains frequency. Ratings over a few watts made the devices too large and heavy to be physically supported by a wall outlet. The output voltage of these adapters varied with load; for equipment requiring a more stable voltage, linear voltage regulator circuitry was added. Losses in the transformer and the linear regulator were considerable; efficiency was relatively low, and significant power dissipated as heat even when not driving a load.

More recently, switched-mode power supplies (SMPSs) have become almost ubiquitous for this purpose. Mains voltage is rectified to a high direct voltage driving a switching circuit, which has a transformer operating at a high frequency and outputs direct current at the desired voltage. The high-frequency ripple is more easily filtered out than mains-frequency. The high frequency allows the transformer to be small, which reduces its losses; and the switching regulator is more efficient than a linear regulator. The result is a much more efficient, smaller, and lighter device. Safety is ensured, same as in the older circuit, because the transformer electrically isolates the output from the mains.

Unless very carefully designed and using suitable components, switching adapters can be more likely to fail than the older type, due in part to complex circuitry and the use of semiconductors. Unless designed well, these adapters may be easily damaged by overloads, even transient ones, which can come from lightning, brief mains overvoltage (sometimes caused by an incandescent light failing), component degradation, etc. A very common mode of failure is due to the use of electrolytic capacitors whose equivalent series resistance (ESR) increases with age; switching regulators are very sensitive to high ESR (the older circuit also used electrolytic capacitors, but the effect of degradation is much less dramatic). Well-designed circuits pay attention to the ESR, ripple current rating, pulse operation, and temperature rating of capacitors. Sometimes circuit designers design SMPSs, and accountants then cut the cost by replacing components such as capacitors with cheaper ones with the same headline characteristics but worse ESR, etc. The cost-reduced power supply may appear to be just as functional as before, but then suffers a high failure rate after a few years.

Advantages

External AC adapters are widely used to power small or portable electronic devices, because of a number of advantages:

- **Safety** — External power adapters can free product designers from worrying about some safety issues. The designer builds a product to run off a low voltage (usually supplied through a coaxial power connector) and does not have to worry about hazardous voltages inside the product enclosure. External power supplies tested and certified by safety agencies such as Underwriters Laboratories (UL) and DIN allow a low-power electronic product to be produced and later modified as needed, without requiring expensive and time-consuming recertification each time a design is changed. Nevertheless, care should be taken if more than a few watts are supplied to a product, even at low voltages, since a malfunction could still start a fire. Thus, an internal fuse, circuit breaker, or thermal limiter may be useful in a powered product, even when a safety-certified external power supply is used. An external, removable AC adapter can be used to help achieve a design with intrinsic safety.
- **Heat reduction** — Heat reduces reliability and longevity of electronic components, and can cause sensitive circuits to drift or malfunction. A separately-

enclosed power supply moves what is often the primary source of heat to a cables-length distance.

- Electrical noise reduction — Because radiated electrical noise falls off with the inverse square of the distance, it is advantageous to convert potentially-noisy AC line power or automotive power to "clean", filtered DC in an external adapter, at a safe distance from noise-sensitive circuitry.
- Weight reduction — When most power adapters were simple transformer-based designs, they were quite heavy, and would have added considerably to the weight of portable or hand-held devices. Even modern light-weight switching circuits for AC line power still would add appreciable weight to hand-held devices, whose design weight budget is often denominated in grams. Moving these heavy power-handling components to a separate power supply reduces the dead weight of parts that are only in use during a battery charging cycle.
- Size reduction — The physical bulk of power supply components can be shed from portable or handheld devices, slimming them considerably.
- Ease of replacement — Power supplies are prone to failure, due to their exposure to power spikes and their internal generation of waste heat. External power supplies exemplify the design principle of modularity, in that they can be easily unplugged and replaced if they should fail.
- Configuration versatility — Externally-powered electronic products can be used with different power sources as needed (e.g. 120VAC, 240VAC, 12VDC, or external battery pack), for convenient use in the field, or when traveling.
- Simplified product inventory and distribution — An electronic product that is sold and used internationally must be powered from a wide range of power sources, and must meet product safety regulations in many jurisdictions. The configuration modularity enabled by a separate, external power supply and/or power cord allow satisfying these diverse power requirements with a small number of product SKUs, reducing product inventory costs and overhead costs of warehousing and distribution.

Problems



"Power brick" in-line configuration, with detachable AC cord at left

Whilst useful for many purposes, some external AC adapters have attracted criticism. Problems with this type of power supply may include:

- Size — The power supply may obscure other power sockets; some power strips attempt to relieve this problem by varying the spacing between their sockets.
- Weight — Some AC adapters can be heavy, exerting excess weight on the plug socket (this depends on the socket design of the country in question). Some external power supplies are "power bricks" having a short AC cord so they can lie on the floor, thus relieving strain, at the expense of clutter. Other wall-hanging types are made long and thin, minimizing the leverage of their weight vector that pulls the plug out, at the expense of exacerbating the size problem. Heavy adapters are a burden on travelers, especially if several different ones must be carried for various equipment.
- Inefficiency — Some AC adapters, especially older linear power supplies, waste significant electrical energy while in use, or even when the powered device is not in use or disconnected.
- Confusion — Some consumers are unable to choose or obtain a suitable replacement AC adapter for a given small appliance. This can result in the large scale discarding of "orphaned" adapters and equipment which have been separated from each other. The sheer number of partially incompatible adapters in use can be overwhelming, especially in the absence of clear labeling. Still worse, mismatching of adapters can cause severe equipment damage, or even fire.

Efficiency



Millions of still-usable AC power adapters are thrown out annually, because of poor compatibility with new equipment.

The issue of inefficiency of some power supplies has become more well known, with US president George W. Bush referring in 2001 to such devices as "Energy Vampires". Legislation is being enacted in the EU and a number of states, including California, to reduce the level of energy wasted by some of these devices.

But others have argued that these inefficient devices are low powered, e.g., devices that are used for small battery chargers, so even if they have a low efficiency, the amount of energy they waste is less than 1% of household consumption of electric energy.

Considering the total efficiency of power supplies for small electronic equipment, the older mains-frequency linear transformer-based power supply was found in a 2002 report to have efficiencies from 20–75%, and have considerable energy loss even when powered up but not supplying power. Switched-mode power supplies (SMPSs) are much more efficient; a good design can be 80–90% efficient, and is also much smaller and lighter. In

2002 most external plug-in "wall wart" power adapters commonly used for low-power consumer electronics devices were of linear design, as well as supplies built into some equipment. External supplies are usually left plugged in even when not in use, and consume from a few watts to 35 watts of power in that state. The report concluded that about 32 billion kilowatt-hours (kWh) per year, about 1% of total electrical energy consumption, could be saved in the United States by replacing all linear power supplies (average efficiency 40–50%) with advanced switching designs (efficiency 80–90%), by replacing older switching supplies (efficiencies of less than 70%) with advanced designs (efficiency of at least 80%), and by reducing standby consumption of supplies to not more than 1 watt.

Since the report was published, SMPSs have indeed replaced linear supplies to a great extent, even in wall warts. The 2002 report estimated that 6% of electrical energy used in the US "flows through" power supplies (not counting only the wall warts). The website where the report was published said in 2010 that despite the spread of SMPSs, "today's power supplies consume at least 2% of all U.S. electricity production. More efficient power supply designs could cut that usage in half"

Since wasted electrical energy is released as heat, an inefficient power supply is hot to the touch, as is one that wastes power without an electrical load. This waste heat is itself a problem in warm weather, since it often requires additional air conditioning to remove the unwanted heat.

Reuse



"Universal" DC power adapter, with a cigarette lighter power plug for obtaining power from an automobile.

AC adapters are often reused on other appliances, but there are 5 parameters which all must suit the appliance:

- Voltage
- Current capacity
- Polarity (or AC)
- Voltage regulation (or stabilization)
- Connector type

"Universal" adapters are available on which the user can adjust these parameters.

Universal power adapters



A six-way connector on a "universal" DC power supply, consisting of a 4-way X connector and two separate individual connectors. The X-connector here provides 3.5 and 2.5 mm phone plugs and two sizes of coaxial power connector

One inherent disadvantage of *external* power adapters is that they can get separated from the product they are intended to power. Consequently, there is a market for replacement adapters. In addition, failed power supplies must be replaced. Not only must the replacement match voltage, current, and polarity requirements, but it must also match the connector. Many electrical products are poorly labeled with information about the power supply they require, so it is prudent to record the specifications of the original power supply in advance, to ease replacement if the original is later lost. Careful labeling of power adapters can also reduce the likelihood of a disastrous mixup which could cause equipment damage.

Some so-called "universal" replacement power supplies allow the voltage and polarity to be switched, which can ease the matching problem. In addition, the power connector must be matched.

Four-way **X connectors** or six-way **star connectors**, also known as **spider connectors**, with multiple plug sizes and types are common on generic power supplies. Other replacement power supplies have arrangements for changing the power connector, with from four to nine different alternatives available when purchased in a set. RadioShack sells universal AC adapters of various capacities, branded as "Enercell Adaptaplug", and fitted with 2-pin female sockets compatible with their Adaptaplug connector lineup. This allows many different configurations of AC adapters to be put together, without requiring soldering. Philmore and other competing brands offer similar AC adapters with interchangeable connectors.

A suitable power supply for a particular use must have the matching plug dimensions, the matching DC (or AC) voltage and polarity, and the ability to supply at least the required current. The input voltage must match the wall socket (115/230 VAC at 60/50 Hz) or other power source, such as 12VDC automotive battery power.

But the label on a power supply may not be a reliable guide to the actual voltage it supplies under varying conditions. Most low-cost power supplies are "unregulated", in that their voltage can change appreciably with load. If they are lightly loaded, they may put out much more than the nominal "name plate" voltage, which could damage the load. If they are heavily loaded, the output voltage may droop appreciably, in some cases well below the nominal label voltage even within the nominal rated current, causing the equipment being supplied to malfunction or be damaged. Cheap external power supplies of traditional design with undersized transformers tend to have poor regulation, whether originally-supplied or replacement units.

In general, more modern high-quality switched-mode power supplies (SMPSs) are smaller, more efficient, and put out a much more constant voltage even as the input voltage and the load current may vary. Configurable switched-mode power supplies have come down considerably in price, and they are especially convenient for use when traveling because of their decreased weight and size.

Standards



AC adapters capable of powering USB devices. Automotive 12VDC models are also available (not shown).

A de facto standard has emerged in low-power AC adapters, namely the USB connector. Although the original purpose of this design was to enable serial digital data exchange, the USB standard also provided the option of providing 5VDC power, up to 500mA per device. This standard has become sufficiently widespread that numerous accessory gadgets ("USB decorations") are available which connect to USB only for DC power, and not for data interchange. Electric fans, lamps, alarms, coffee warmers, battery chargers, and even toys have been designed to tap power from a USB connector. Plug-in adapters are widely available to convert 115VAC or 230VAC power or 12VDC automotive power to 5VDC USB power.

Portable "USB chargers" are available which convert energy from an internal battery to deliver DC power via a standard USB connector, which can be used to power a variety of portable electronics (e.g. MP3 player, cellphone). There is even a popular DIY Open Hardware USB charger which can be built from a kit. Also, pocket-sized portable "USB battery packs" are available which can charge from a powered USB port, and can later in turn provide power from their own USB port.

The trend towards more-compact electronic devices has driven a shift towards the micro-USB connector, which is identical in function to the original USB connector but physically smaller. In 2009, the International Telecommunication Union (ITU) announced adoption of a world standard based on the micro-USB connector and interchangeable chargers for standards-compliant cellphones. This should markedly reduce the profusion of non-interchangeable power adapters previously needed for each year's new crop of cellphone models.

Note that the previous assertions regarding USB power and the micro-USB charger standards are fairly-well documented in the USB article, and interested readers are referred there for much more detailed information.

Substitutes

A "Green Plug" system has been proposed, based on USB technology, by which the consuming device would tell the external power supply what kind of power is needed. Some commercial adapters, for example those by iGo, already automatically set their output according to which of a range of interchangeable tips is fitted; tips are available to fit and supply appropriate power to many notebook computers and mobile devices. Adapters can be manufactured to operate from any AC mains supply anywhere in the world (however iGo products are not available in many countries, including Australia) with an appropriate interchangeable plug and voltage-tolerant circuitry, and also operate from 12V DC vehicle supplies—a truly universal device.

Larry Page, a founder of Google, has proposed a 12V 15A standard for almost all equipment requiring an external converter. New buildings would also have 12V DC wiring, so that in effect the AC adapter would be built into the wall.

Chapter-4

80 PLUS

80 PLUS is an initiative to promote energy efficiency in computer power supply units (PSU). It certifies products that have more than 80% energy efficiency at 20%, 50% and 100% of rated load, and a power factor of 0.9 or greater at 100% load. That is, PSUs that waste 20% or less electric energy as heat at the specified load levels, thus reducing electricity use and bills compared to less efficient PSUs. Sometimes rebates are given for manufacturers who use 80 PLUS-certified PSUs.

History

- Ecos & EPRI develop the Generalized Internal Power Supply Efficiency Test Protocol for desktop derived multi-output power supplies
- In March 2004 the 80 PLUS idea was presented as an initiative at the ACEEE Market Transformation Symposium.
- In February 2005 the first market ready power supply was created by Seasonic.
- In 2006 Energy Star added 80 PLUS requirements to their upcoming (in effect since July 2007) Energy Star 4.0 computer specifications.
- In November and February 2006 HP and Dell certify their PSUs to the 80 PLUS spec.
- July 20, 2007 — ENERGY STAR Computer Specification 4.0 goes into effect. The specification includes 80 PLUS power supply efficiency levels for desktop computers.
- December 2007 — over 200 PSUs on the market are 80 PLUS certified and it is becoming the market standard.
- First quarter 2008 — Standards revised to add Bronze, Silver and Gold higher efficiency level certifications.
- October 2009 - Added specification for Platinum efficiency level.

Efficiency level certifications

80 PLUS Test Type	115V Internal Non-Redundant			230V Internal Redundant		
	20%	50%	100%	20%	50%	100%
80 PLUS	80%	80%	80%	Not defined		
80 PLUS Bronze	82%	85%	82%	81%	85%	81%
80 PLUS Silver	85%	88%	85%	85%	89%	85%
80 PLUS Gold	87%	90%	87%	88%	92%	88%
80 PLUS Platinum	90%	92%	89%	90%	94%	91%

Redundant are typically used in data centers.

For the higher certification levels, the requirement of 0.9 or better power factor was extended to apply to 20% and 50% load levels, as well as at 100% load. The Platinum level requires 0.95 or better power factor for servers.

The Climate Savers Computing Initiative efficiency level targets for workstations for 2007 through 2011, correspond to the 80 PLUS certification levels. From July 2007 through June 2008, basic 80 PLUS level (Energy Star 4.0). For next year target is, 80 PLUS bronze level, the following year 80 PLUS silver, then 80 PLUS gold, and finally platinum.

Misleading power supply advertising

There have been a few instances where companies claim or imply that their supplies are 80 PLUS when they haven't been certified, and in some cases do not meet the requirements. When a company resells an OEM power supply under a new name it must be certified under the new name and company, even if the OEM supply is certified. In some instances a reseller has claimed a higher wattage than the supply can deliver - in which case the reseller's supply would not meet 80 PLUS requirements. The 80 PLUS web site has a list of all certified supplies, so it is possible to confirm that a supply really meets the requirements.

Although some power supply manufacturers name their products with similar names, like "85 Plus," there is no such official certification or standard.

What it means

The efficiency of a computer power supply is its output power divided by its input power. The remaining power is converted into heat. For instance, a 600-watt power supply with 60% efficiency running at full load would draw 1000W from the mains and would therefore waste 400W as heat. On the other hand a 600-watt power supply with 80%

efficiency running at full load would draw 750W from the mains and would therefore waste only 150W as heat.

For a given power supply, efficiency varies depending on how much power is being delivered. Supplies are typically most efficient at between half and three quarters load, much less efficient at low load, and somewhat less efficient at maximum load. Older ATX power supplies were typically 60% to 75% efficient. To qualify for 80 PLUS, a power supply must achieve at least 80% efficiency at three specified loads (20%, 50% and 100% of maximum rated power). However, 80 PLUS supplies may still be less than 80% efficient at lower loads. For instance, an 80 PLUS, 520 watt supply could still be 70% or less efficient at 60 watts (a typical idle power for a desktop computer). Thus it is still important to select a supply with capacity appropriate to the device being powered.

It is easier to achieve the higher efficiency levels for higher wattage supplies, so gold and platinum supplies may be less available in consumer level supplies of reasonable capacity for typical desktop machines.

Typical computer power supplies may have power factors as low as 0.5 to 0.6. The higher power factor reduces the peak current draw, reducing load on the circuit or on an uninterruptible power supply.

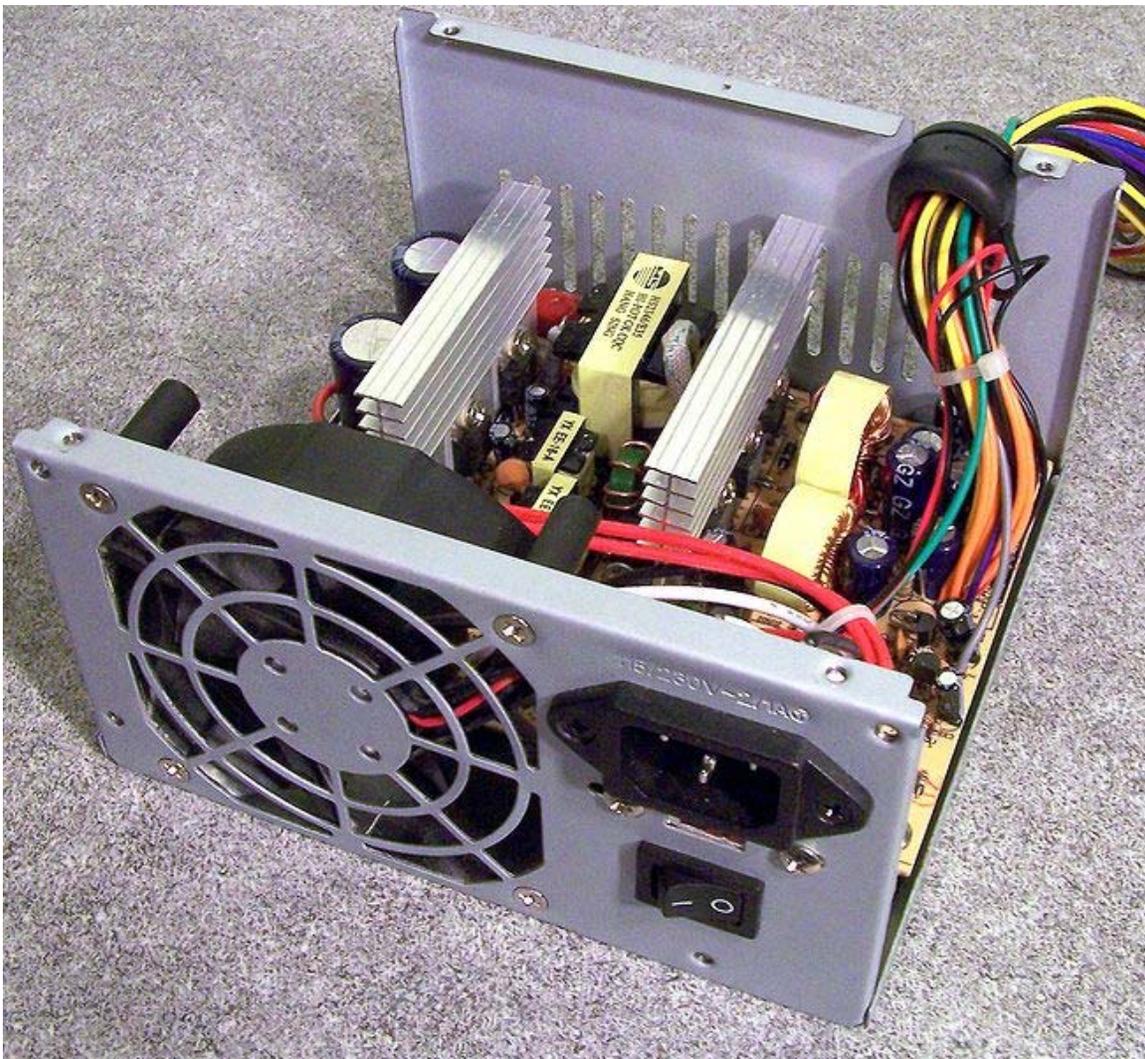
Reducing the heat output of the computer helps reduce noise, since fans do not have to spin as fast to cool the computer. Reduced heat and resulting lower cooling demands may increase computer reliability.

The testing conditions may give an unrealistic expectation of efficiency for heavily loaded, high power (rated much larger than 300W) supplies. A heavily loaded power supply and the computer it is powering generate significant amounts of heat, which may raise the power supply temperature, which is likely to decrease its efficiency. Since power supplies are certified at room temperature, this effect is not taken into account.

80PLUS does not set efficiency targets for very low load. For instance, generation of standby power may still be relatively inefficient, and may not meet requirements of the One Watt Initiative. Testing of 80 PLUS power supplies shows that they vary considerably in standby efficiency. Some consume half a watt or less in standby with no load, where others consume several times as much at standby, even though they may meet higher 80PLUS certification requirement levels. Inefficiencies in generating standby power are magnified by the amount of time that computers spend turned off.

Chapter-5

Power Supply Unit (Computer)



The top cover has been removed to show the internals of a computer Power supply unit.

A **power supply unit (PSU)** is the component that supplies power to the other components in a computer. More specifically, a power supply unit is typically designed to convert general-purpose alternating current (AC) electric power from the mains (100-127V in North America, parts of South America, Japan, and Taiwan; 220-240V in most of the rest of the world) to usable low-voltage direct current (DC) power for the internal components of the computer. Some power supplies have a switch to change between 230 V and 115 V. Other models have automatic sensors that switch input voltage automatically, or are able to accept any voltage between those limits.

The most common computer power supplies are built to conform to the ATX form factor. This enables different power supplies to be interchangeable with different components inside the computer. ATX power supplies also are designed to turn on and off using a signal from the motherboard, and provide support for modern functions such as the standby mode available in many computers. The most recent specification of the ATX standard PSU as of mid-2008 is version 2.31.

Power rating

Computer power supplies are rated based on their maximum output power. Typical power ranges are from 500 W to lower than 300 W for small form factor systems intended as ordinary home computers, the use of which is limited to web-surfing and burning and playing DVDs. Power supplies used by gamers and enthusiasts mostly range from 450 W to 1400 W. Typical gaming PCs feature power supplies in the range of 500-800 W, with higher-end PCs demanding 800-1400 W supplies. The highest-end units are up to 2 kW strong and are intended mainly for servers and, to a lesser degree, extreme performance computers with multiple processors, several hard disks and multiple graphics cards. The power rating of a PC power supply is not officially certified and is self-claimed by each manufacturer. A common way to reach the power figure for PC PSUs is by adding the power available on each rail, which will not give a true power figure. Therefore it is possible to overload a PSU on one rail without having to use the maximum rated power.

This may mean that if:

- PSU A has a **peak** rating of **550 watts at 25°C**, with **25 amps** (300 W) on the **12 volt** line, and
- PSU B has a **continuous** rating of **450 watts at 40°C**, with **33 amps** (400 W) on the **12 volt** line,

and if those ratings are accurate, then PSU B would have to be considered a vastly superior unit, despite its lower overall power rating. PSU A may only be capable of delivering a fraction of its rated power under real world conditions.

This tendency has led in turn to greatly overspecified power supply recommendations, and a shortage of high-quality power supplies with reasonable capacities. Very few computers require more than 300–350 watts maximum. Higher end computers such as

servers and gaming machines with multiple high power GPUs are among the few exceptions, although in recent years the power demand of "video cards" in the ability to watch high definition (HD) media has led to even the average ATX computer to consume between 400 and 500 watts.

Appearance

Most computer power supplies are a square metal box, and have a large bundle of wires emerging from one end. Opposite the wire bundle is the back face of the power supply, with an air vent and C14 IEC connector to supply AC power. There may optionally be a power switch and/or a voltage selector switch. A label on one side of the box lists technical information about the power supply, including safety certifications maximum output power. Common certification marks for safety are the UL mark, GS mark, TÜV, NEMKO, SEMKO, DEMKO, FIMKO, CCC, CSA, VDE, GOST R and BSMI. Common certificate marks for EMI/RFI are the CE mark, FCC and C-tick. The CE mark is required for power supplies sold in Europe and India.

A RoHS or 80 PLUS can also sometimes be seen.

Dimensions of an ATX power supply are 150 mm width, 86 mm height, and typically 140 mm depth, although the depth can vary from brand to brand.

Connectors



Various connectors from a computer PSU.

Typically, power supplies have the following connectors:

- **PC Main** power connector (usually called **P1**): This is the connector that goes to the motherboard to provide it with power. The connector has 20 or 24 pins. One of the pins belongs to the PS-ON wire (it is usually green). This connector is the largest of all the connectors. In older AT power supplies, this connector was split in two: **P8** and **P9**. A power supply with a 24-pin connector can be used on a motherboard with a 20-pin connector. In cases where the motherboard has a 24-

- pin connector, some power supplies come with two connectors (one with 20-pin and other with 4-pin) which can be used together to form the 24-pin connector.
- **ATX12V** 4-pin power connector (also called the **P4 power connector**). A second connector that goes to the motherboard (in addition to the main 24-pin connector) to supply dedicated power for the processor. For high-end motherboards and processors, more power is required, therefore EPS12V has an 8 pin connector.
 - **4-pin Peripheral** power connectors (usually called **Molex** for its manufacturer): These are the other, smaller connectors that go to the various disk drives of the computer. Most of them have four wires: two black, one red, and one yellow. Unlike the standard mains electrical wire color-coding, each *black wire* is a ground, the *red wire* is +5 V, and the *yellow wire* is +12 V. In some cases these are also used to provide additional power to PCI cards such as FireWire 800 cards.
 - **4-pin Berg** power connectors (usually called **Mini-connector** or "mini-Molex"): This is one of the smallest connectors that supplies the floppy drive with power. In some cases, it can be used as an auxiliary connector for AGP video cards. Its cable configuration is similar to the Peripheral connector.
 - **Auxiliary** power connectors: There are several types of auxiliary connectors designed to provide additional power if it is needed.
 - **Serial ATA** power connectors: a 15-pin connector for components which use SATA power plugs. This connector supplies power at three different voltages: +3.3, +5, and +12 volts.
 - **6-pin** Most modern computer power supplies include 6-pin connectors which are generally used for PCI Express graphics cards, but a newly introduced 8-pin connector should be seen on the latest model power supplies. Each PCI Express 6-pin connector can output a maximum of 75 W.
 - **6+2 pin** For the purpose of backwards compatibility, some connectors designed for use with high end PCI Express graphics cards feature this kind of pin configuration. It allows either a 6-pin card or an 8-pin card to be connected by using two separate connection modules wired into the same sheath: one with 6 pins and another with 2 pins.
 - A **C14 IEC connector** with an appropriate C13 cord is used to attach the power supply to the local power grid.

AT vs. ATX



A typical installation of an ATX form factor computer power supply.

There are two basic differences between AT and ATX power supplies: The connectors that provide power to the motherboard, and the soft switch. On older AT power supplies, the Power-on switch wire from the front of the computer is connected directly to the power supply.

On newer ATX power supplies, the power switch on the front of the computer goes to the motherboard over a connector labeled something like; PS ON, Power SW, SW Power, etc. This allows other hardware and/or software to turn the system on and off.

The motherboard controls the power supply through pin #14 of the 20 pin connector or #16 of the 24 pin connector on the motherboard. This pin carries 5V when the power supply is in standby. It can be grounded to turn the power supply on without having to turn on the rest of the components. This is useful for testing or to use the computer ATX power supply for other purposes.

AT stands for **A**dvanced **T**echnology when ATX means **A**dvanced **T**echnology **e**Xtended.

Laptops

Most portable computers have power supplies that provide 25 to 200 watts. In portable computers (such as laptops) there is usually an external power supply (sometimes referred to as a "power brick" due to its similarity, in size, shape and weight, to a real brick) which converts AC power to one DC voltage (most commonly 19 V), and further

DC-DC conversion occurs within the laptop to supply the various DC voltages required by the other components of the portable computer.

Servers

Some web servers use a single-voltage 12 volt power supply. All other voltages are generated by voltage regulator modules on the motherboard.

Energy efficiency

Computer power supplies are generally about 70–75% efficient. That means in order for a 75% efficient power supply to produce 75 W of DC output it would require 100 W of AC input and dissipate the remaining 25 W in heat. Higher-quality power supplies can be over 80% efficient; higher energy efficient PSU's waste less energy in heat, and requires less airflow to cool, and as a result will be quieter. Google's server power supplies are more than 90% efficient. HP's server power supplies have reached 94% efficiency. Standard PSUs sold for server workstations have around 90% efficiency, as of 2010.

It's important to match the capacity of a power supply to the power needs of the computer. The energy efficiency of power supplies drops significantly at low loads. Efficiency generally peaks at about 50-75% load. The curve varies from model to model (examples of how this curve looks can be seen on test reports of energy efficient models found on the 80 PLUS website). As a rule of thumb for standard power supplies it is usually appropriate to buy a supply such that the calculated typical consumption of one's computer is about 60% of the rated capacity of the supply provided that the calculated maximum consumption of the computer does not exceed the rated capacity of the supply. Note that advice on overall power supply ratings often given by the manufacturer of single component, typically graphics cards, should be treated with great skepticism. These manufacturers want to minimize support issues due to under rating of the power supply specifications and advise customers to use a more powerful power supply to avoid these issues.

Various initiatives are underway to improve the efficiency of computer power supplies. Climate savers computing initiative promotes energy saving and reduction of greenhouse gas emissions by encouraging development and use of more efficient power supplies. 80 PLUS certifies power supplies that meet certain efficiency criteria, and encourages their use via financial incentives. On top of that the businesses end up using less electricity to cool the PSU and the computer's themselves and thus save an initially large sum(i.e. incentive + saved electricity = higher profit).

Facts



Redundant power supply.

- Life span is usually measured in mean time between failures (MTBF). Higher MTBF ratings are preferable for longer device life and reliability. Quality construction consisting of industrial grade electrical components and/or a larger or higher speed fan can help to contribute to a higher MTBF rating by keeping critical components cool, thus preventing the unit from overheating. Overheating is a major cause of PSU failure. MTBF value of 100,000 hours (about 11 years continuous operation) is not uncommon.

- Power supplies may have passive or active power factor correction (PFC). Passive PFC is a simple way of increasing the power factor by putting a coil in series with the primary filter capacitors. Active PFC is more complex and can achieve higher PF, up to 99%.
- In computer power supplies that have more than one +12V power rail, it is preferable for stability reasons to spread the power load over the 12V rails evenly to help avoid overloading one of the rails on the power supply.
 - Multiple 12V power supply rails are separately current limited as a safety feature; they are not generated separately. Despite widespread belief to the contrary, this separation has no effect on mutual interference between supply rails.
 - The ATX12V 2.x and EPS12V power supply standards defer to the IEC 60950 standard, which requires that no more than 240 volt-amperes be present between any two accessible points. Thus, each wire must be current-limited to no more than 20 A; typical supplies guarantee 18 A without triggering the current limit. Power supplies capable of delivering more than 18 A at 12 V connect wires in groups to two or more current sensors which will shut down the supply if excess current flows. Unlike a fuse or circuit breaker, these limits reset as soon as the overload is removed.
 - Because of the above standards, almost all high-power supplies claim to implement separate rails, however this claim is often false; many omit the necessary current-limit circuitry, both for cost reasons and because it is an irritation to customers. (The lack is sometimes advertised as a feature under names like "rail fusion" or "current sharing".)
- When the computer is powered down but the power supply is still on, it can be started remotely via Wake-on-LAN and Wake-on-Ring or locally via Keyboard Power ON (KBPO) if the motherboard supports it.
- Early PSUs used a conventional (heavy) step-down transformer, but most modern computer power supplies are a type of switched-mode power supply (SMPS) with a ferrite-cored High Frequency transformer.
- Computer power supplies may have short circuit protection, overpower (overload) protection, overvoltage protection, undervoltage protection, overcurrent protection, and over temperature protection.
- Some power supplies come with sleeved cables, which is aesthetically nicer, makes wiring easier and cleaner and have less detrimental effect on airflow.
- There is a popular misconception that a greater power capacity (watt output capacity) is always better. Since supplies are self-certified, a manufacturer's claims may be double or more what is actually provided. Although a too-large power supply will have an extra margin of safety as far as not over-loading, a

larger unit is often less efficient at lower loads (under 20% of its total capability) and therefore will waste more electricity than a more appropriately sized unit. Additionally, computer power supplies generally do not function properly if they are too lightly loaded. (less than about 15% of the total load.) Under no-load conditions they may shut down or malfunction. For this reason the no-load protection was introduced in some power supplies.

- Another popular misconception is that the greater the total watt capacity is, the more suitable the power supply becomes for higher-end graphics cards. The most important factor for judging a PSU's suitability for certain graphics cards is the PSU's total 12V output, as it is that voltage on which modern graphics cards operate. If the total 12V output stated on the PSU is higher than the suggested minimum of the card, then that PSU can fully supply the card. It is however recommended that a PSU should not just cover the graphics cards' demands, as there are other components in the PC that depend on the 12V output, including the CPU, disk drives and optical drives.
- Power supplies can feature magnetic amplifiers or double-forward converter circuit design.

Wiring diagrams

AT power connector (Used on older AT style mainboards)

Color	Pin	Signal
	P8.1	Power Good
	P8.2	+5 V
	P8.3	+12 V
	P8.4	-12 V
	P8.5	Ground
	P8.6	Ground
	P9.1	Ground
	P9.2	Ground
	P9.3	-5 V
	P9.4	+5 V
	P9.5	+5 V
	P9.6	+5 V

24-pin ATX12V 2.x power supply connector
(20-pin omits the last four: 11, 12, 23 and 24)

Color	Signal	Pin	Pin	Signal	Color
	+3.3 V	1	13	+3.3 V	

				+3.3 V sense	Brown
Orange	+3.3 V	2	14	-12 V	Blue
Black	Ground	3	15	Ground	Black
Red	+5 V	4	16	Power on	Green
Black	Ground	5	17	Ground	Black
Red	+5 V	6	18	Ground	Black
Black	Ground	7	19	Ground	Black
Grey	Power good	8	20	Reserved	N/C
Purple	+5 V standby	9	21	+5 V	Red
Yellow	+12 V	10	22	+5 V	Red
Yellow	+12 V	11	23	+5 V	Red
Orange	+3.3 V	12	24	Ground	Black

- Pins 8, 13, and 16 (shaded) are control signals, not power:
 - "Power On" is pulled up to +5V by the PSU, and must be driven low to turn on the PSU.
 - "Power good" is low when other outputs have not yet reached, or are about to leave, correct voltages.
 - The "+3.3 V sense" line is for remote sensing.
- Pin 20 (formerly -5V, white wire) is absent in current power supplies; it was optional in ATX and ATX12V ver. 1.2, and deleted as of ver. 1.3.
- The right-hand pins are numbered 11–20 in the 20-pin version.

Modular power supplies

A **modular power supply** is a relatively new approach to cabling, allowing users to omit unused cables. Whereas a conventional design has numerous cables permanently connected to the power supply, a modular power supply provides connectors at the power supply end, allowing unused cables to be detached from the power supply, producing less clutter, a neater appearance and less interference with airflow. It also makes it possible to supply a wider variety of cables, providing different lengths of Serial ATA power connectors instead of Molex connectors.

While modular cabling can help reduce case clutter, they have often been criticized for creating electrical resistance. Some third party websites that do power supply testing have confirmed that the quality of the connector, the age of the connector, the number of times it was inserted/removed, and various other variables such as dust can all raise resistance. However, this is somewhat inconsequential as the amount of this resistance in a good connector is small compared to the resistance generated by the length of the wire itself.

Chapter-6

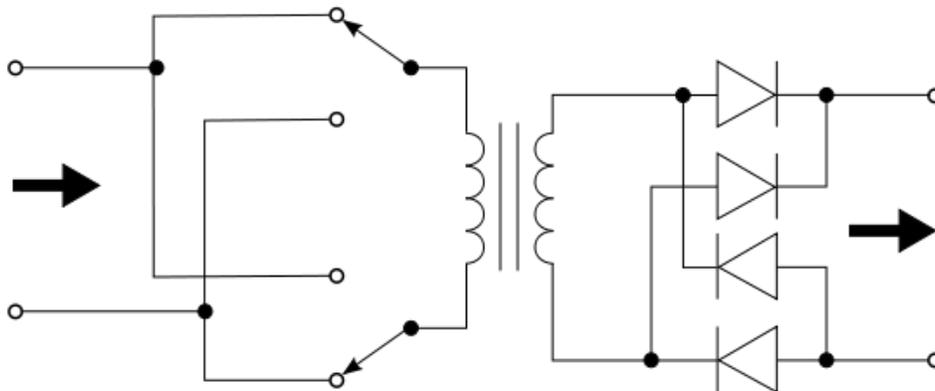
Push-pull Converter and Single-ended Primary-inductor Converter

Push-pull converter

A **push-pull converter** is a type of DC to DC converter that uses a transformer to change the voltage of a DC power supply. The transformer's ratio is arbitrary but fixed; however, in many circuit implementations the duty cycle of the switching action can be varied to effect a range of voltage ratios. The primary advantages of push-pull converters are their simplicity and ability to scale up to high power throughput, earning them a place in industrial DC power applications.

The push-pull converter is similar to the flyback converter and especially the forward converter.

Circuit operation



The term *push-pull* is sometimes used to generally refer to any converter with bidirectional excitation of the transformer. For example, in a full-bridge converter, the switches (connected as an H-bridge) alternate the voltage across the supply side of the transformer, causing the transformer to function as it would for AC power and produce a voltage on its output side.

However, *push-pull* more commonly refers to a two-switch topology with a split primary winding.

In any case, the output is then rectified and sent to the load. Capacitors are often included at the output to buffer against the inevitable switching noise.

In practice, it is necessary to allow a small interval between powering the transformer one way and powering it the other: the “switches” are usually pairs of transistors (or similar devices), and were the two transistors in the pair to switch simultaneously there would be a risk of shorting out the power supply. Hence, a small wait is needed to avoid this problem. This wait time is called "Dead Time" and is necessary to avoid transistor shoot-through.

Transistors

N-type and P-type power transistors can be used. Power MOSFETs are often chosen for this role due to their high current switching capability and their inherently low ON resistance. The gates (base) of the power transistors are tied via a resistor to one of the supply voltages. A P-type transistor is used to pull up the N-type power transistor gate (common source) and an N-type transistor is used to pull down the P-type power transistor gate.

Alternatively, all power transistors can be N-type, which offer around three times the gain of their P-type equivalents. In this alternative the N-type transistor used in place of the P-type has to be driven in this way: The voltage is amplified by one P-type transistor and one N-type transistor in common base configuration to rail-to-rail amplitude. Then the power transistor is driven in common drain configuration to amplify the current.

In high frequency applications both transistors are driven with common source.

The operation of the circuit means that both transistors are actually pushing, and the pulling is done by a low pass filter (coil) in general, and by a center tap of the transformer in the converter application. But because the transistors push in an alternating fashion, the device is called a push-pull converter.

Timing

If both transistors are in their on state, a short circuit results. On the other hand if both transistors are in their off state, high voltage peaks appear due to back EMF.

If the driver for the transistors is powerful and fast enough, the back EMF has no time to charge the capacity of the windings and of the body-diode of the MOSFETs to high voltages.

If a microcontroller is used, it can be used to measure the peak voltage and digitally adjust the timing for the transistors, so that the peak only just appears. This is especially

useful when the transistors are starting from cold with no peaks, and are in their boot phase.

The cycle starts with no voltage and no current. Then one transistor turns on, a constant voltage is applied to the primary, current increases linearly, and a constant voltage is induced in the secondary. After some time T the transistor is turned off, the parasitic capacities of the transistors and the transformer and the inductance of the transformer form an LC circuit which swings to the opposite polarity. Then the other transistor turns on. For the same time T charge flows back into the storage capacitor, then changes the direction automatically, and for another time T the charge flows in the transformer. Then again the first transistor turns on until the current is stopped. Then the cycle is finished, another cycle can start anytime later. The S-shaped current is needed to improve over the simpler converters and deal efficiently with remanence.

Single-ended primary-inductor converter

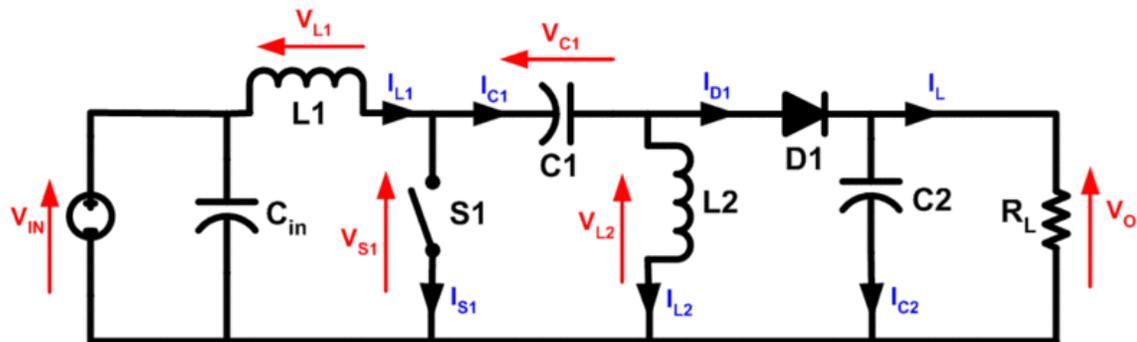


Figure 1: Schematic of SEPIC

Single-ended primary-inductor converter (SEPIC) is a type of DC-DC converter allowing the electrical potential (voltage) at its output to be greater than, less than, or equal to that at its input; the output of the SEPIC is controlled by the duty cycle of the control transistor.

A SEPIC is similar to a traditional buck-boost converter, but has advantages of having non-inverted output (the output voltage is of the same polarity as the input voltage), the isolation between its input and output (provided by a capacitor in series), and true shutdown mode: when the switch is turned off, its output drops to 0 V.

SEPICs are useful in applications in which a battery voltage can be above and below that of the regulator's intended output. For example, a single lithium ion battery typically

discharges from 4.2 volts to 3 volts; if other components require 3.3 volts, then the SEPIC would be effective.

Circuit operation

The schematic diagram for a basic SEPIC is shown in Figure 1. As with other switched mode power supplies (specifically DC-to-DC converters), the SEPIC exchanges energy between the capacitors and inductors in order to convert from one voltage to another. The amount of energy exchanged is controlled by switch S1, which is typically a transistor such as a MOSFET; MOSFETs offer much higher input impedance and lower voltage drop than bipolar junction transistors (BJTs), and do not require biasing resistors (as MOSFET switching is controlled by differences in voltage rather than a current, as with BJTs).

Continuous mode

A SEPIC is said to be in continuous-conduction mode ("continuous mode") if the current through the inductor L1 never falls to zero. During a SEPIC's steady-state operation, the average voltage across capacitor C1 (V_{C1}) is equal to the input voltage (V_{in}). Because capacitor C1 blocks direct current (DC), the average current across it (I_{C1}) is zero, making inductor L2 the only source of load current. Therefore, the average current through inductor L2 (I_{L2}) is the same as the average load current and hence independent of the input voltage.

Looking at average voltages, the following can be written:

$$V_{IN} = V_{L1} + V_{C1} + V_{L2}$$

Because the average voltage of V_{C1} is equal to V_{IN} , $V_{L1} = -V_{L2}$. For this reason, the two inductors can be wound on the same core. Since the voltages are the same in magnitude, their effects of the mutual inductance will be zero, assuming the polarity of the windings is correct. Also, since the voltages are the same in magnitude, the ripple currents from the two inductors will be equal in magnitude.

The average currents can be summed as follows:

$$I_{D1} = I_{L1} - I_{L2}$$

When switch S1 is turned on, current I_{L1} increases and the current I_{L2} increases in the negative direction. (Mathematically, it decreases due to arrow direction.) The energy to increase the current I_{L1} comes from the input source. Since S1 is a short while closed, and the instantaneous voltage V_{C1} is approximately V_{IN} , the voltage V_{L2} is approximately $-V_{IN}$. Therefore, the capacitor C1 supplies the energy to increase the magnitude of the current in I_{L2} and thus increase the energy stored in L2. The easiest way to visualize this is to consider the bias voltages of the circuit in a d.c. state, then close S1.

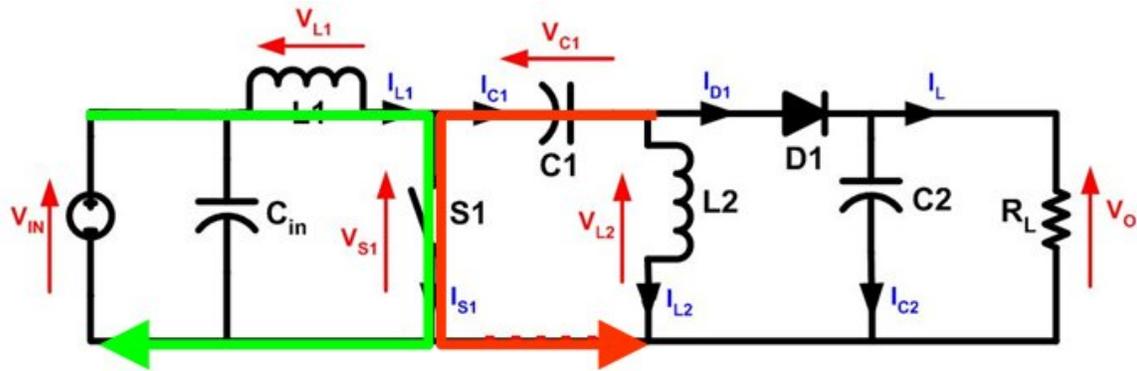


Figure 2: With S1 closed current increases through L1 (green) and C1 discharges increasing current in L2 (red)

When switch S1 is turned off, the current I_{C1} becomes the same as the current I_{L1} , since inductors do not allow instantaneous changes in current. The current I_{L2} will continue in the negative direction, in fact it never reverses direction. It can be seen from the diagram that a negative I_{L2} will add to the current I_{L1} to increase the current delivered to the load. Using Kirchoff's Current Law, it can be shown that $I_{D1} = I_{C1} - I_{L2}$. It can then be concluded, that while S1 is off, power is delivered to the load from both L2 and L1. C1, however is being charged by L1 during this off cycle, and will in turn recharge L2 during the on cycle.

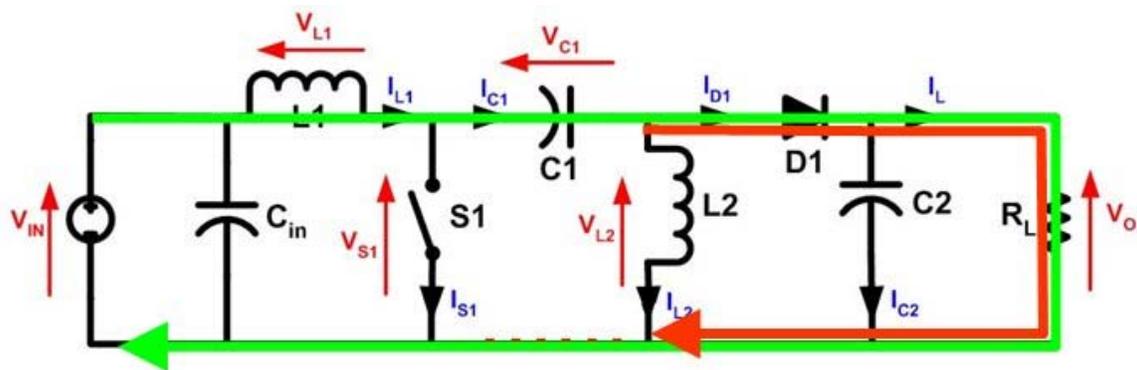


Figure 3: With S1 open current through L1 (green) and current through L2 (red) produce current through the load

Because the potential (voltage) across capacitor C1 may reverse direction every cycle, a non-polarized capacitor should be used. However, a polarized tantalum or electrolytic capacitor may be used in some cases, because the potential (voltage) across capacitor C1 will not change unless the switch is closed long enough for a half cycle of resonance with inductor L2, and by this time the current in inductor L1 could be quite large.

The capacitor C_{IN} is required to reduce the effects of the parasitic inductance and internal resistance of the power supply. The boost/buck capabilities of the SEPIC are possible because of capacitor C1 and inductor L2. Inductor L1 and switch S1 create a standard

boost converter, which generate a voltage (V_{S1}) that is higher than V_{IN} , whose magnitude is determined by the duty cycle of the switch S1. Since the average voltage across C1 is V_{IN} , the output voltage (V_O) is $V_{S1} - V_{IN}$. If V_{S1} is less than double V_{IN} , then the output voltage will be less than the input voltage. If V_{S1} is greater than double V_{IN} , then the output voltage will be greater than the input voltage.

The evolution of switched-power supplies can be seen by coupling the two inductors in a SEPIC converter together, which begins to resemble a Flyback converter, the most basic of the transformer-isolated SMPS topologies.

Discontinuous mode

A SEPIC is said to be in discontinuous-conduction mode (or, discontinuous mode) if the current through the inductor L1 is allowed to fall to zero.

Reliability and Efficiency

The voltage drop and switching time of diode D1 is critical to a SEPIC's reliability and efficiency. The diode's switching time needs to be extremely fast in order to not generate high voltage spikes across the inductors, which could cause damage to components. Fast conventional diodes or Schottky diodes may be used.

The resistances in the inductors and the capacitors can also have large effects on the converter efficiency and ripple. Inductors with lower series resistance allow less energy to be dissipated as heat, resulting in greater efficiency (a larger portion of the input power being transferred to the load). Capacitors with low equivalent series resistance (ESR) should also be used for C1 and C2 to minimize ripple and prevent heat build-up, especially in C1 where the current is changing direction frequently.

Chapter-7

Ćuk Converter and Grid Tie Inverter

Ćuk converter

The **Ćuk converter** is a type of DC-DC converter that has an output voltage magnitude that is either greater than or less than the input voltage magnitude.

The non-isolated Ćuk converter can only have opposite polarity between input and output. It uses a capacitor as its main energy-storage component, unlike most other types of converters which use an inductor. It is named after Slobodan Ćuk of the California Institute of Technology, who first presented the design.

Non-isolated Ćuk converter

Operating Principle

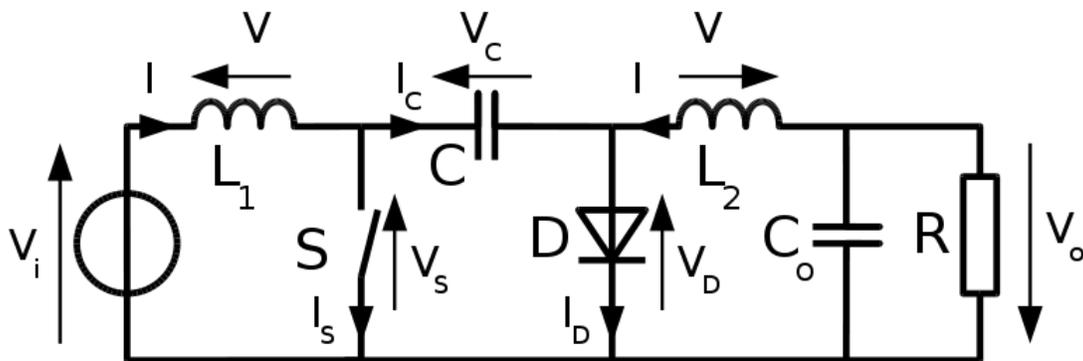
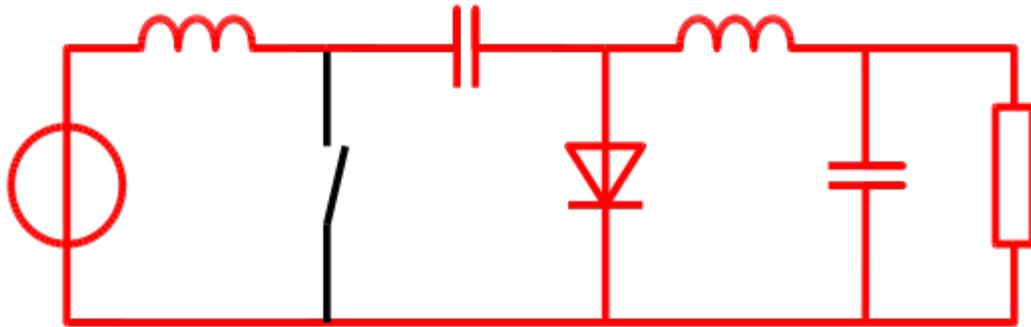


Fig 1: Schematic of a non-isolated Ćuk converter.

Off-State



On-State

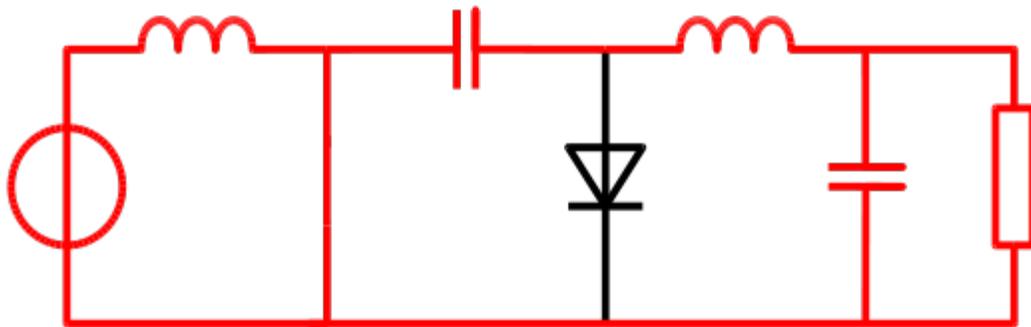


Fig 2: The two operating states of a non-isolated Ćuk converter.

State

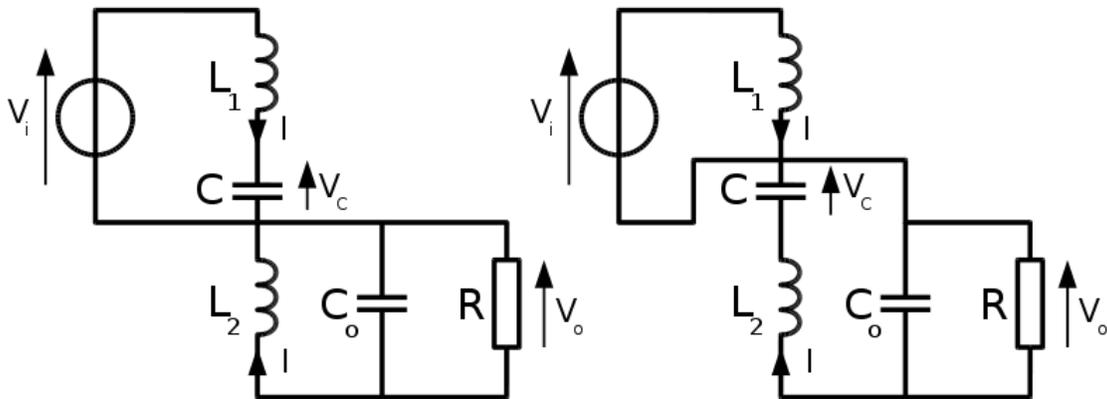


Fig 3: The two operating states of a non-isolated Ćuk converter. In this figure, the diode and the switch are either replaced by a short circuit when they are on or by an open circuit when they are off. It can be seen that when in the Off state, the capacitor C is being charged by the input source through the inductor L_1 . When in the On state, the capacitor C transfers the energy to the output capacitor through the inductance L_2 .

A non-isolated Ćuk converter comprises two inductors, two capacitors, a switch (usually a transistor), and a diode. Its schematic can be seen in figure 1. It is an inverting converter, so the output voltage is negative with respect to the input voltage.

The capacitor C is used to transfer energy and is connected alternately to the input and to the output of the converter *via* the commutation of the transistor and the diode.

The two inductors L_1 and L_2 are used to convert respectively the input voltage source (V_i) and the output voltage source (C_o) into current sources. Indeed, at a short time scale an inductor can be considered as a current source as it maintains a constant current. This conversion is necessary because if the capacitor were connected directly to the voltage source, the current would be limited only by (parasitic) resistance, resulting in high energy loss. Charging a capacitor with a current source (the inductor) prevents resistive current limiting and its associated energy loss.

As with other converters (buck converter, boost converter, buck-boost converter) the Ćuk converter can either operate in continuous or discontinuous current mode. However, unlike these converters, it can also operate in discontinuous voltage mode (i.e., the voltage across the capacitor drops to zero during the commutation cycle).

Continuous mode

In steady state, the energy stored in the inductors has to remain the same at the beginning and at the end of a commutation cycle. The energy in an inductor is given by:

$$E = \frac{1}{2}LI^2$$

This implies that the current through the inductors has to be the same at the beginning and the end of the commutation cycle. As the evolution of the current through an inductor is related to the voltage across it:

$$V_L = L \frac{dI}{dt}$$

it can be seen that the average value of the inductor voltages over a commutation period have to be zero to satisfy the steady-state requirements.

If we consider that the capacitors C and C_o are large enough for the voltage ripple across them to be negligible, the inductor voltages become:

- in the off-state, inductor L_1 is connected in series with V_i and C. Therefore $V_{L1} = V_i - V_C$. As the diode D is forward biased (we consider zero voltage drop), L_2 is directly connected to the output capacitor. Therefore $V_{L2} = V_o$

- in the on-state, inductor L_1 is directly connected to the input source. Therefore $V_{L1} = V_i$. Inductor L_2 is connected in series with C and the output capacitor, so $V_{L2} = V_o + V_C$

The converter operates in on-state from $t=0$ to $t=D \cdot T$ (D is the duty cycle), and in off state from $D \cdot T$ to T (that is, during a period equal to $(1-D) \cdot T$). The average values of V_{L1} and V_{L2} are therefore:

$$\bar{V}_{L1} = D \cdot V_i + (1 - D) \cdot (V_i - V_C) = (V_i - (1 - D) \cdot V_C)$$

$$\bar{V}_{L2} = D (V_o + V_C) + (1 - D) \cdot V_o = (V_o + D \cdot V_C)$$

As both average voltage have to be zero to satisfy the steady-state conditions we can write, using the last equation:

$$V_C = -\frac{V_o}{D}$$

So the average voltage across L_1 becomes:

$$\bar{V}_{L1} = \left(V_i + (1 - D) \cdot \frac{V_o}{D} \right) = 0$$

Which can be written as:

$$\frac{V_o}{V_i} = -\frac{D}{1 - D}$$

It can be seen that this relation is the same as that obtained for the Buck-boost converter.

Related structures

Inductor coupling

Instead of using two discrete inductor components, many designers implement a *coupled inductor Ćuk converter*, using a single magnetic component that includes both inductors on the same core. The transformer action between the inductors inside that component gives a *coupled inductor Ćuk converter* lower output ripple than a Ćuk converter using two independent discrete inductor components.

Single-ended primary-inductance converter (SEPIC)

A SEPIC converter is able to step-up or step-down the voltage.

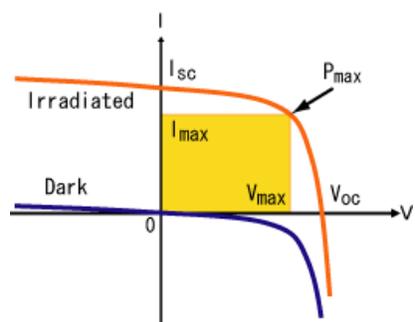
Grid tie inverter



Inverter for grid connected PV



Example of large 3-phase inverter for commercial and utility scale grid-tied PV systems



Schematic drawing of current-voltage characteristics of a solar cell The area of the yellow rectangle gives the output power. P_{max} denotes the maximum power point

A **grid-tie inverter (GTI)** is a special type of inverter that converts direct current electricity into alternating current electricity and feeds it into an existing electrical grid. GTIs are often used to convert direct current produced by many renewable energy sources, such as solar panels or small wind turbines, into the alternating current used to power homes and businesses. The technical name for a grid-tie inverter is "grid-interactive inverter". They may also be called synchronous inverters. Grid-interactive inverters typically cannot be used in standalone applications where utility power is not available.

Residences and businesses that have a grid-tied electrical system are permitted in many countries to sell their energy to the utility grid through a policy known as "net metering", whereby the entity that owns the renewable energy power source receives compensation from the utility for its net outflow of power. So for example, if during a given month a power system feeds 500 kilowatt-hours into the grid and uses 100 kilowatt-hours from the grid, it would receive compensation for 400 kilowatt-hours. In the US, net metering policies vary by jurisdiction.

In the United States, grid-interactive power systems are covered by specific provisions in the National Electric Code, which also mandates certain requirements for grid-interactive inverters.

Typical operation

Inverters take DC power and invert it to AC power so it can be fed into the electric utility company grid. The grid tie inverter must synchronize its frequency with that of the grid (e.g. 50 or 60 Hz) using a local oscillator and limit the voltage to no higher than the grid voltage. A typical modern GTI has a fixed unity power factor, which means its output voltage and current are perfectly lined up, and its phase angle is within 1 degree of the AC power grid. The inverter has an on-board computer which will sense the current AC grid waveform, and output a voltage to correspond with the grid.

Grid-tie inverters are also designed to quickly disconnect from the grid if the utility grid goes down. This is an NEC requirement that ensures that in the event of a blackout, the grid tie inverter will shut down to prevent the energy it produces from harming any line workers who are sent to fix the power grid.

Properly configured, a grid tie inverter enables a home owner to use an alternative power generation system like solar or wind power without extensive rewiring and without batteries. If the alternative power being produced is inadequate, the deficit will be sourced from the electricity grid.

Technology

Grid-tie inverters that are available on the market today use a number of different technologies. The inverters may use the newer high-frequency transformers, conventional low-frequency transformers, or no transformer. Instead of converting direct current

directly to 120 or 240 volts AC, high-frequency transformers employ a computerized multi-step process that involves converting the power to high-frequency AC and then back to DC and then to the final AC output voltage. Transformerless inverters, which boast lighter weight and higher efficiencies than their counterparts with transformers, are popular in Europe. However, transformerless inverters have been slow to enter the US market. Until 2005, NEC code required all solar electric systems to be negative grounded, an electrical configuration that interferes with the operation of transformerless inverters. The issue at stake currently is that there are concerns about having transformerless electrical systems feed into the public utility grid since the lack of galvanic isolation between the DC and AC circuits could allow the passage of dangerous DC faults to be transmitted to the AC side.

Most grid-tie inverters on the market include a maximum power point tracker on the input side that enables the inverter to extract an optimal amount of power from its intended power source. Since MPPT algorithms differ for solar panels and wind turbines, specially made inverters for each of these power sources are available.

Characteristics

Inverter manufacturers publish datasheets for the inverters in their product line. While the terminology and content will vary by manufacturer, datasheets generally include the information listed below.

- *Rated output power*: This value will be provided in watts or kilowatts. For some inverters, they may provide an output rating for different output voltages. For instance, if the inverter can be configured for either 240 VAC or 208 VAC output, the rated power output may be different for each of those configurations.
- *Output voltage(s)*: This value indicates to which utility voltages the inverter can connect. For smaller inverters that are designed for residential use, the output voltage is usually 240 VAC. Inverters that target commercial applications are often compatible with 208, 240, 277, and/or 480 VAC.
- *Peak efficiency*: The peak efficiency represents the highest efficiency that the inverter can achieve. Most grid-tie inverters on the market as of July 2009 have peak efficiencies of over 94%, some as high as 96%. The energy lost during inversion is for the most part converted into heat. This means that in order for an inverter to put out the rated amount of power it will need to have a power input that exceeds the output. For example, a 5000 W inverter operating at full power at 95% efficiency will require an input of 5,263 W (rated power divided by efficiency). Inverters that are capable of producing power at different AC voltages may have different efficiencies associated with each voltage.
- *CEC weighted efficiency*: This efficiency is published by the California Energy Commission on its GoSolar website. In contrast to peak efficiency, this value is an average efficiency and is a better representation of the inverter's operating profile. Inverters that are capable of producing power at different AC voltages may have different efficiencies associated with each voltage.

- *Maximum input current*: This is the maximum amount of direct current that the inverter will use. If a DC power source, such as a solar array, produces an amount of current that exceeds the maximum input current, that current will not be used by the inverter.
- *Maximum output current*: The maximum output current is the maximum continuous alternating current that the inverter will supply. This value is typically used to determine the minimum current rating of the over-current protection devices (e.g., breakers and fuses) and disconnects required for the output circuit. Inverters that are capable of producing power at different AC voltages will have different maximum outputs for each voltage.
- *Peak power tracking voltage*: This represents the DC voltage range in which the inverter's maximum point power tracker will operate. The system designer must configure the strings optimally so that during the majority of the year, the voltage of the strings will be within this range. This can be a difficult task since voltage will fluctuate with changes in temperature.
- *Start voltage*: This value is not listed on all inverter datasheets. The value indicates the minimum DC voltage that is required in order for the inverter to turn on and begin operation. This is especially important for solar applications, because the system designer must be sure that there is a sufficient number of solar modules wired in series in each string to produce this voltage. If this value is not provided by the manufacturer, system designers typically use the lower band of the peak power tracking voltage range as the inverter's minimum voltage.
- *NEMA rating (US only)*: The NEMA rating indicates the level of protection the device has against water intrusion. Most inverters are NEMA 3R which means they are outdoor rated for most situations.
- *IP56 rating (rest of the world)*: This is similar to the above NEMA rating which indicates suitability for outdoor use and installation.

Chapter-8

Power Supply Rail

A **power supply rail** or **voltage rail** refers to a single voltage provided by a power supply unit (PSU) relative to some understood ground. Although the term is generally used in electronic engineering, most people encounter it in the context of personal computer power supplies.

Original IBM PC standard

The original IBM PC power supply unit (PSU) supplied two main voltage rails: +5 V and +12 V. It supplied two other voltages, -5 V and -12 V, but with limited amounts of power.

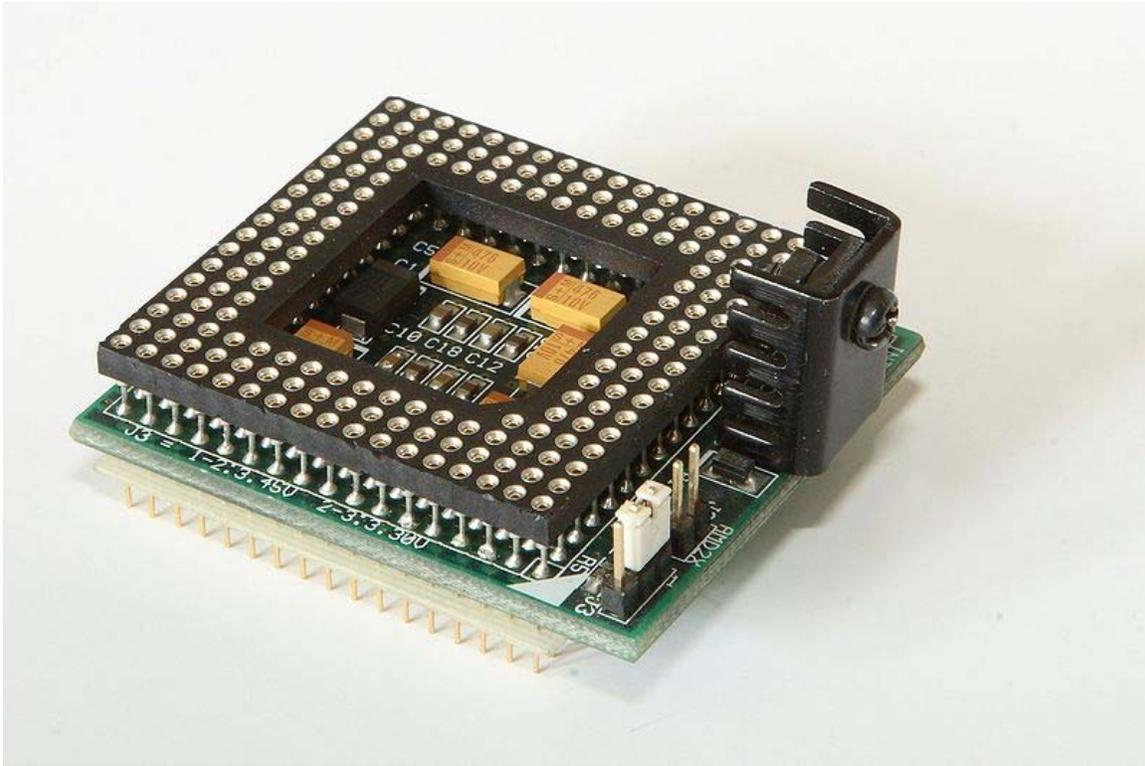
Most of the standard silicon microchips of the time operated on 5 V power. Of the 63.5 watts these PSUs could deliver, most of it was on this +5 V rail.

The +12 V supply was used primarily to operate motors. Fan motors, floppy disk drives and later, hard disk drives. As more peripherals were added, more power was delivered on the 12 V rail. However, since most of the power is consumed by chips, the 5 V rail still delivered most of the power.

The -12 V rail was used primarily to provide the negative supply voltage to the RS-232 serial ports.

An additional wire referred to as *Power Good* is used to prevent digital circuitry operation during the initial microseconds of power supply turn-on, where output voltages and currents are rising but not yet sufficient or stable for proper device operation. Once the output power is ready to use, the Power Good signal tells the digital circuitry that it can begin to operate.

ATX standard



Voltage converter for 80486DX4 processors (5 V to 3.3 V). Note the heat sink on the linear regulator, required to dissipate the wasted power.

When Intel developed the ATX standard power supply connector (published in 1995), microchips operating on 3.3 V were becoming more popular, beginning with the Intel 80486DX4 microprocessor in 1994, and the ATX standard supplies three positive rails: +3.3 V, +5 V, and +12 V. Earlier computers which wished to operate on 3.3 V typically used a simple but inefficient linear regulator to generate it from the +5 V rail.

The ATX connector provides multiple wires and power connections for the 3.3 V supply, because it is most sensitive to voltage drop in the supply connections.

Another ATX addition was the +5sb rail for providing a small amount of standby power, even when the computer was nominally "off".

Increase in +12 V demand

As transistors become smaller on chips, it becomes preferable to operate them on lower supply voltages, and the lowest supply voltage is often desired by the densest chip, the central processing unit. In order to supply large amounts of low-voltage power to the Pentium and subsequent microprocessors, a special power supply, the voltage regulator module began to be included on motherboards.

Initially, this was supplied by the main +5 V supply, but as power demands increased, the high currents required to supply sufficient power became problematic. To reduce the power losses in the 5 V supply, with the introduction of the Pentium 4 microprocessor, Intel changed the processor power supply to operate on +12 V, and added the separate P4 connector to the new ATX12V 1.0 standard to supply that power.

Modern high-powered graphics processing units do the same thing, resulting in the vast majority of the power requirements of a modern personal computer being on the +12 V rail.

When high-powered GPUs were first introduced, typical ATX power supplies were "5 V-heavy", and could only supply 50–60% of their output in the form of 12 V power. Thus, GPU manufacturers, to ensure 200–250 watts of 12 V power (peak load, CPU+GPU), recommended power supplies of 500–600 W or higher.

More modern ATX power supplies can deliver almost all (typically 80–90%) of their total rated capacity in the form of +12 V power.

Because of this change, it is important to consider the +12 V supply capacity, rather than the overall power capacity, when using an older ATX power supply with a more recent computer.

Low-quality power supply manufacturers sometimes take advantage of this overspecification by assigning unrealistically high power supply ratings, knowing that very few customers fully understand power supply ratings.

+3.3 V and +5 V rails

As mentioned above, these supplies are rarely a limiting factor when selecting a power supply for a modern personal computer; generally any supply with a sufficient +12 V rating will have adequate capacity at lower voltages. However, a large quantity of hard drives or PCI cards will create a greater load on the +5 V rail. A linear regulator could be used to convert the +12 V rail into a +5 V rail for each hard drive if the +5 V rail is overloaded.

It is worth noting that most PSUs create their 3.3 V output by regulating down their 5 V rail. As such, 3.3 V and 5 V typically have a combined limit as well. For example, a 3.3 V rail may have a 10 A rating by itself (33 W), and the 5 V rail may have a 20 A rating (100 W) by itself, but the two together may only be able to output 110 W. In this case, loading the 3.3 V rail to maximum (33 W), would leave the 5 V rail only be able to output 77 W.

As all of the rails come from one transformer and primary-side switching components, there is also an overall maximum power limit.

Multiple +12 V Rails

As power supply capacity increased, the ATX power supply standard was amended (beginning with version 2.0) to include:

3.2.4. Power Limit / Hazardous Energy Levels

Under normal or overload conditions, no output shall continuously provide more than 240 VA under any conditions of load including output short circuit, per the requirement of UL 1950/ CSA 950/ EN 60950/ IEC 950.

—ATX12V Power Supply Design Guide, version 2.2

This is a safety limit on the amount of power that may pass, in case of a fault, through any one wire. That much power can significantly overheat a wire, and would be more likely to melt the insulation and possibly start a fire.

Ideally, there would be one current limit per wire, but that would be prohibitively expensive. Since the limit is far larger than the reasonable current draw through a single wire, manufacturers typically group several wires together and apply the current limit to the entire group. Obviously, if the group is limited to 240 VA, so is each wire in it. Typically, a power supply will guarantee at least 17 A at 12 V by having a current limit of 18.5 A, plus or minus 8%. Thus, it is guaranteed to supply at least 17 A, and guaranteed to cut off before 20 A.

These groups are the so-called "multiple power supply rails". They are not fully independent; they are all connected to a single high-current 12 V source inside the power supply, but have separate current limit circuitry. The current limit groups are documented so the user can avoid placing too many high-current loads in the same group.

This works in the same way, and for the same reason, as the many small circuit breakers in a circuit breaker panel as well as the main supply breaker. And just like typical domestic wiring, multiple outlets are connected to each circuit breaker for reasons of cost.

Originally, a power supply featuring "multiple +12 V rails" implied one able to deliver more than 20 A of +12 V power, and was seen as a good thing. However, people found the need to balance loads across many +12 V rails inconvenient. This problem was exacerbated by the fact that the assignment of connectors to rails is done at manufacturing time, and it is not always possible to move a given load to a different rail.

Rather than add more current limit circuits, many manufacturers have chosen to ignore the requirement and increase the current limits above 20 A per rail, or provide "single-rail" power supplies that omit the current limit circuitry. (In some cases, in violation of their own advertising claims to include it.) The requirement was deleted from version 2.3 (March 2007) of the ATX12V power supply specifications.

Operation of overcurrent protection

When a power supply has multiple-rail overcurrent protection, if any rail reaches that limit, the entire power supply will shut down. This is not associated with any overheating or increase in ripple voltage by the power supply as a whole, as might be caused by an overall overload. The only reliability penalty from operating a rail close to its current limit comes from the risk of triggering the shutdown.

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:

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

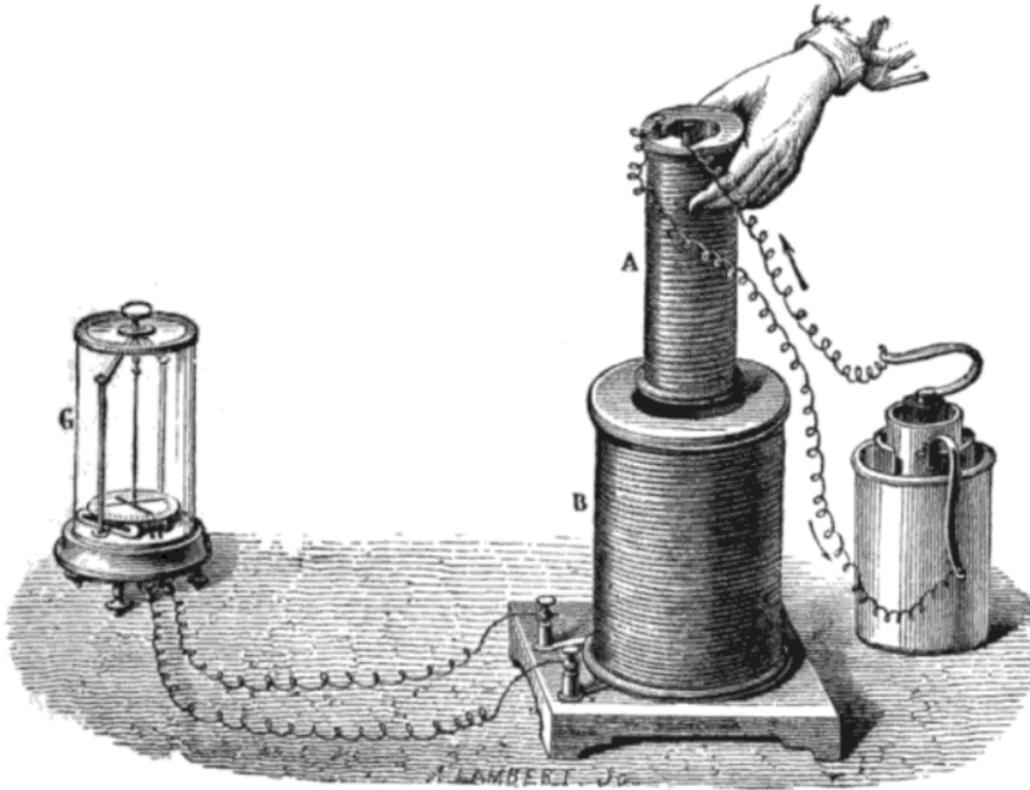
By appropriate selection of the ratio of turns, a transformer thus allows an alternating current (AC) voltage to be "stepped up" by making N_s greater than N_p , or "stepped down" by making N_s less than N_p .

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

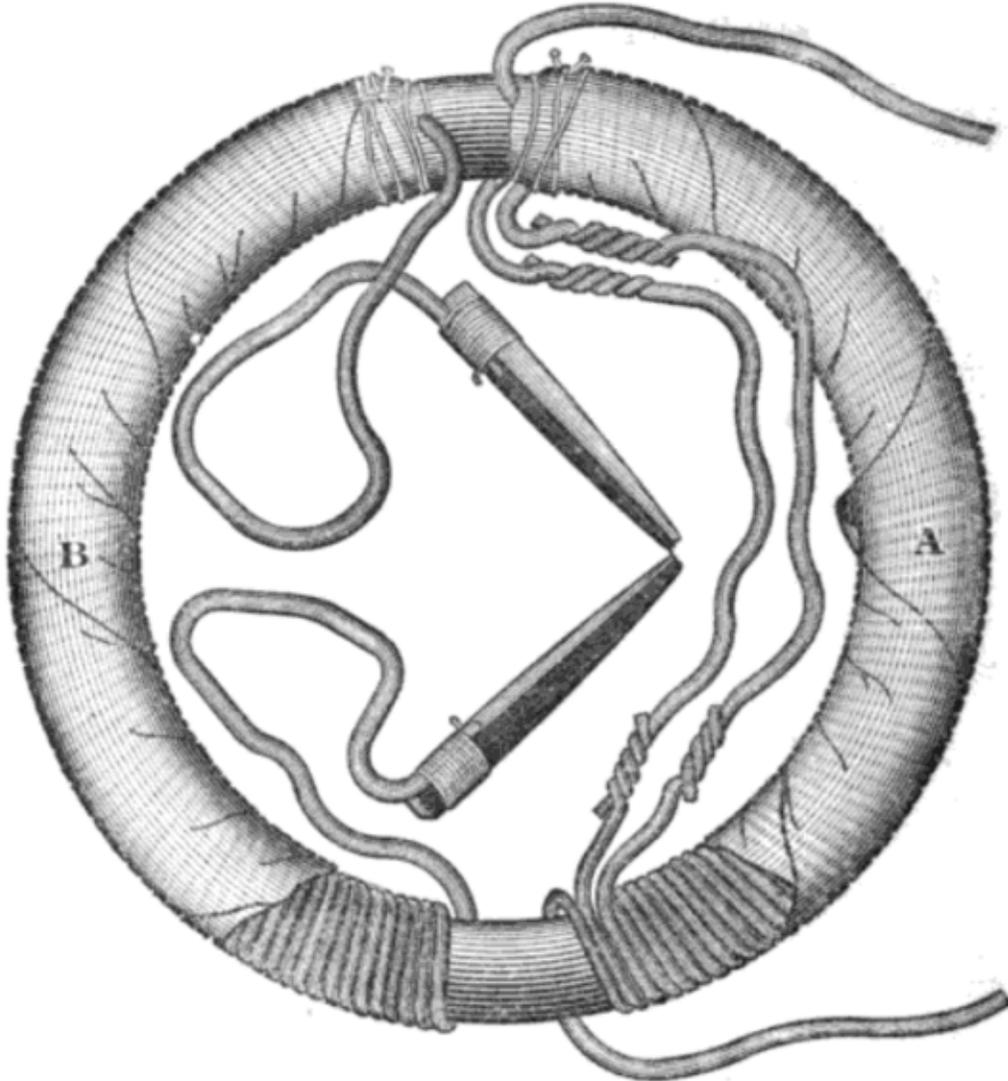
The phenomenon of electromagnetic induction was discovered independently by Michael Faraday and Joseph Henry in 1831. However, Faraday was the first to publish the results of his experiments and thus receive credit for the discovery. The relationship between electromotive force (EMF) or "voltage" and 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.

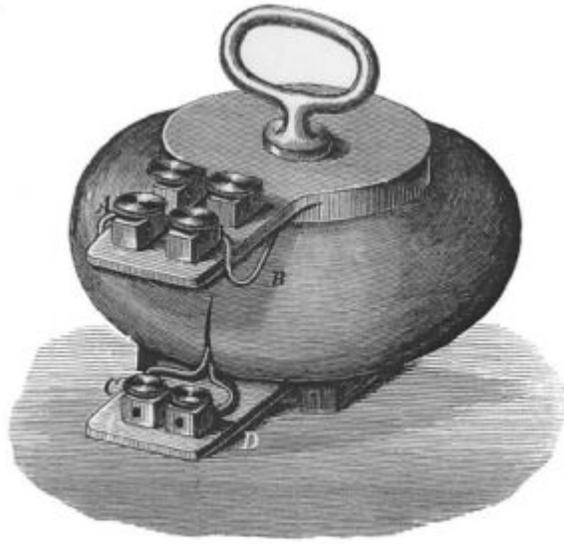
In 1878, the Ganz Company in Hungary began manufacturing equipment for electric lighting and, by 1883, had installed over fifty systems in Austria-Hungary. Their systems used alternating current exclusively and included those comprising both arc and incandescent lamps, along with generators and other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

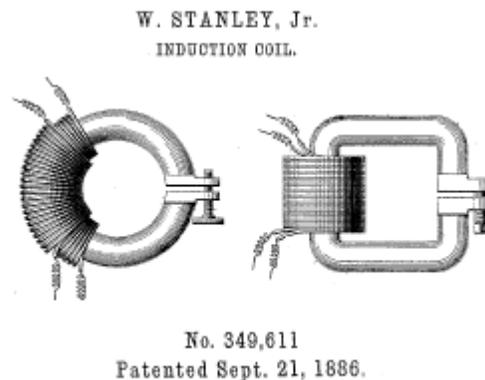


Drawing of Ganz Company's 1885 prototype. Capacity: 1400 VA, frequency: 40 Hz, voltage ratio: 120/72 V



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

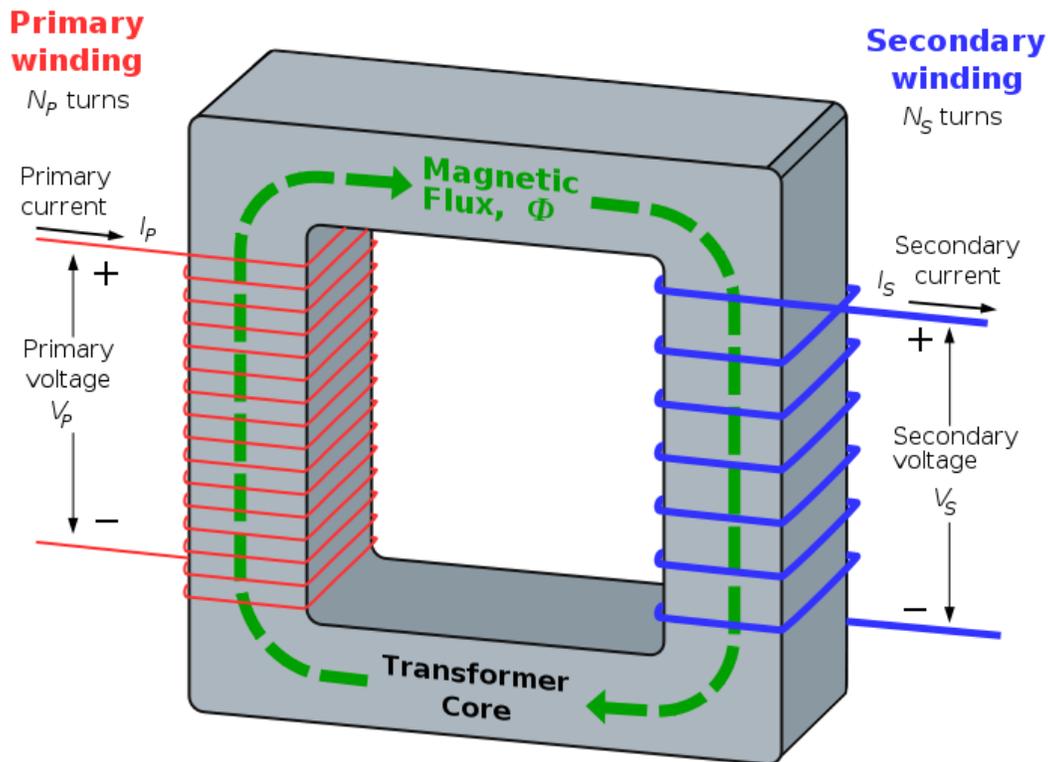
In 1889, Russian-born engineer Mikhail Dolivo-Dobrovolsky developed the first three-phase transformer at the Allgemeine Elektrizitäts-Gesellschaft ("General Electricity Company") in Germany.

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

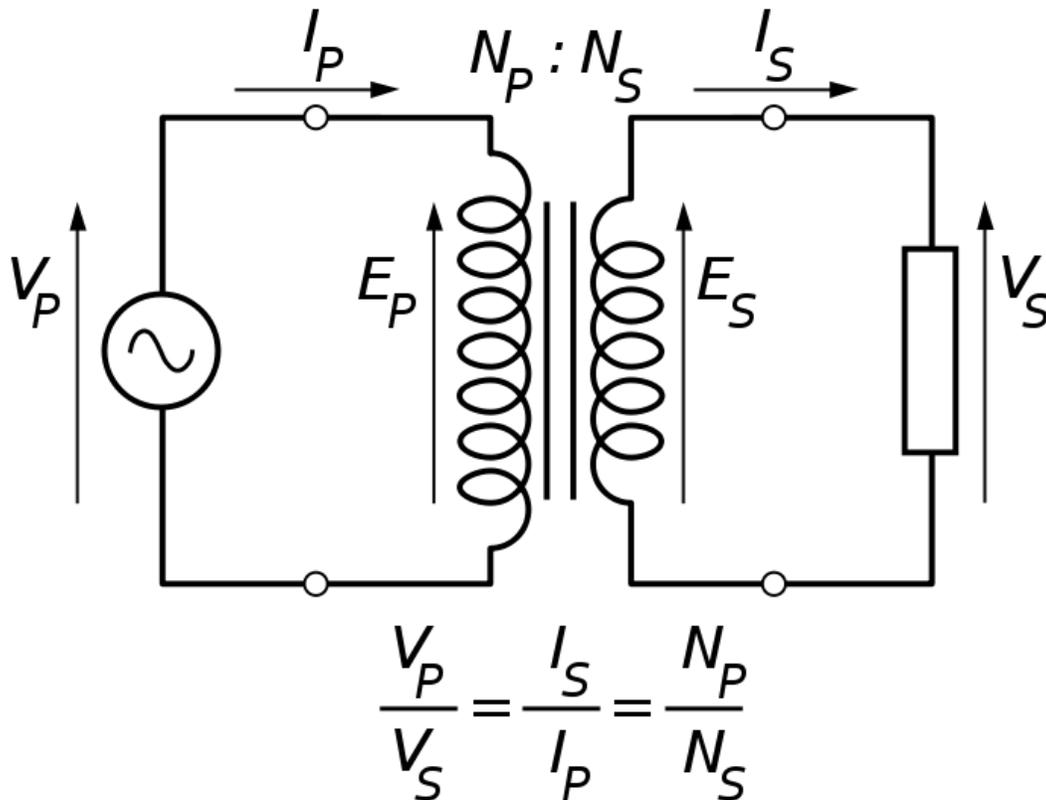
$$V_P = N_P \frac{d\Phi}{dt}.$$

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

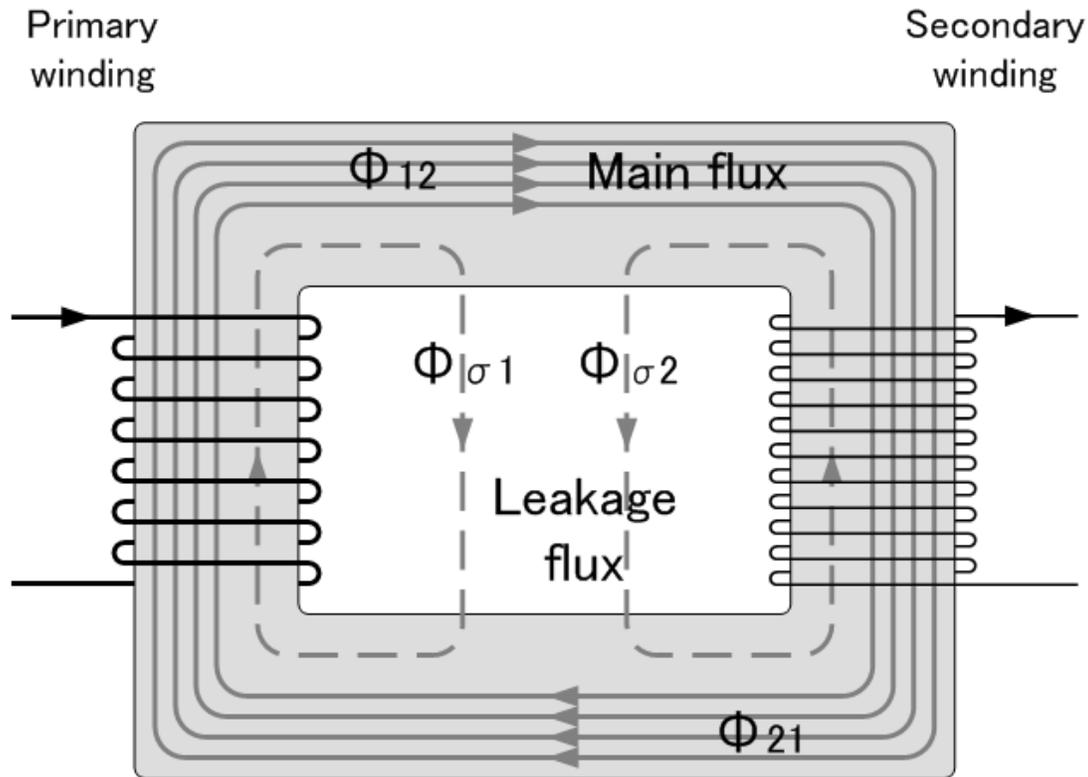
The simplified description above neglects several practical factors, in particular the primary current required to establish a magnetic field in the core, and the contribution to the field due to current in the secondary circuit.

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

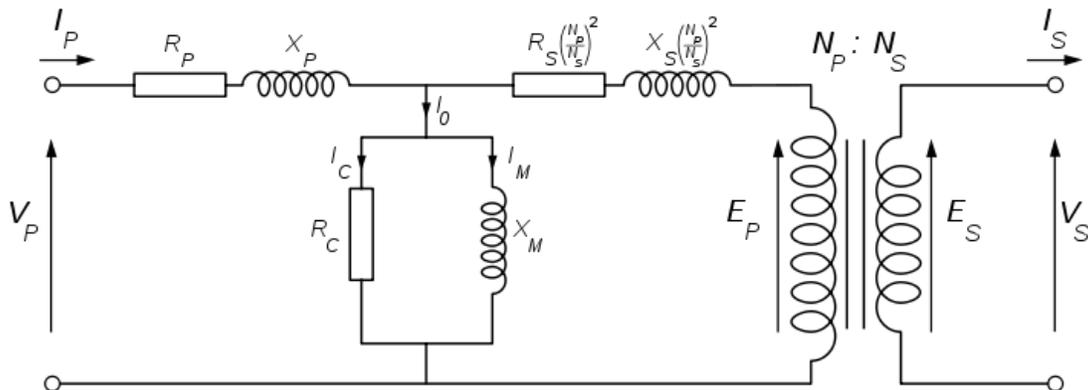
The physical limitations of the practical transformer may be brought together as an equivalent circuit model (shown below) built around an ideal lossless transformer. Power loss in the windings is current-dependent and is represented as in-series resistances R_p and R_s . Flux leakage results in a fraction 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



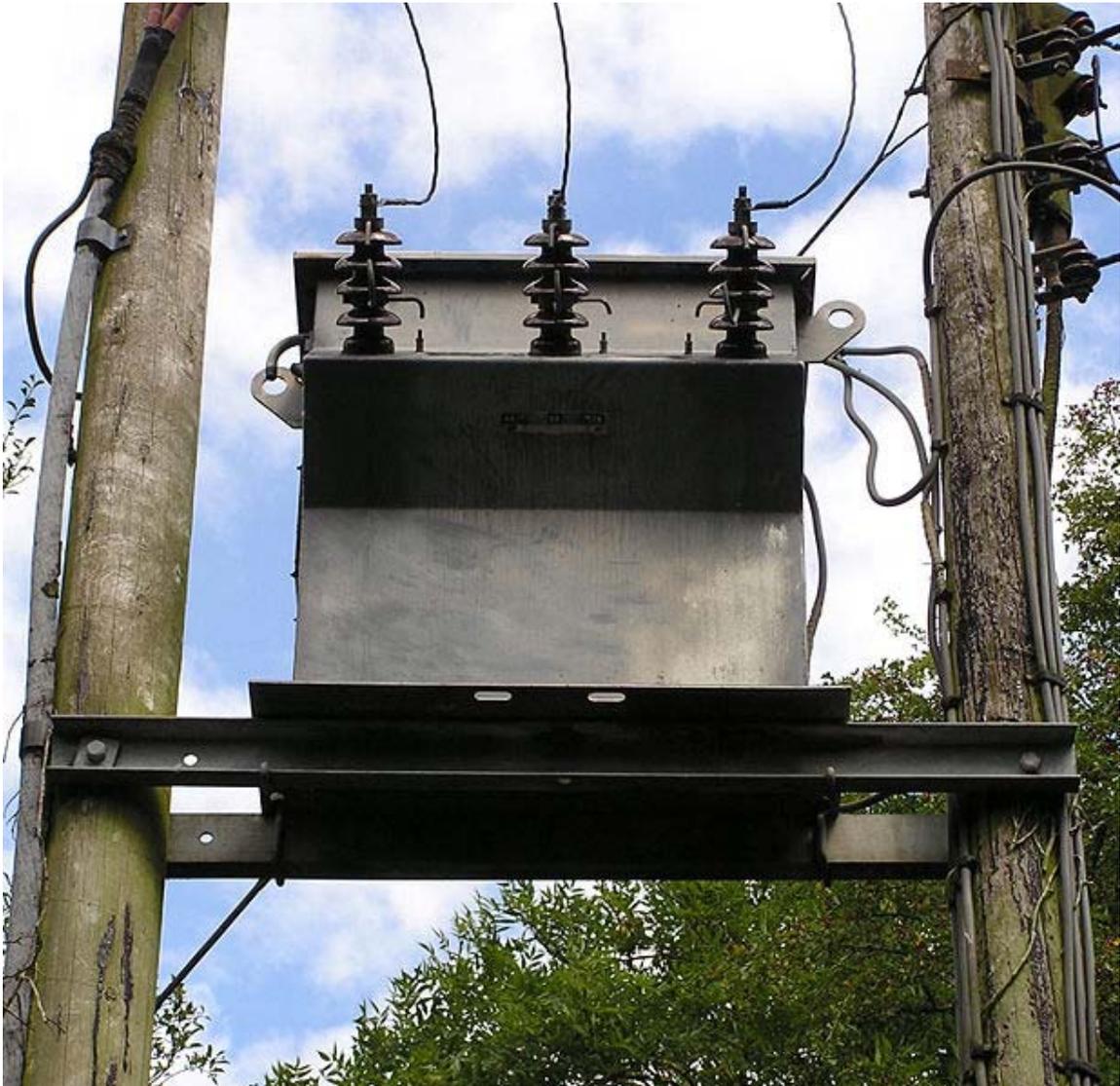
A variable autotransformer

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*.

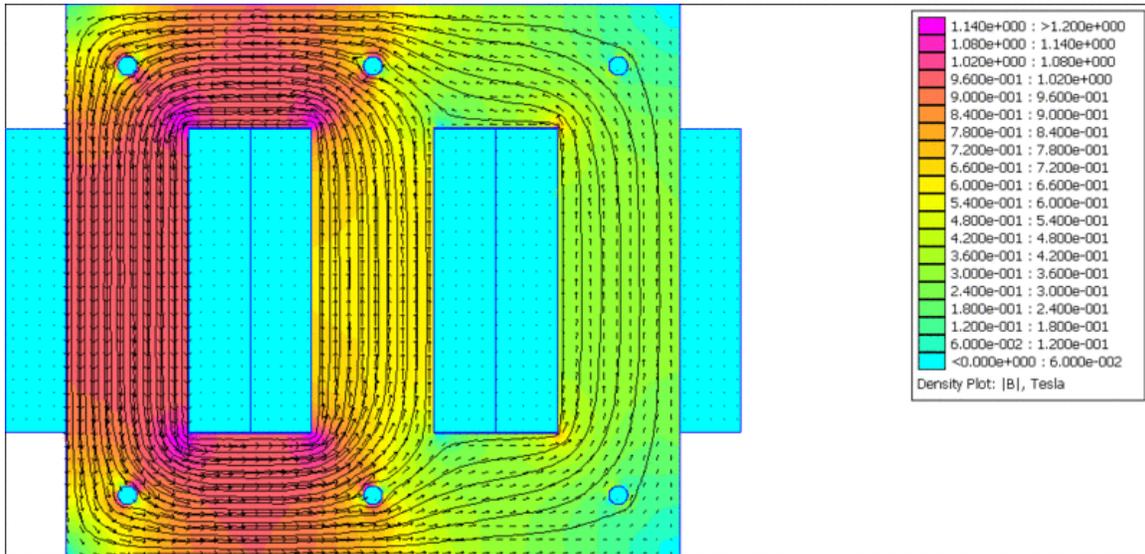
Polyphase transformers



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

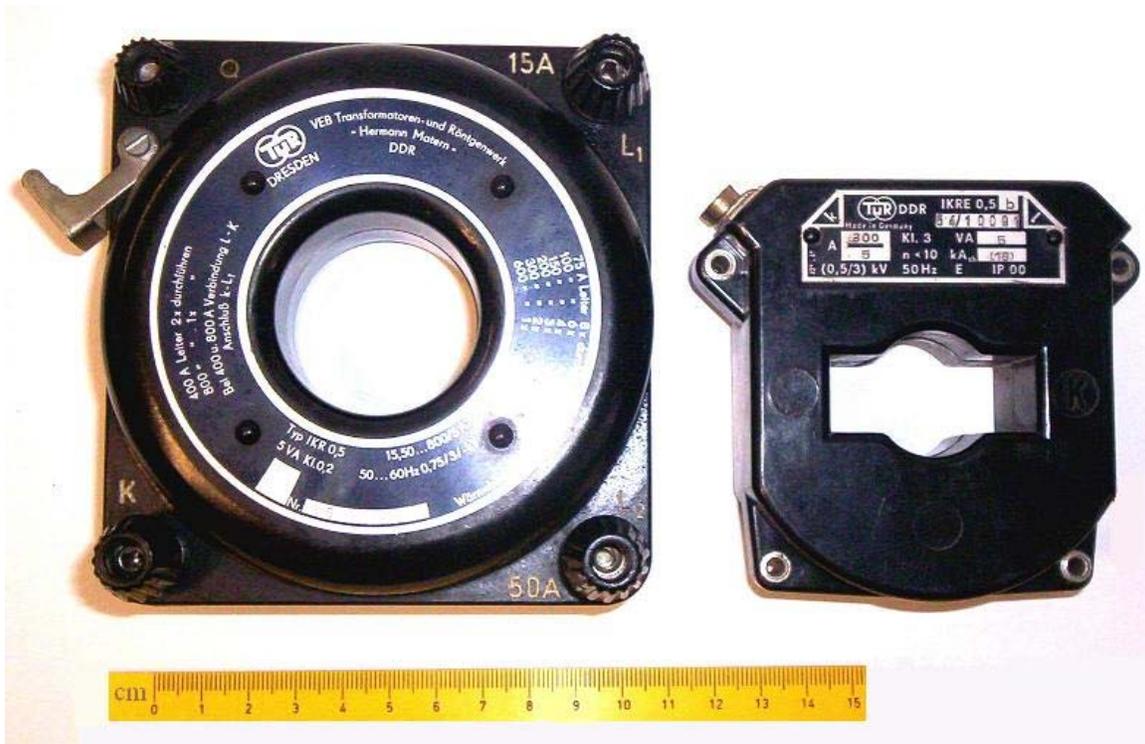
Audio transformers are those specifically designed for use in audio circuits. They can be used to block radio frequency interference or the DC component of an audio signal, to split or combine audio signals, or to provide impedance matching between high and low impedance circuits, such as between a high 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

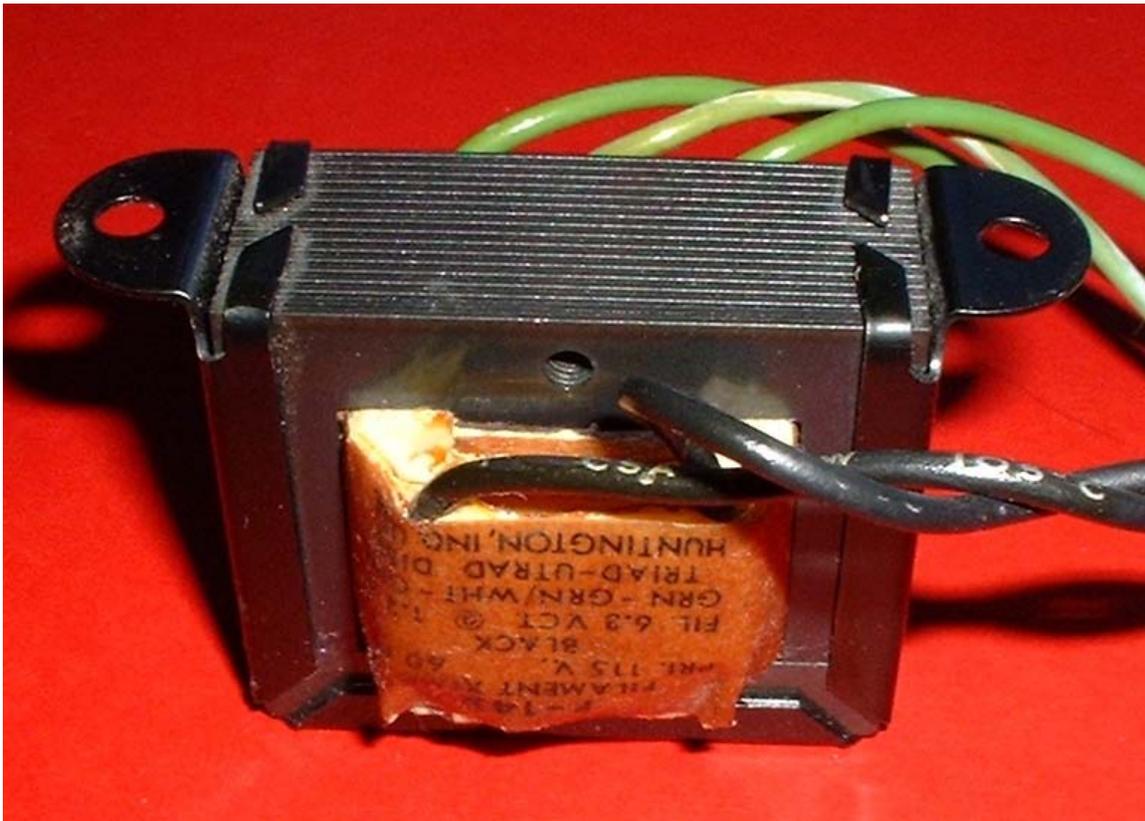
Transformers can be classified in many different ways; an incomplete list is:

- *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



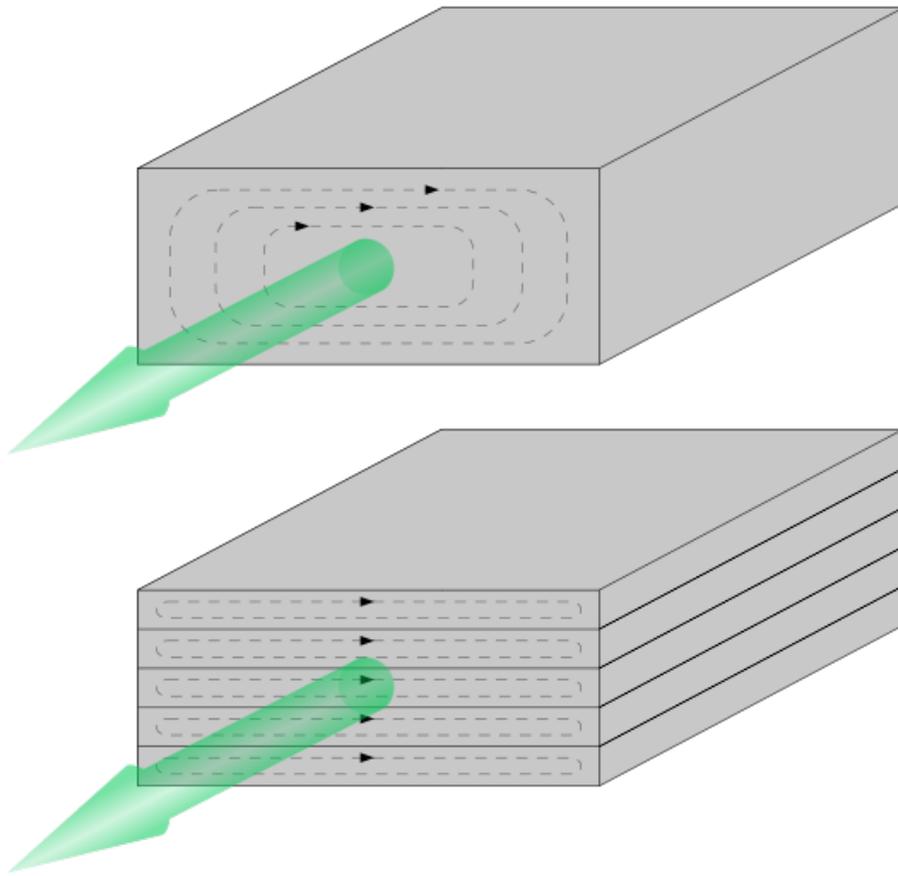
Laminated core transformer showing edge of laminations at top of photo

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.

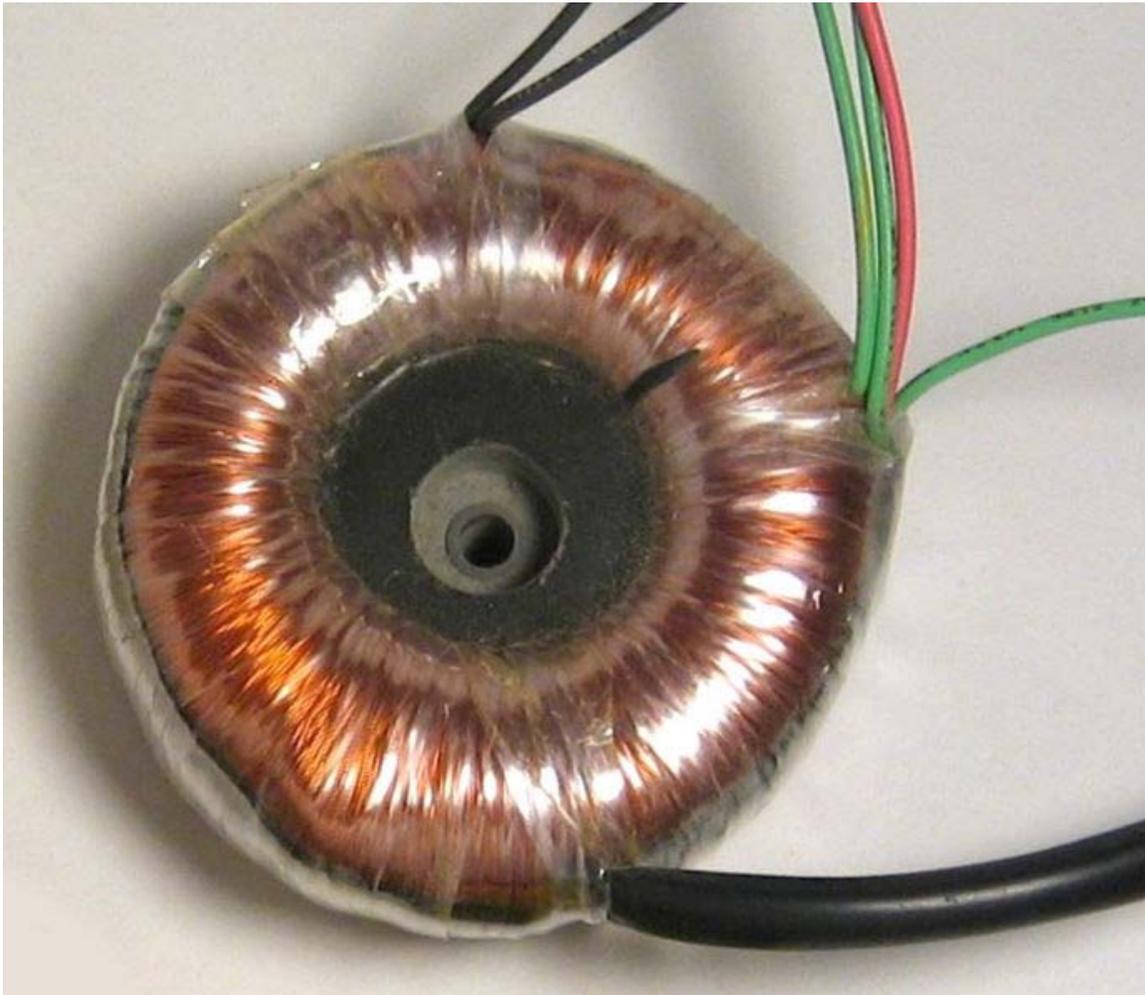
A steel core's remanence means that it retains a static magnetic field when power is removed. When power is then reapplied, the residual field will cause a high inrush current until the effect of the remaining magnetism is reduced, usually after a few cycles of the applied alternating current. Overcurrent 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

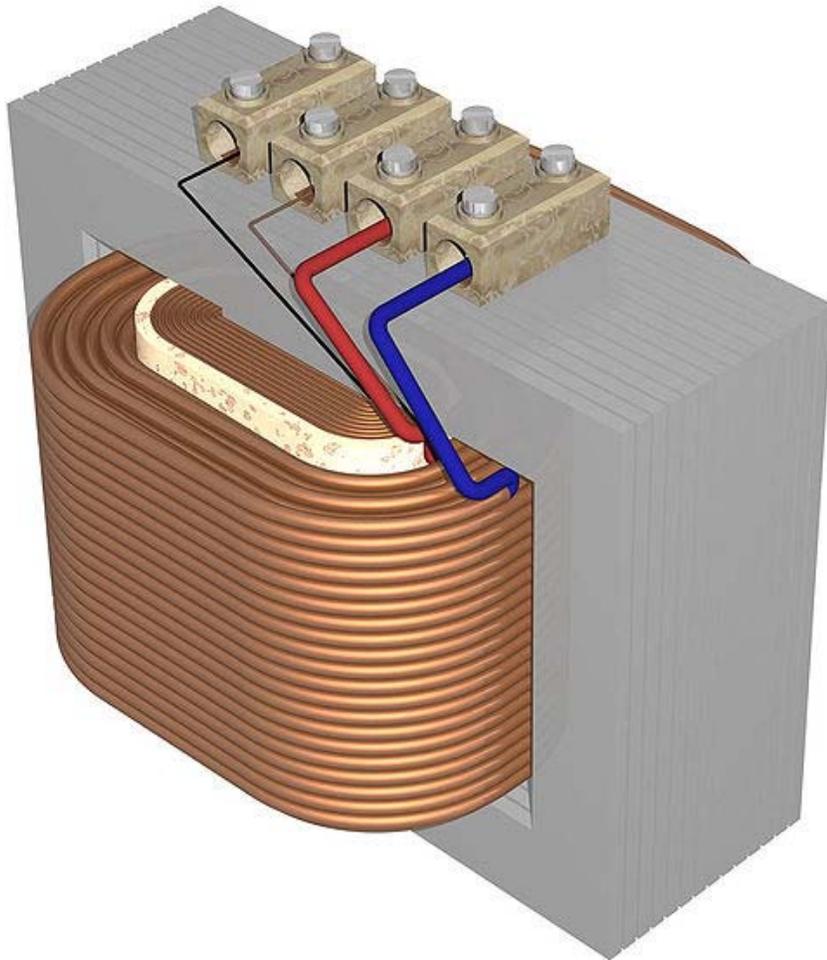
amplifiers), lower exterior magnetic field (about one tenth), low off-load losses (making them more efficient in standby circuits), single-bolt mounting, and greater choice of shapes. The main disadvantages are higher cost and limited power capacity. Because of the lack of a residual gap in the magnetic 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.

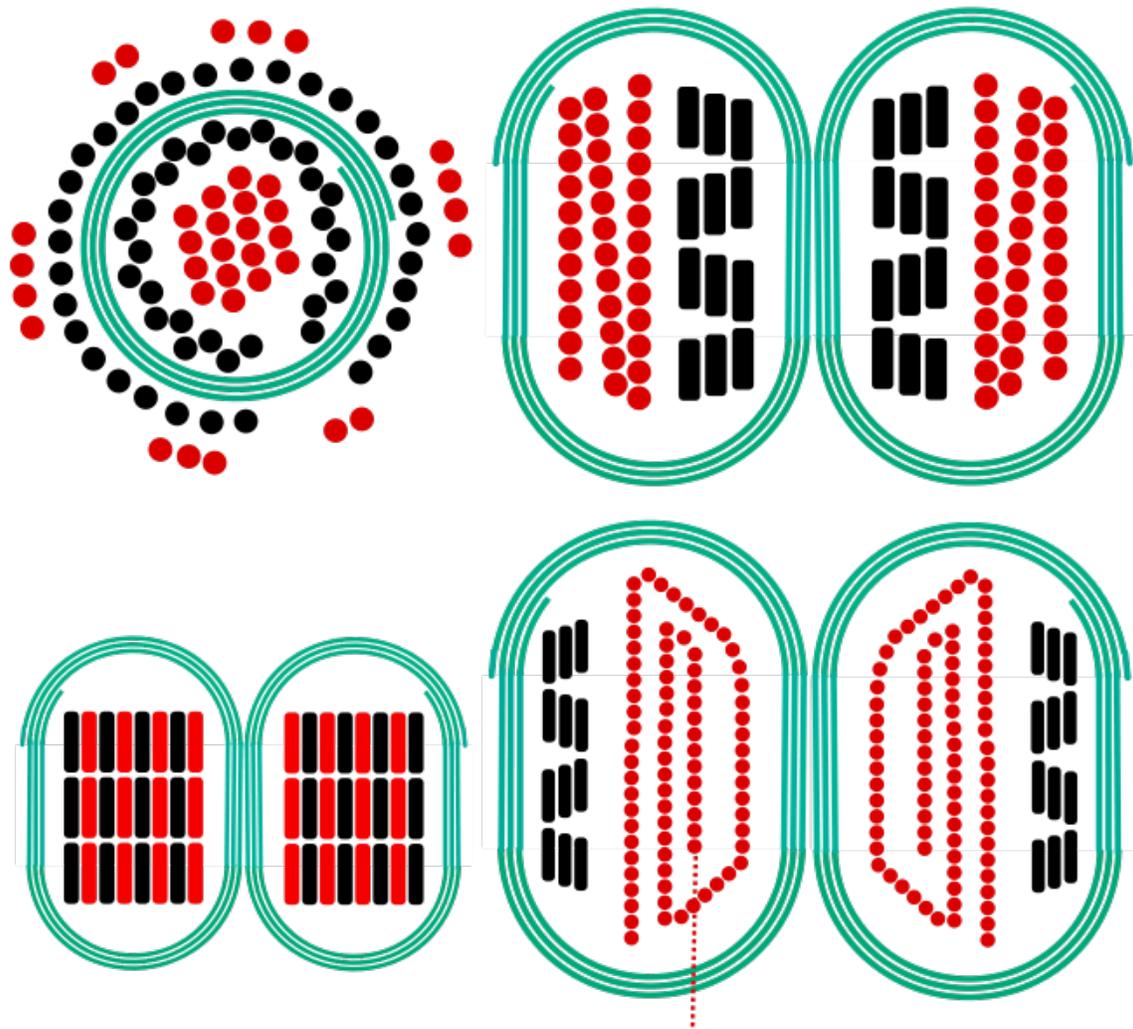
Air cores

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.

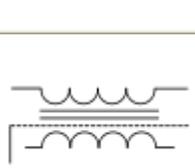
Transformers are also used extensively in electronic products to step down the supply voltage to a level suitable for the low voltage circuits they contain. The transformer also electrically isolates the end user from contact with the supply voltage.

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

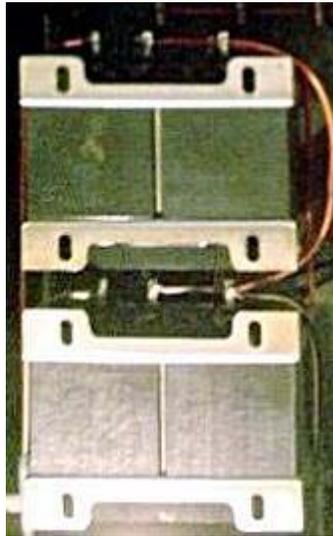
Transformer Types

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

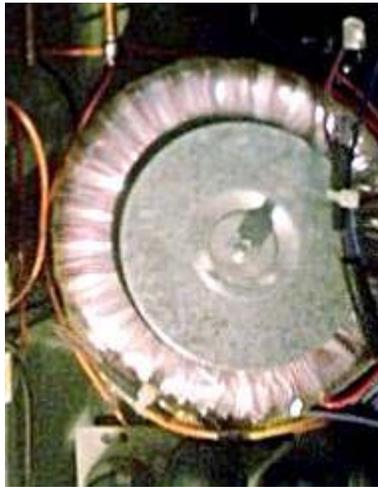


Laminated Core Transformer

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.

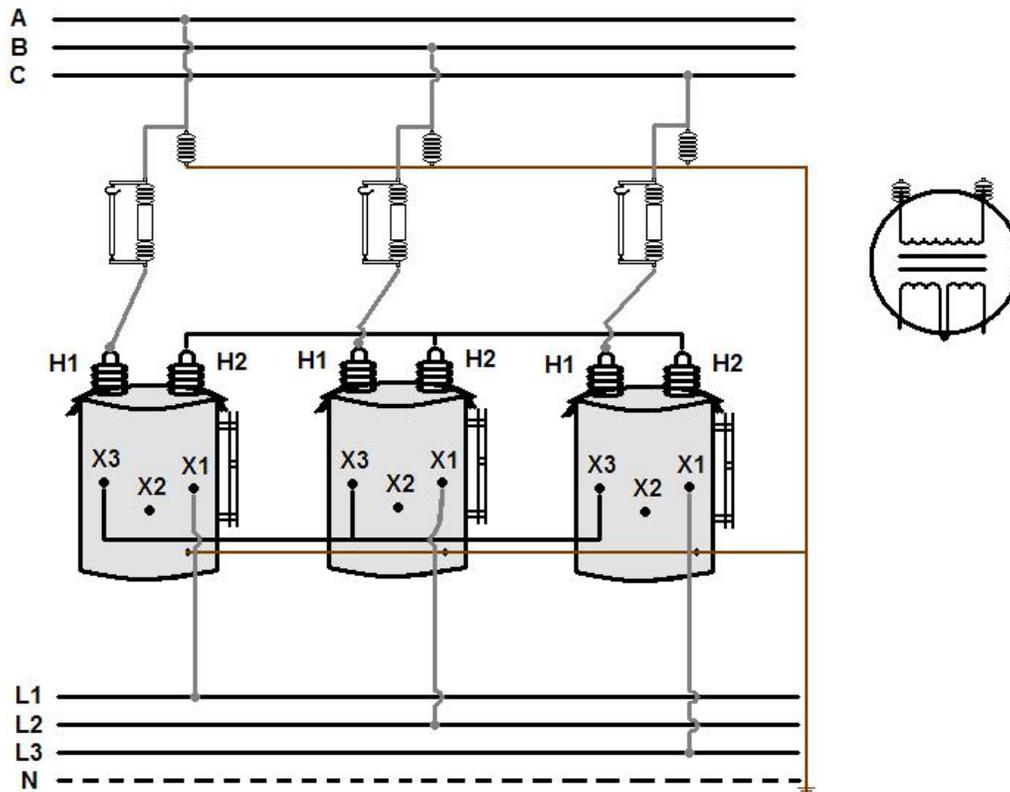
Hence, such regulators find widespread use in high-voltage laboratories.

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.

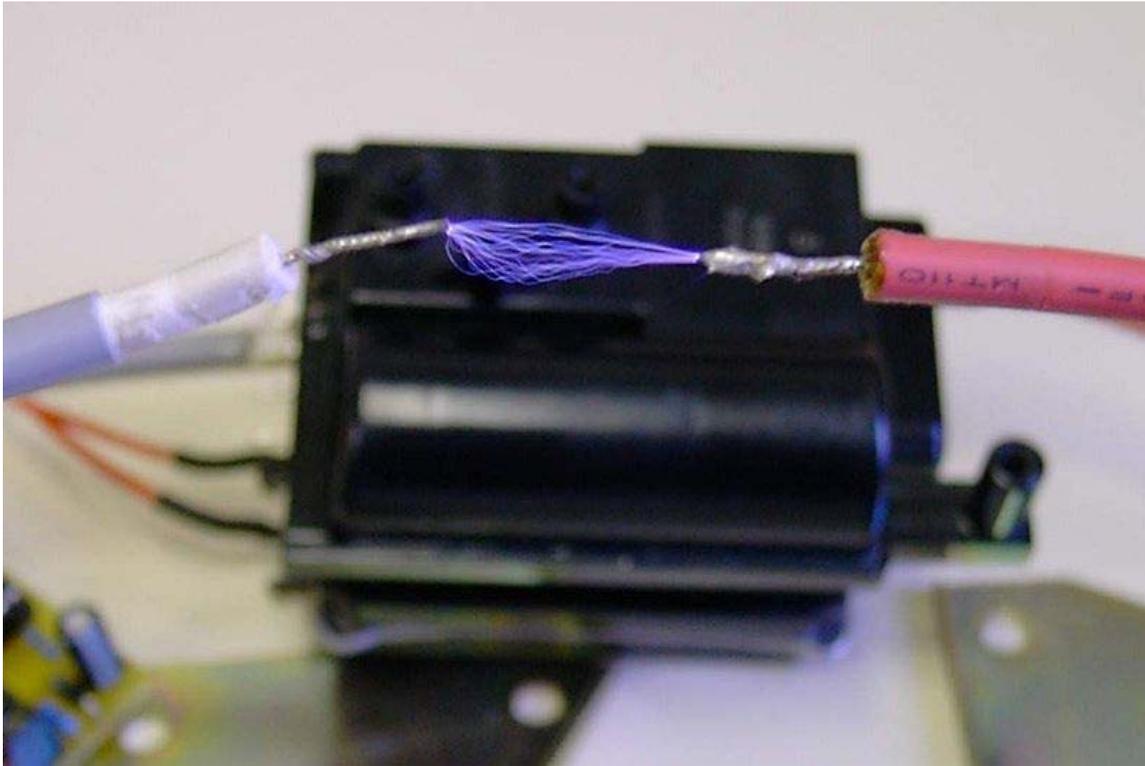
Polyphase transformers



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

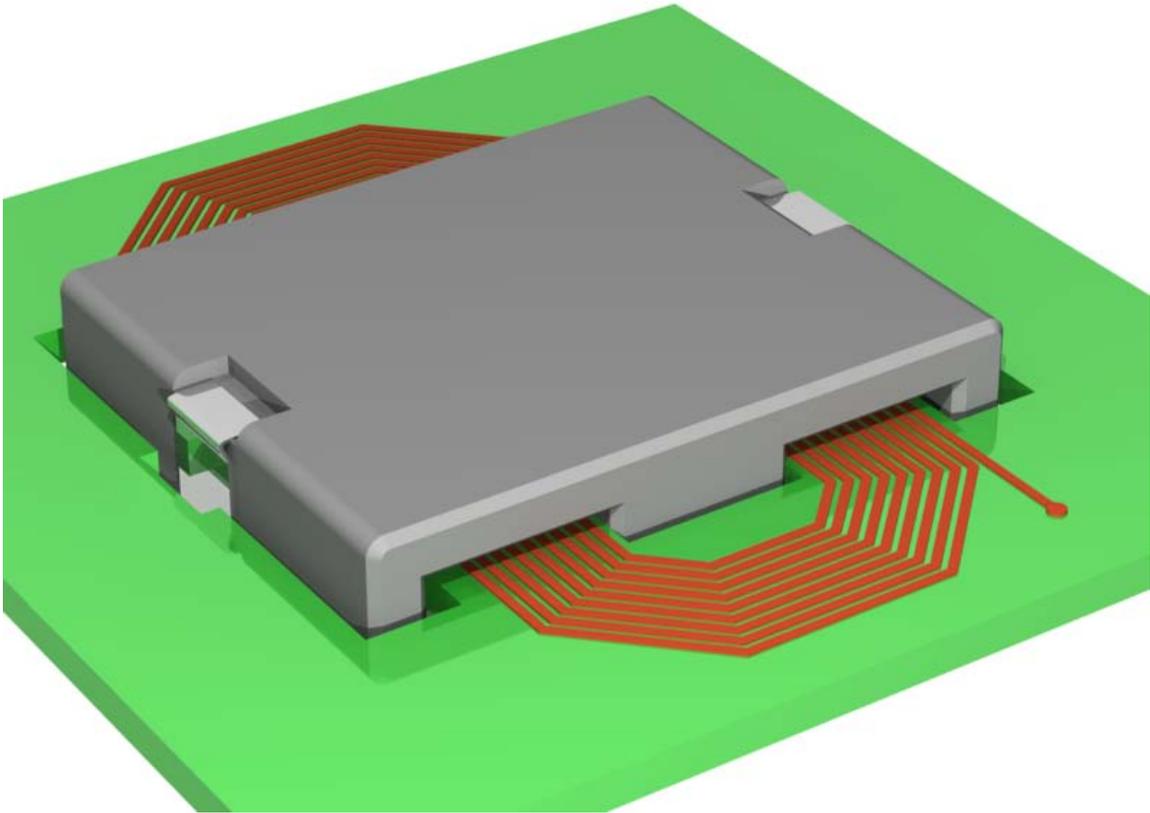
By arranging particular magnetic properties of a transformer core, and installing a ferro-resonant tank circuit (a capacitor and an additional winding), a transformer can be arranged to automatically keep the secondary winding voltage relatively constant for varying primary supply without additional 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

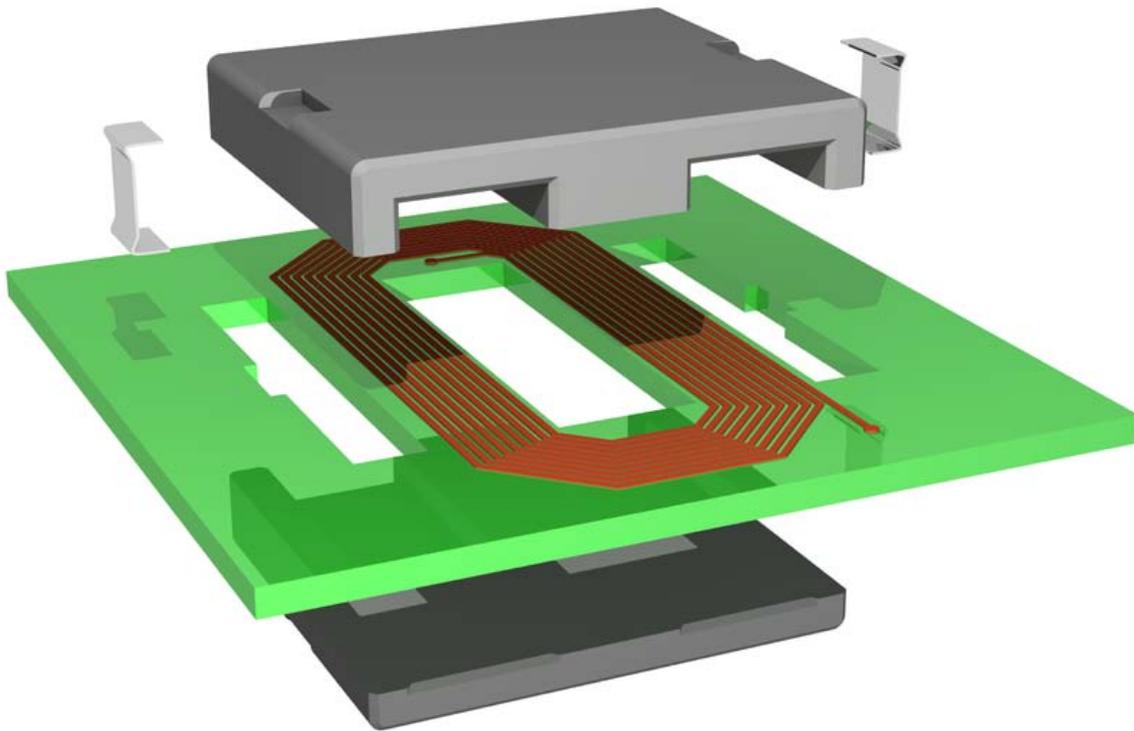
Ferrite core power transformers are widely used in switched-mode power supplies (SMPSs). The powder core enables high-frequency operation, and hence much smaller size-to-power ratio than laminated-iron transformers.

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

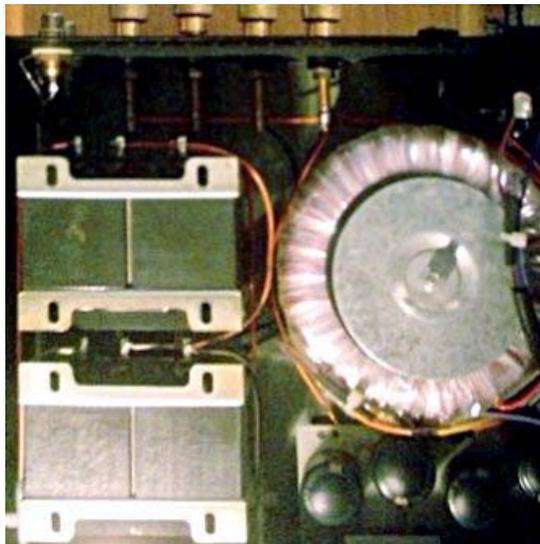
For radio frequency use, transformers are sometimes made from configurations of transmission line, sometimes bifilar or coaxial cable, wound around ferrite or other types of core. This style of transformer gives an extremely wide bandwidth but only a limited number of ratios (such as 1:9, 1:4 or 1:2)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

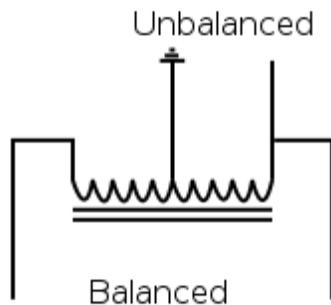


2 balun matching transformers

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

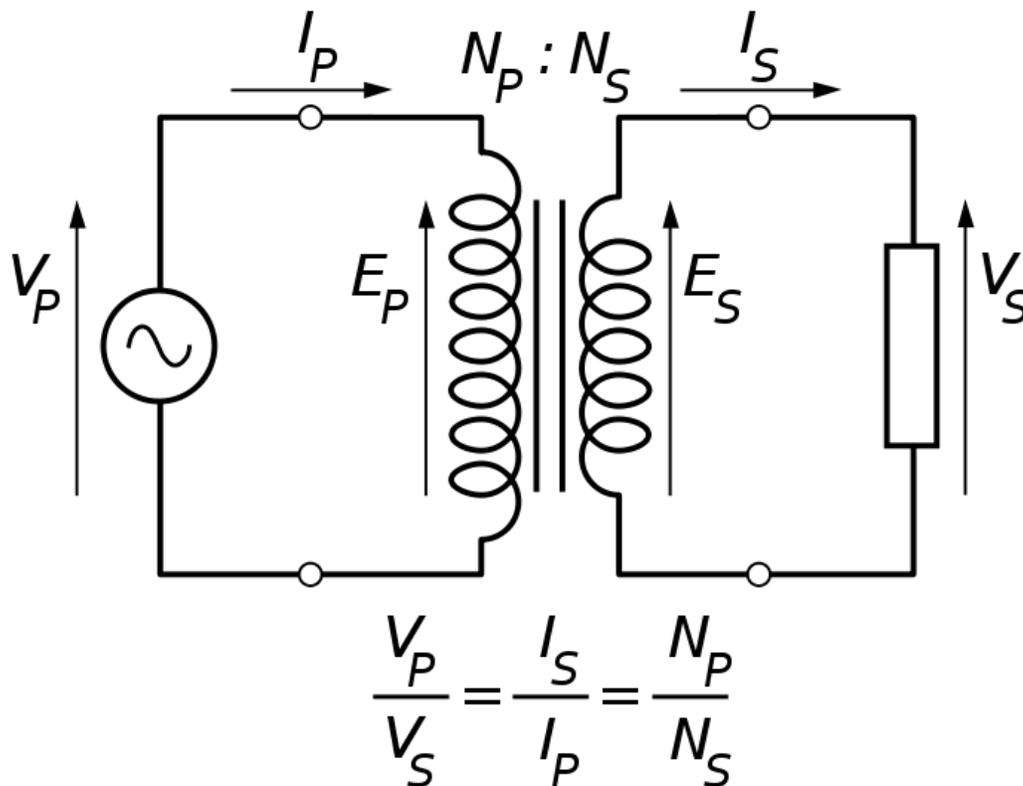


Autotransformer 4:1 wideband balun using two windings on a ferrite rod.

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.

Chapter-12

Current Transformer

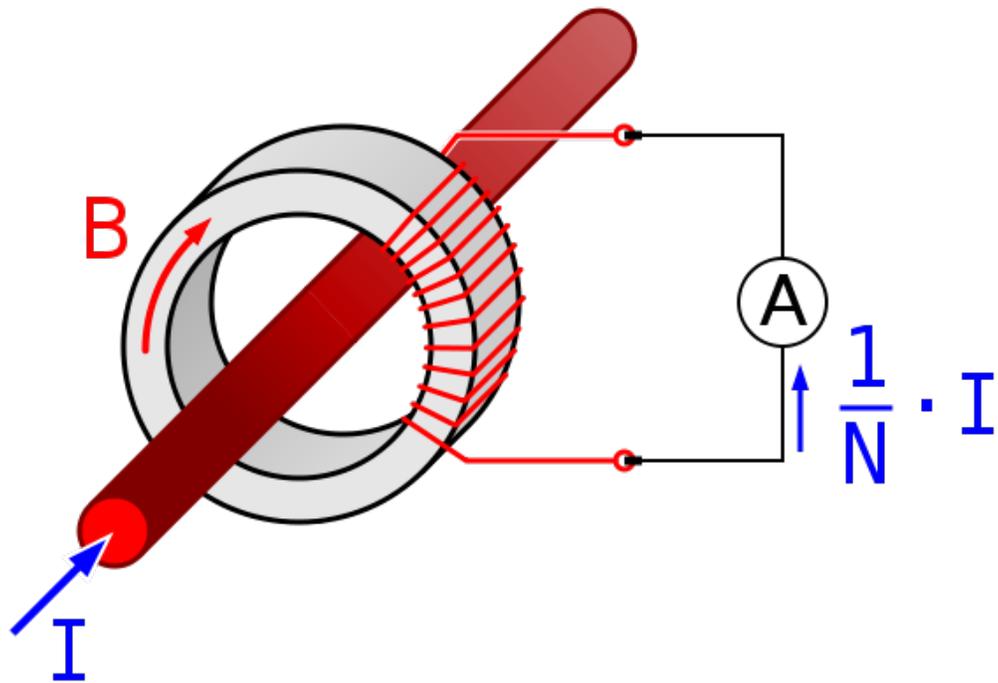


A CT for operation on a 110 kV grid

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-13

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.

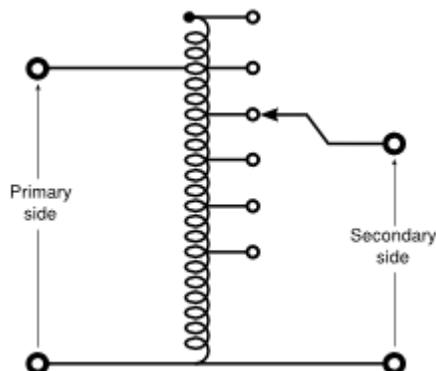
Chapter-14

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).

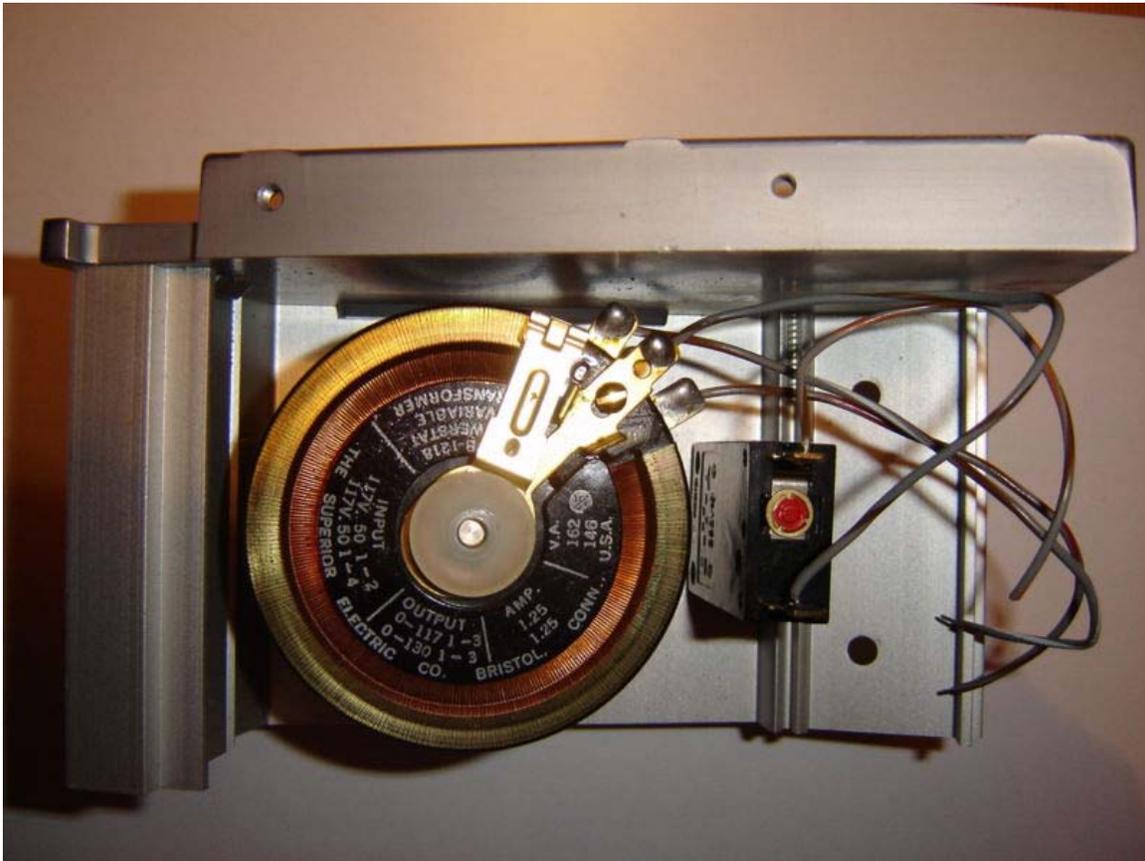
In audio applications, tapped autotransformers are used to adapt speakers to constant-voltage audio distribution systems, and for impedance matching such as between a low-impedance microphone and a high-impedance amplifier input.

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-15

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

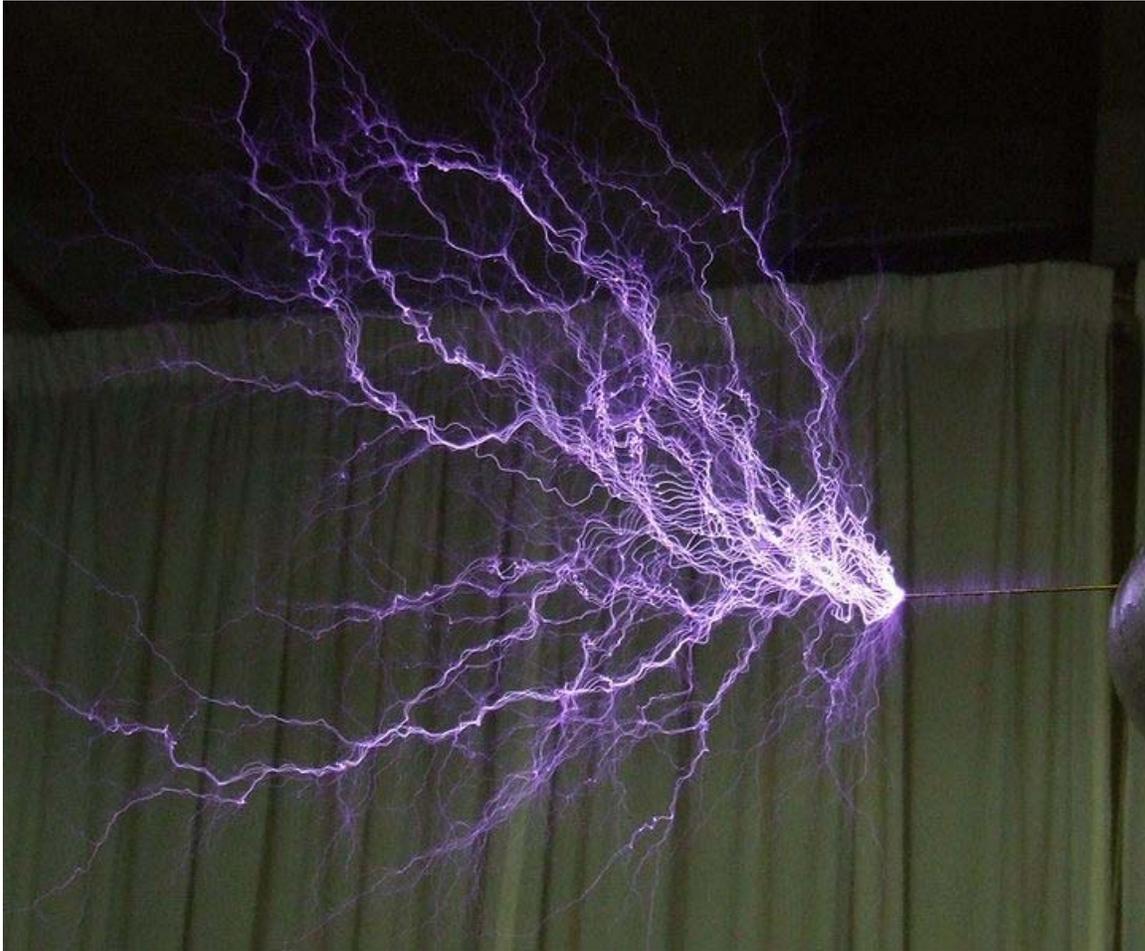
A Tesla coil transformer operates in a significantly different fashion than a conventional (i.e., iron core) transformer. In a conventional transformer, the windings are very tightly coupled, and voltage gain is determined by the ratio of the numbers of turns in the windings. This works well at normal 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.



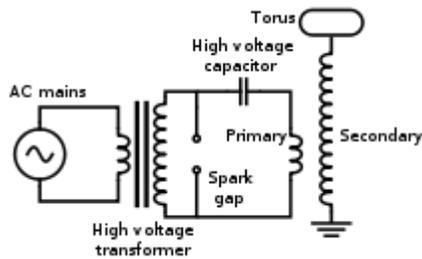
Demonstration of the Nevada Lightning Laboratory 1:12 scale prototype twin Tesla Coil at Maker Faire 2008.

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.

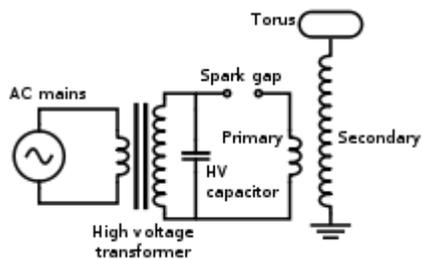
Applications

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

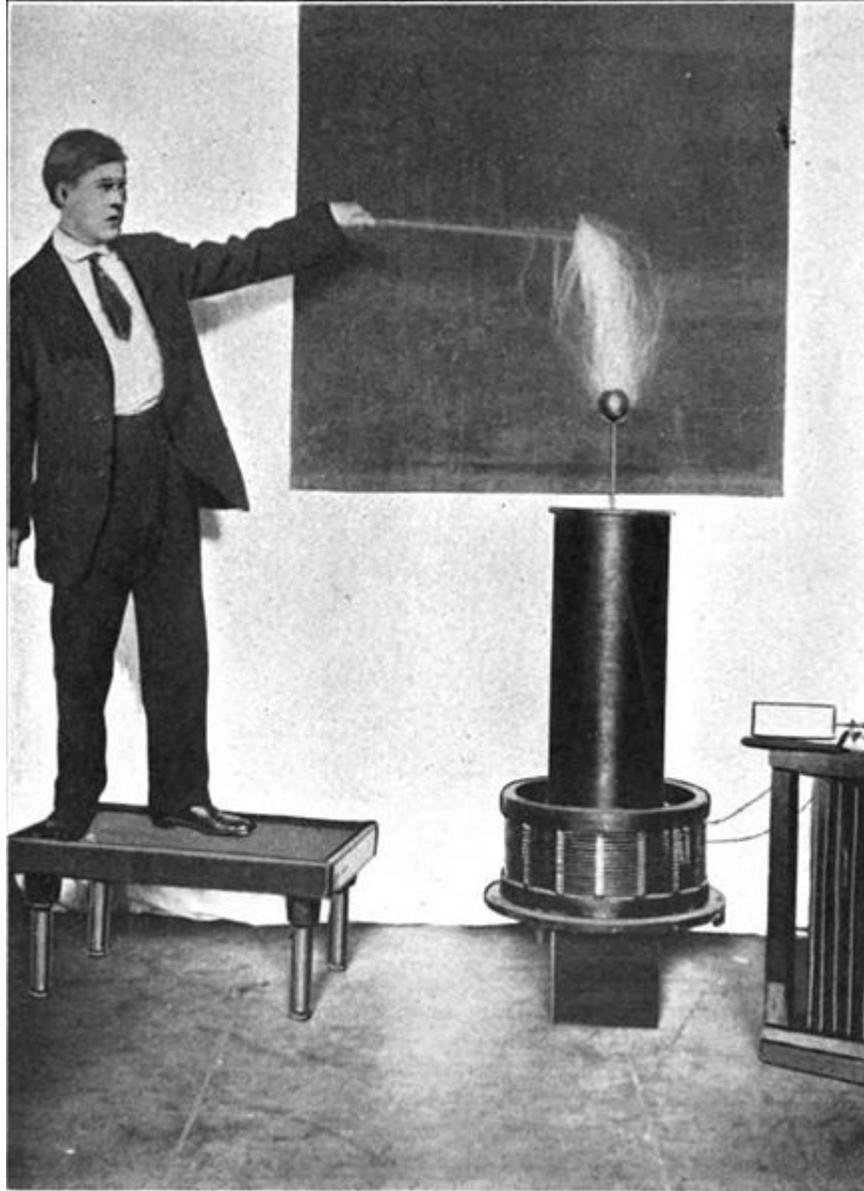
receiver with limitations that result in great disadvantages for utilization, though. The methods of ground conduction and the various induction methods can also be used to excite the Tesla coil receiver, but are again at a disadvantages for utilization. The charging-circuit can be adapted to be energized 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.

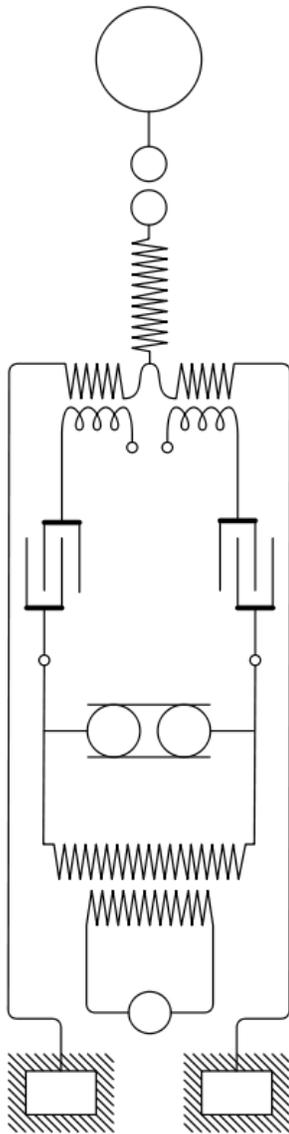
The most serious dangers associated with Tesla coil operation are associated with the primary circuit. It is the primary circuit that is capable of delivering a sufficient current at a significant voltage to stop the heart of a careless experimenter. Because these components are not the source of the 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.