Handbook of

Power Electronics & Electric Power Conversion

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Chapter 1

Introduction to Power Electronics

Power electronics is the application of solid-state electronics for the control and conversion of electric power.

Introduction

Power electronic converters can be found wherever there is a need to modify a form of electrical energy (i.e. change its voltage, current or frequency). The power range of these converters is from some milliwatts (as in a mobile phone) to hundreds of megawatts (e.g. in a HVDC transmission system). With "classical" electronics, electrical currents and voltage are used to carry information, whereas with power electronics, they carry power. Thus, the main metric of power electronics becomes the efficiency.

The first very high power electronic devices were mercury arc valves. In modern systems the conversion is performed with semiconductor switching devices such as diodes, thyristors and transistors. In contrast to electronic systems concerned with transmission and processing of signals and data, in power electronics substantial amounts of electrical energy are processed. An AC/DC converter (rectifier) is the most typical power electronics device found in many consumer electronic devices, e.g. television sets, personal computers, battery chargers, etc. The power range is typically from tens of watts to several hundred watts. In industry the most common application is the variable speed drive (VSD) that is used to control an induction motor. The power range of VSDs start from a few hundred watts and end at tens of megawatts.

The power conversion systems can be classified according to the type of the input and output power

DC-to-DC converter

A DC-to-DC converter is an electronic circuit which converts a source of direct current (DC) from one voltage level to another. It is a class of power converter.

Usage

DC to DC converters are important in portable electronic devices such as cellular phones and laptop computers, which are supplied with power from batteries primarily. Such electronic devices often contain several sub-circuits, each with its own voltage level requirement different from that supplied by the battery or an external supply (sometimes higher or lower than the supply voltage). Additionally, the battery voltage declines as its stored power is drained. Switched DC to DC converters offer a method to increase voltage from a partially lowered battery voltage thereby saving space instead of using multiple batteries to accomplish the same thing.

Most DC to DC converters also regulate the output voltage. Some exceptions include high-efficiency LED power sources, which are a kind of DC to DC converter that regulates the current through the LEDs, and simple charge pumps which double or triple the input voltage.

Conversion methods

Electronic

DC-DC

Linear

Linear regulators can only output at lower voltages from the input. They are very inefficient when the voltage drop is large and the current is high as they dissipate heat equal to the product of the output current and the voltage drop; consequently they are not normally used for large-drop high-current applications.

The inefficiency wastes power and requires higher-rated, and consequently more expensive and larger, components. The heat dissipated by high-power supplies is a problem in itself as it must be removed from the circuitry to prevent unacceptable temperature rises.

They are practical if the current is low, the power dissipated being small, although it may still be a large fraction of the total power consumed. They are often used as part of a simple regulated power supply for higher currents: a transformer generates a voltage which, when rectified, is a little higher than that needed to bias the linear regulator. The linear regulator drops the excess voltage, reducing hum-generating ripple current and

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providing a constant output voltage independent of normal fluctuations of the unregulated input voltage from the transformer / bridge rectifier circuit and of the load current.

Linear regulators are inexpensive, reliable if good heat sinking is used and much simpler than switching regulators. As part of a power supply they may require a transformer, which is larger for a given power level than that required by a switch-mode power supply. Linear regulators can provide a very low-noise output voltage, and are very suitable for powering noise-sensitive low-power analog and radio frequency circuits. A popular design approach is to use an LDO, Low Drop-out Regulator, that provides a local "point of load" DC supply to a low power circuit.

Switched-mode conversion

Electronic switch-mode DC to DC converters convert one DC voltage level to another, by storing the input energy temporarily and then releasing that energy to the output at a different voltage. The storage may be in either magnetic field storage components (inductors, transformers) or electric field storage components (capacitors). This conversion method is more power efficient (often 75% to 98%) than linear voltage regulation (which dissipates unwanted power as heat). This efficiency is beneficial to increasing the running time of battery operated devices. The efficiency has increased since the late 1980's due to the use of power FETs, which are able to switch at high frequency more efficiently than power bipolar transistors, which have more switching losses and require a more complex drive circuit. Another important innovation in DC-DC converters is the use of synchronous rectification which replaces the flywheel diode with a power FET with low "On" resistance, thereby reducing switching losses.

Most DC to DC converters are designed to move power in only one direction, from the input to the output. However, all switching regulator topologies can be made bi-directional by replacing all diodes with independently controlled active rectification. A bi-directional converter can move power in either direction, which is useful in applications requiring regenerative braking.

Drawbacks of switching converters include complexity, electronic noise (EMI / RFI) and to some extent cost, although this has come down with advances in chip design.

DC to DC converters are now available as integrated circuits needing minimal additional components. DC to DC converters are also available as a complete hybrid circuit component, ready for use within an electronic assembly.

Magnetic

In these DC to DC converters, energy is periodically stored into and released from a magnetic field in an inductor or a transformer, typically in the range from 300 kHz to 10 MHz. By adjusting the duty cycle of the charging voltage (that is, the ratio of on/off time), the amount of power transferred can be controlled. Usually, this is done to control the output voltage, though it could be done to control the input current, the output current, or maintain a constant power. Transformer-based converters may provide isolation between the input and the output. In general, the term "DC to DC converter" refers to one of these switching converters. These circuits are the heart of a switched-mode power supply. Many topologies exist. This table shows the most common.

	Forward • **Energy goes from the input, through the magnetics and to the load, simultaneously**	**Flyback** • **Energy goes from the input and stored in the magnetics** • **Later, it is released from the magnetics to the load**

No transformer
• **Non-isolated**
	Step-down (Buck) - The output voltage is lower than the input voltage, and of the same polarity	• **Non-inverting**: The output voltage is the same polarity as the input
		    o Step-up (Boost) - The output voltage is higher than the input voltage
		    o SEPIC - The output voltage can be lower or higher than the input
		• **Inverting**: the output voltage is of the opposite polarity as the input
		    o Inverting (Buck-Boost)
		    o Ćuk - Output current is continuous

	True Buck-Boost - The output voltage is the same polarity as the input and can be lower or higher Split-Pi (Boost-Buck) - Allows bidirectional voltage conversion with the output voltage the same polarity as the input and can be lower or higher	

With transformer • **May be isolated**	• Half bridge - 2 transistors drive • Full bridge - 4 transistor drive	Flyback - 1 or 2 transistor drive

In addition, each topology may be:

- **Hard switched -** transistors switch quickly while exposed to both full voltage and full current
- **Resonant -** an LC circuit shapes the voltage across the transistor and current through it so that the transistor switches when either the voltage or the current is zero

Magnetic DC to DC converters may be operated in two modes, according to the current in its main magnetic component (inductor or transformer):

- **Continuous -** the current fluctuates but never goes down to zero
- **Discontinuous -** the current fluctuates during the cycle, going down to zero at or before the end of each cycle

A converter may be designed to operate in Continuous mode at high power, and in Discontinuous mode at low power.

The Half bridge and Flyback topologies are similar in that energy stored in the magnetic core needs to be dissipated so that the core does not saturate. Power transmission in a flyback circuit is limited by the amount of energy that can be stored in the core, while forward circuits are usually limited by the I/V characteristics of the switches.

Although MOSFET switches can tolerate simultaneous full current and voltage (although thermal stress and electromigration can shorten the MTBF), bipolar switches generally can't so require the use of a snubber (or two).

Capacitive

Switched capacitor converters rely on alternately connecting capacitors to the input and output in differing topologies. For example, a switched-capacitor reducing converter might charge two capacitors in series and then discharge them in parallel. This would produce an output voltage of half the input voltage, but at twice the current (minus various inefficiencies). Because they operate on discrete quantities of charge, these are also sometimes referred to as charge pump converters. They are typically used in applications requiring relatively small amounts of current, as at higher current loads the increased efficiency and smaller size of switch-mode converters makes them a better choice. They are also used at extremely high voltages, as magnetics would break down at such voltages.

Electrochemical

A further means of DC to DC conversion in the kW to many MW range is presented by using redox flow batteries such as the vanadium redox battery, although this technique has not been applied commercially to date.

Terminology

Step-down - A converter where output voltage is lower than the input voltage. Like a Buck converter.

Step-up - A converter that outputs a voltage higher than the input voltage. Like a Boost converter.

Continuous Current Mode - Current and thus the magnetic field in the inductive energy storage never reach zero.

Discontinuous Current Mode - Current and thus the magnetic field in the inductive energy storage may reach or cross zero.

Noise - Since all properly designed DC to DC converters are completely inaudible, "noise" in discussing them always refers to unwanted electrical and electromagnetic signal noise.

Output noise - The output of a DC to DC converter is designed to have a flat, constant output voltage. Unfortunately, all real DC to DC converters produce an output that constantly varies up and down from the nominal designed output voltage. This varying voltage on the output is the output noise. All DC to DC converters, including linear regulators, have some thermal output noise. Switching converters have, in addition, switching noise at the switching frequency and its harmonics. Some sensitive radio frequency and analog circuits require a power supply with so little noise that it can only be provided by a linear regulator. Many analog circuits require a power supply with relatively low noise, but can tolerate some of the less-noisy switching converters .

Input noise - If the converter loads the input with sharp load edges. Electrical noise can be emitted from the supplying power lines as RF noise. Which should be prevented with proper filtering in the input stage of the converter.

RF noise - Switching converters inherently emit radio waves at the switching frequency and its harmonics. Switching converters that produce triangular switching current, such as the Split-Pi or Ćuk converter in continuous current mode, produce less harmonic noise

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than other switching converters. Linear converters produce practically no RF noise. Too much RF noise causes electromagnetic interference (EMI).

AC/AC converter

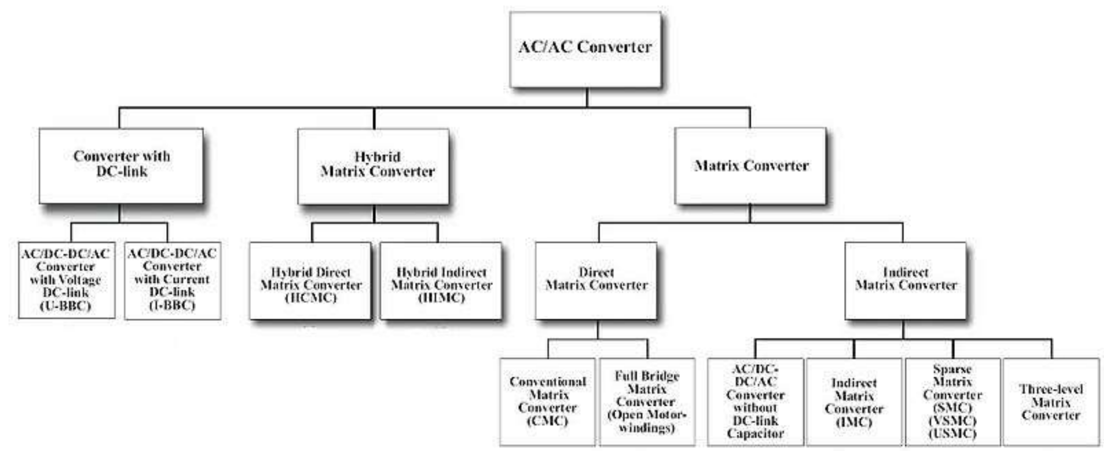

Fig 1: Classification of three-phace AC/AC converter circuits

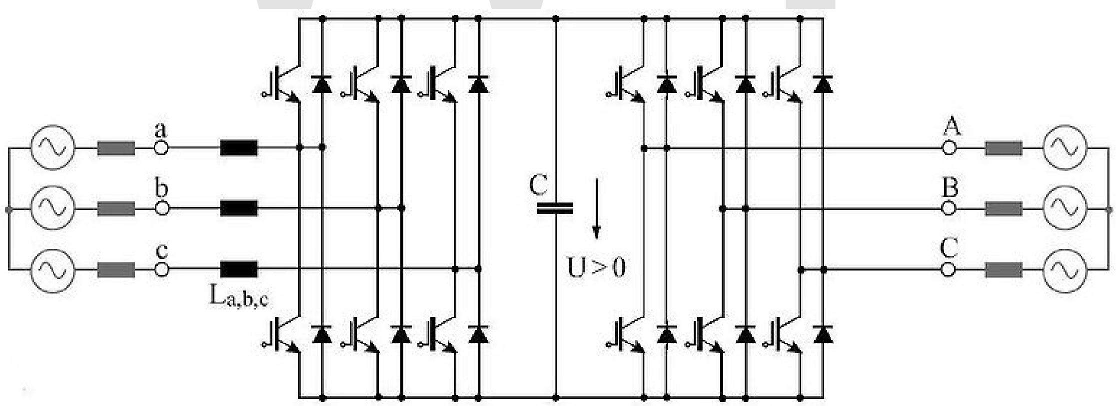

Fig 2: Topology of the three-phase AC/AC converter with voltage DC-link

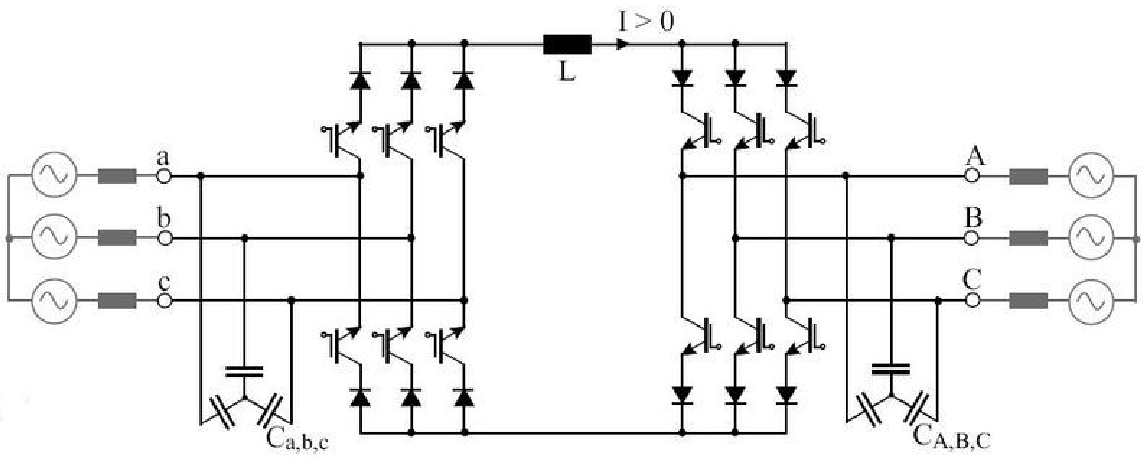

Fig 3: Topology of the three-phase AC/AC converter with current DC-link

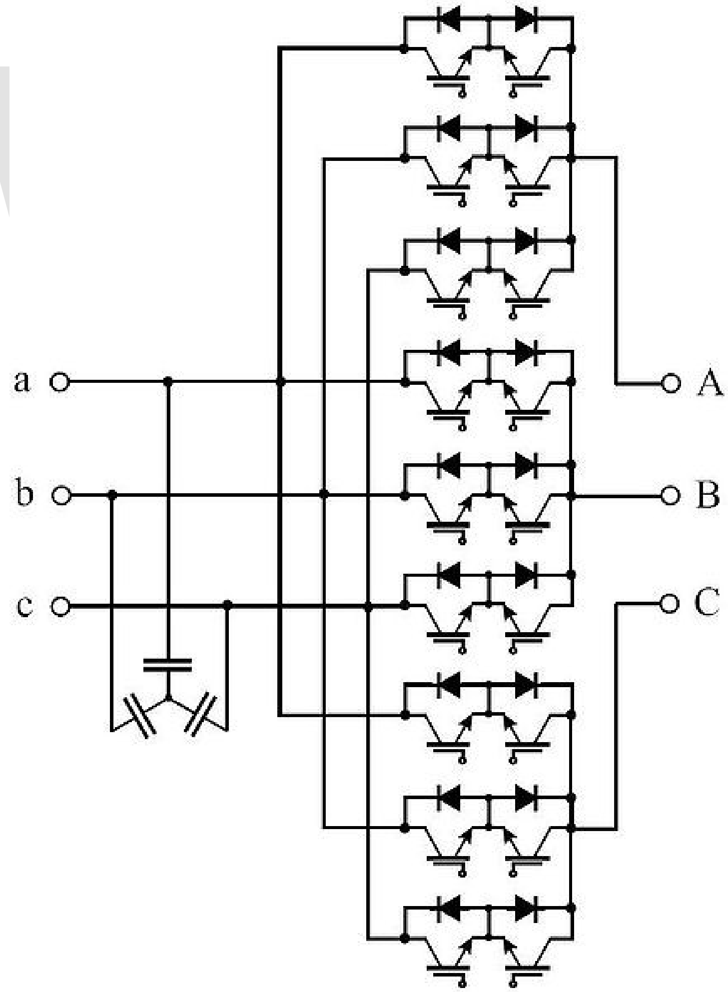

Fig 4: Topology of the Conventional Direct Matrix Converter

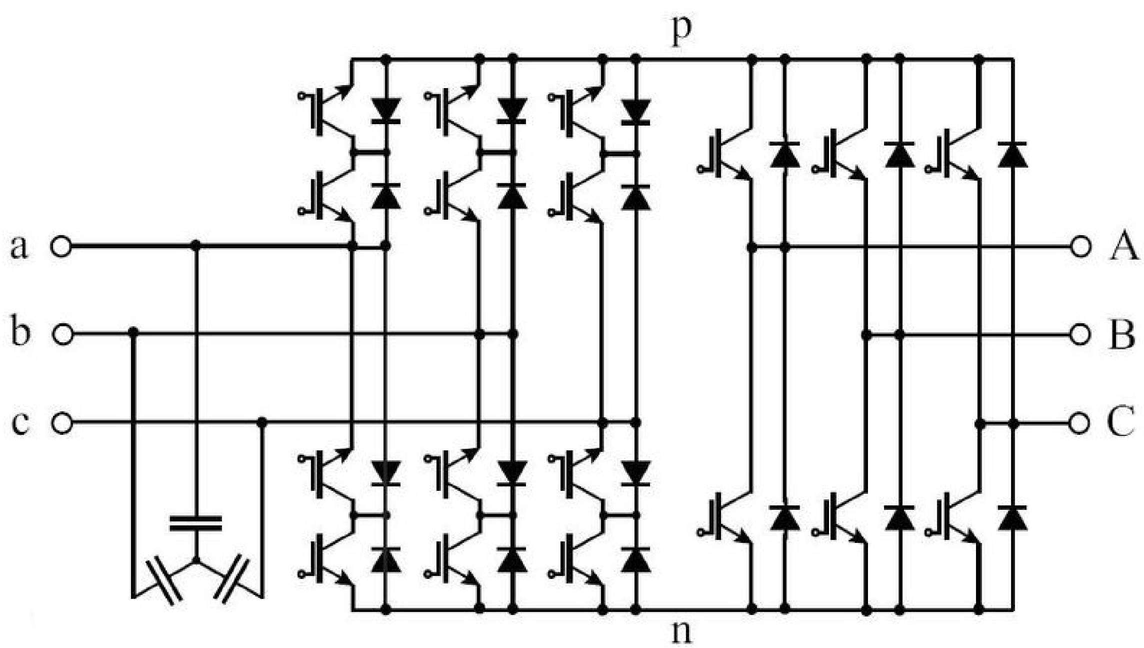

Fig 5: Topology of the indirect matrix converter

An **AC/AC converter** converts an AC waveform such as the mains supply, to another AC waveform, where the output voltage and frequency can be set arbitrarily.

AC/AC converters can be categorized into

- Converters with a DC-link.
- Cycloconverters
- Hybrid Matrix Converters.
- Matrix Converters.

As shown in Fig 1. For such AC-AC conversion today typically converter systems with a voltage (Fig. 2) or current (Fig. 3) DC-link are employed. For the voltage DC-link, the mains coupling could be implemented by a diode bridge. To accomplish braking operation of a motor, a braking resistor must be placed in the DC-link. Alternatively, an anti-parallel thyristor bridge must be provided on the mains side for feeding back energy into the mains. The disadvantages of this solution are the relatively high mains distortion and high reactive power requirements (especially during inverter operation).

An AC/AC converter with approximately sinusoidal input currents and bidirectional power flow can be realized by coupling a PWM rectifier and a PWM inverter to the DC-link. The DC-link quantity is then impressed by an energy storage element that is common to both stages, which is a capacitor C for the voltage DC-link or an inductor L for the current DC-link. The PWM rectifier is controlled in a way that a sinusoidal mains current is drawn, which is in phase or anti-phase (for energy feedback) with the corresponding mains phase voltage.

Due to the DC-link storage element, there is the advantage that both converter stages are to a large extent decoupled for control purposes. Furthermore, a constant, mains independent input quantity exists for the PWM inverter stage, which results in high utilization of the converter's power capability. On the other hand, the DC-link energy storage element has a relatively large physical volume, and when electrolytic capacitors are used, in the case of a voltage DC-link, there is potentially a reduced system lifetime.

In order to achieve higher power density and reliability, it is makes sense to consider Matrix Converters that achieve three-phase AC/AC conversion without any intermediate energy storage element. Conventional Direct Matrix Converters (Fig. 4) perform voltage and current conversion in one single stage.

A cycloconverter constructs an output, variable-frequency, approximately sinusoid waveform by switching segments of the input waveform to the output; there is no intermediate DC link. With switching elements such as SCRs, the output frequency must be lower than the input. Very large cycloconverters (on the order of 10 MW) are manufactured for compressor and wind-tunnel drives, or for variable-speed applications such as cement kilns.

There is the alternative option of indirect energy conversion by employing the Indirect Matrix Converter (Fig. 5) or the Sparse Matrix Converter which was invented by Prof. Johann W. Kolar from the ETH Zurich. As with the DC-link based systems (Fig. 2 and Fig. 3), separate stages are provided for voltage and current conversion, but the DC-link has no intermediate storage element. Generally, by employing matrix converters, the storage element in the DC-link is eliminated at the cost of a larger number of semiconductors. Matrix converters are often seen as a future concept for variable speed drives technology, but despite intensive research over the decades they have until now only achieved low industrial penetration. The reason for this could be the higher complexity in modulation and analysis effort.

Principle

As efficiency is at a premium in a power electronic converter, the losses that a power electronic device generates should be as low as possible. The instantaneous dissipated power of a device is equal to the product of the voltage across the device and the current through it ($P = V \times I$). From this, one can see that the losses of a power device are at a minimum when the voltage across it is zero (the device is in the On-State) or when no current flows through it (Off-State). Therefore, a power electronic converter is built around one (or more) device operating in switching mode (either On or Off). With such a structure, the energy is transferred from the input of the converter to its output by bursts. To convert the power electronics by using rectifier

Applications

Power electronic systems are found in virtually every electronic device. For example:

- DC/DC converters are used in most mobile devices (mobile phones, PDA etc.) to maintain the voltage at a fixed value whatever the voltage level of the battery is. These converters are also used for electronic isolation and power factor correction.
- AC/DC converters (rectifiers) are used every time an electronic device is connected to the mains (computer, television etc.). These may simply change AC to DC or can also change the voltage level as part of their operation.
- AC/AC converters are used to change either the voltage level or the frequency (international power adapters, light dimmer). In power distribution networks AC/AC converters may be used to exchange power between utility frequency 50 Hz and 60 Hz power grids.
- DC/AC converters (inverters) are used primarily in UPS or emergency lighting systems. When mains power is available, it will charge the DC battery. If the mains fails, an inverter will be used to produce AC electricity at mains voltage from the DC battery.

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Chapter 2

Rectifier

A **rectifier** is an electrical device that converts alternating current (AC), which periodically reverses direction, to direct current (DC), which is in only one direction, a process known as **rectification**. Rectifiers have many uses including as components of power supplies and as detectors of radio signals. Rectifiers may be made of solid state diodes, vacuum tube diodes, mercury arc valves, and other components.

A device which performs the opposite function (converting DC to AC) is known as an inverter.

When only one diode is used to rectify AC (by blocking the negative or positive portion of the waveform), the difference between the term *diode* and the term *rectifier* is merely one of usage, i.e., the term *rectifier* describes a *diode* that is being used to convert AC to DC. Almost all rectifiers comprise a number of diodes in a specific arrangement for more efficiently converting AC to DC than is possible with only one diode. Before the development of silicon semiconductor rectifiers, vacuum tube diodes and copper(I) oxide or selenium rectifier stacks were used.

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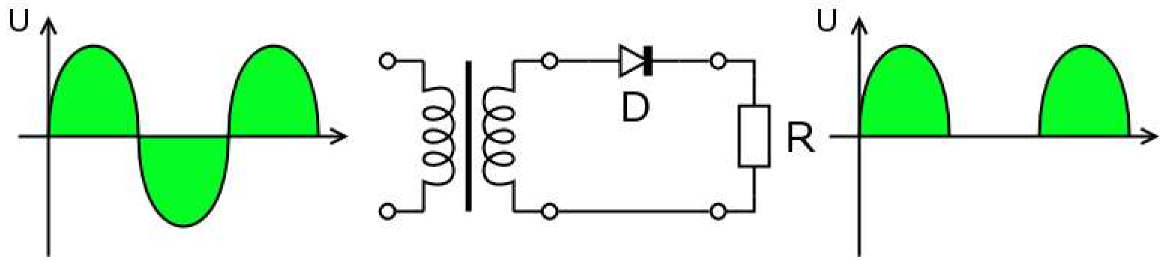
Early radio receivers, called crystal radios, used a "cat's whisker" of fine wire pressing on a crystal of galena (lead sulfide) to serve as a point-contact rectifier or "crystal detector". Rectification may occasionally serve in roles other than to generate direct current per se. For example, in gas heating systems *flame rectification* is used to detect presence of flame. Two metal electrodes in the outer layer of the flame provide a current path, and rectification of an applied alternating voltage will happen in the plasma, but only while the flame is present to generate it.

Half-wave rectification

In half wave rectification, either the positive or negative half of the AC wave is passed, while the other half is blocked. Because only one half of the input waveform reaches the output, it is very inefficient if used for power transfer. Half-wave rectification can be achieved with a single diode in a one-phase supply, or with three diodes in a three-phase supply.



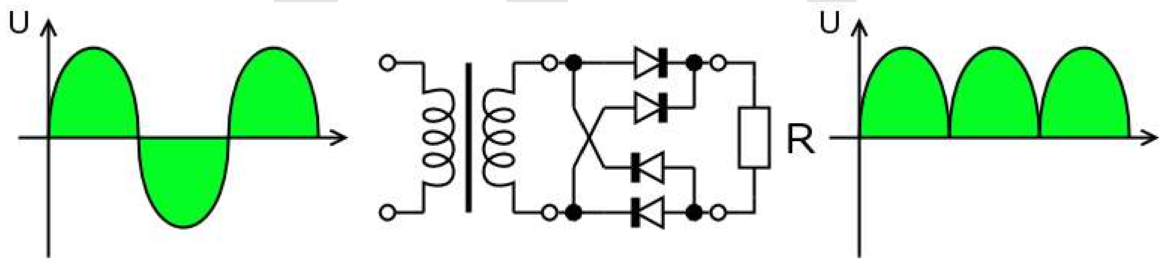
The output DC voltage of a half wave rectifier can be calculated with the following two ideal equations:

$$V_{rms} = \frac{V_{peak}}{2}$$

$$V_{dc} = \frac{V_{peak}}{\pi}$$

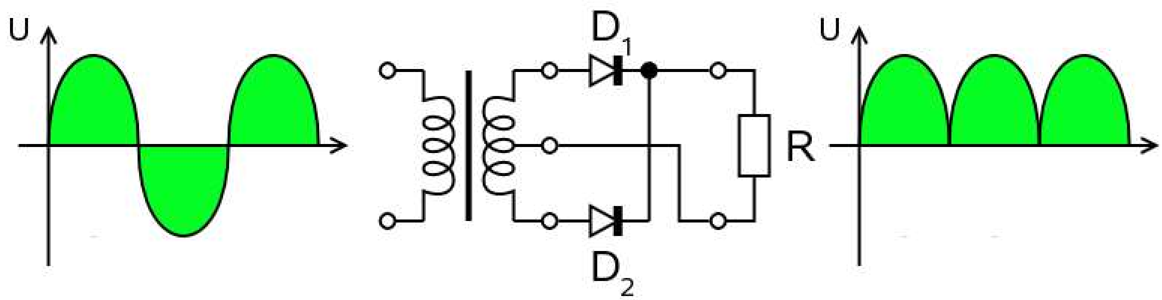
Full-wave rectification

A full-wave rectifier converts the whole of the input waveform to one of constant polarity (positive or negative) at its output. Full-wave rectification converts both polarities of the input waveform to DC (direct current), and is more efficient. However, in a circuit with a non-center tapped transformer, four diodes are required instead of the one needed for half-wave rectification. Four diodes arranged this way are called a diode bridge or bridge rectifier:

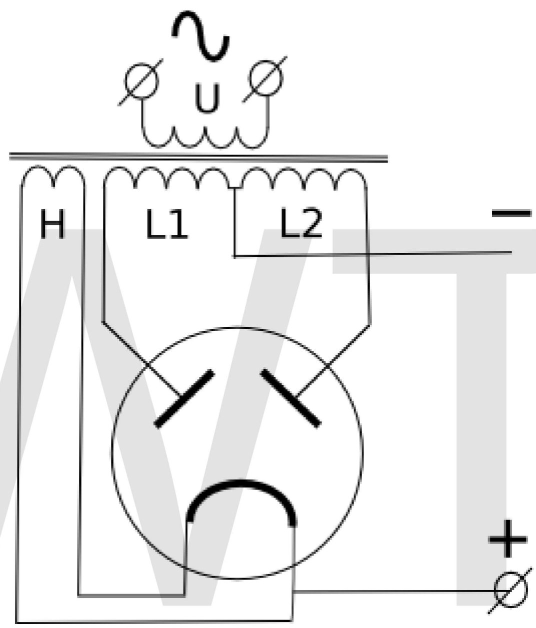


Graetz bridge rectifier: a full-wave rectifier using 4 diodes

For single-phase AC, if the transformer is center-tapped, then two diodes back-to-back (i.e. anodes-to-anode or cathode-to-cathode) can form a full-wave rectifier. Twice as many windings are required on the transformer secondary to obtain the same output voltage compared to the bridge rectifier above.

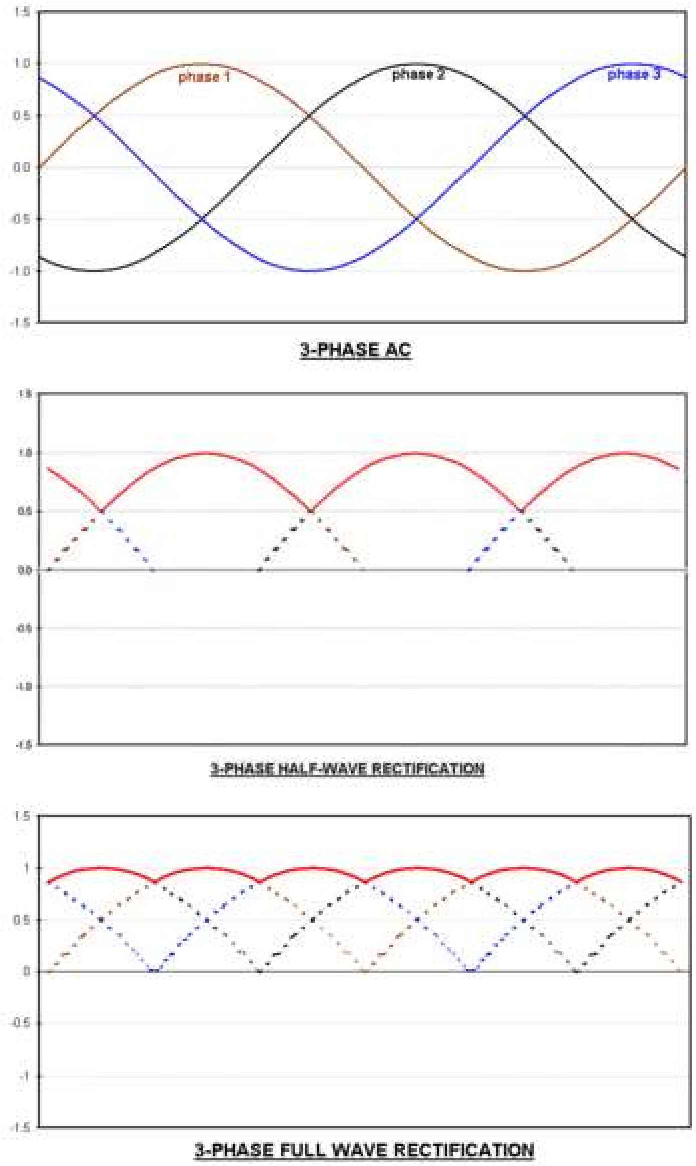


Full-wave rectifier using a transformer and 2 diodes



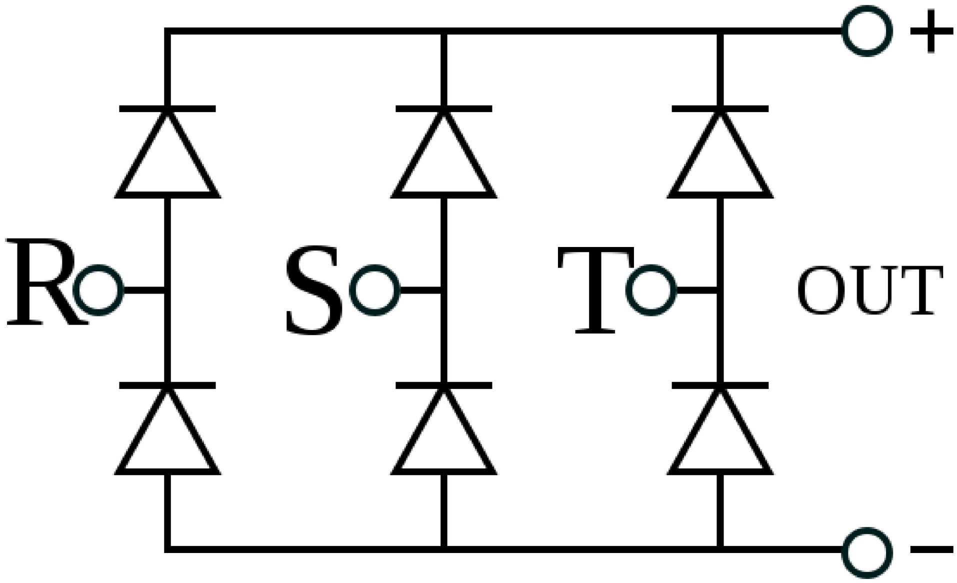
Full-wave rectifier, with vacuum tube having two anodes

A very common vacuum tube rectifier configuration contained one cathode and twin anodes inside a single envelope; in this way, the two diodes required only one vacuum tube. The 5U4 and 5Y3 were popular examples of this configuration.



3-phase AC input, half & full wave rectified DC output waveforms

WORLD TECHNOLOGIES



A three-phase bridge rectifier

For three-phase AC, six diodes are used. Typically there are three pairs of diodes, each pair, though, is not the same kind of **double diode** that would be used for a full wave single-phase rectifier. Instead the pairs are in series (anode to cathode). Typically, commercially available double diodes have four terminals so the user can configure them as single-phase split supply use, for half a bridge, or for three-phase use.

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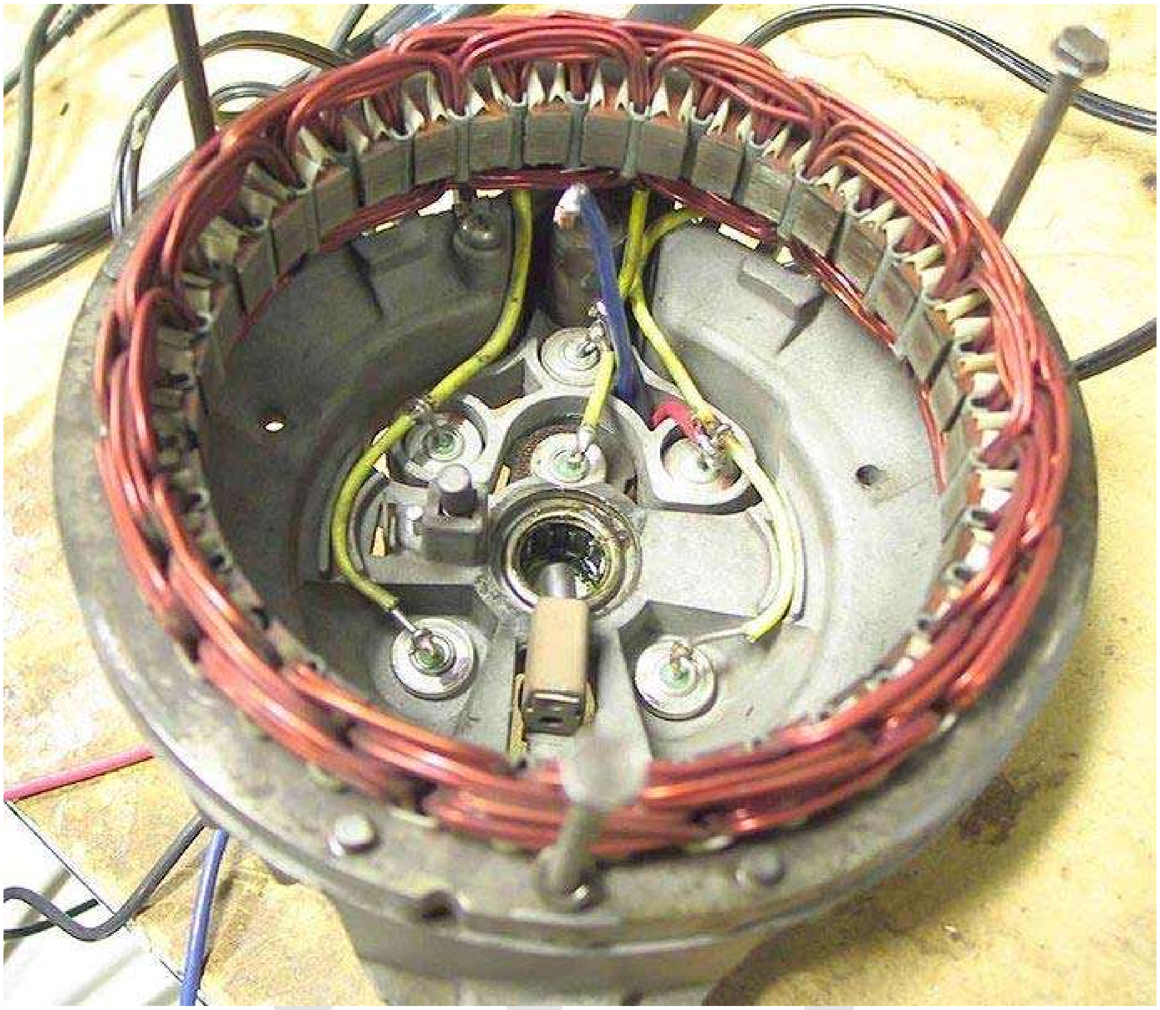


Disassembled automobile alternator, showing the six diodes that comprise a full-wave three-phase bridge rectifier.

Most devices that generate alternating current (such devices are called alternators) generate three-phase AC. For example, an automobile alternator has six diodes inside it to function as a full-wave rectifier for battery charging applications.

The average and root-mean-square output voltages of an ideal single phase full wave rectifier can be calculated as:

$$V_{dc} = V_{av} = \frac{2V_p}{\pi}$$
$$V_{rms} = \frac{V_p}{\sqrt{2}}$$

Where:

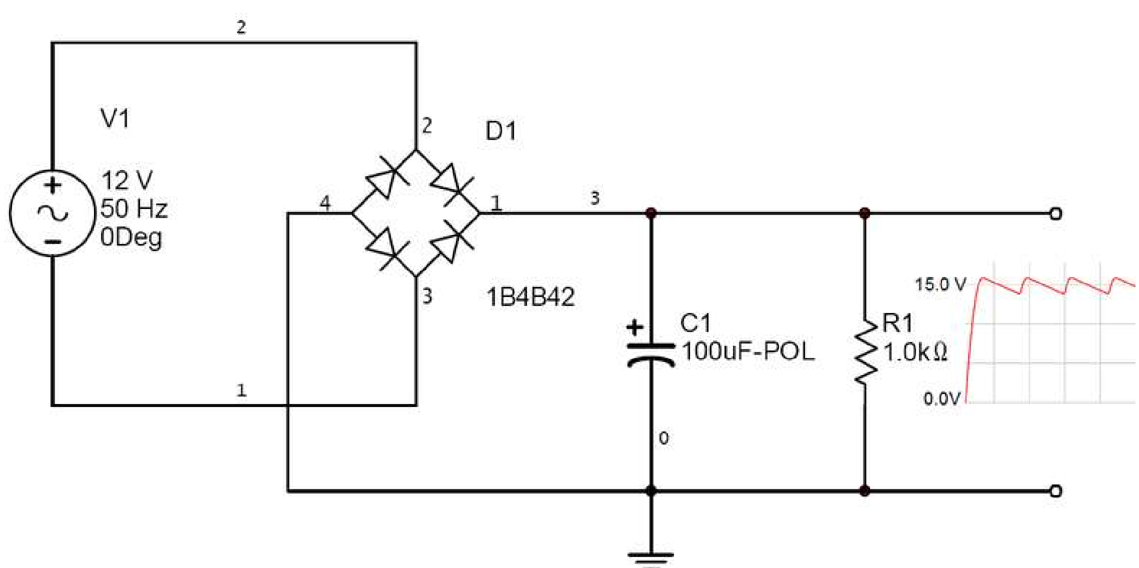
V_{dc},V_{av} - the average or DC output voltage,
V_p - the peak value of half wave,
V_{rms} - the root-mean-square value of output voltage.
π = ~ 3.14159

Peak loss

An aspect of most rectification is a loss from the peak input voltage to the peak output voltage, caused by the built-in voltage drop across the diodes (around 0.7 V for ordinary silicon p-n-junction diodes and 0.3 V for Schottky diodes). Half-wave rectification and full-wave rectification using two separate secondaries will have a peak voltage loss of one diode drop. Bridge rectification will have a loss of two diode drops. This may represent significant power loss in very low voltage supplies. In addition, the diodes will not conduct below this voltage, so the circuit is only passing current through for a portion of each half-cycle, causing short segments of zero voltage to appear between each "hump".

Rectifier output smoothing

While half-wave and full-wave rectification suffice to deliver a form of DC output, neither produces constant-voltage DC. In order to produce steady DC from a rectified AC supply, a smoothing circuit or filter is required. In its simplest form this can be just a reservoir capacitor or smoothing capacitor, placed at the DC output of the rectifier. There will still remain an amount of AC ripple voltage where the voltage is not completely smoothed.



RC-Filter Rectifier: This circuit was designed and simulated using Multisim 8 software.

Sizing of the capacitor represents a tradeoff. For a given load, a larger capacitor will reduce ripple but will cost more and will create higher peak currents in the transformer secondary and in the supply feeding it. In extreme cases where many rectifiers are loaded onto a power distribution circuit, it may prove difficult for the power distribution authority to maintain a correctly shaped sinusoidal voltage curve.

For a given tolerable ripple the required capacitor size is proportional to the load current and inversely proportional to the supply frequency and the number of output peaks of the rectifier per input cycle. The load current and the supply frequency are generally outside the control of the designer of the rectifier system but the number of peaks per input cycle can be affected by the choice of rectifier design.

A half-wave rectifier will only give one peak per cycle and for this and other reasons is only used in very small power supplies. A full wave rectifier achieves two peaks per cycle and this is the best that can be done with single-phase input. For three-phase inputs a three-phase bridge will give six peaks per cycle and even higher numbers of peaks can be achieved by using transformer networks placed before the rectifier to convert to a higher phase order.

To further reduce this ripple, a capacitor-input filter can be used. This complements the reservoir capacitor with a choke (inductor) and a second filter capacitor, so that a steadier DC output can be obtained across the terminals of the filter capacitor. The choke presents a high impedance to the ripple current.

A more usual alternative to a filter, and essential if the DC load is very demanding of a smooth supply voltage, is to follow the reservoir capacitor with a voltage regulator. The reservoir capacitor needs to be large enough to prevent the troughs of the ripple getting below the voltage the DC is being regulated to. The regulator serves both to remove the last of the ripple and to deal with variations in supply and load characteristics. It would be possible to use a smaller reservoir capacitor (these can be large on high-current power supplies) and then apply some filtering as well as the regulator, but this is not a common strategy. The extreme of this approach is to dispense with the reservoir capacitor altogether and put the rectified waveform straight into a choke-input filter. The advantage of this circuit is that the current waveform is smoother and consequently the rectifier no longer has to deal with the current as a large current pulse, but instead the current delivery is spread over the entire cycle. The downside is that the voltage output is much lower – approximately the average of an AC half-cycle rather than the peak.

Voltage-doubling rectifiers

The simple half wave rectifier can be built in two versions with the diode pointing in opposite directions, one version connects the negative terminal of the output direct to the AC supply and the other connects the positive terminal of the output direct to the AC supply. By combining both of these with separate output smoothing it is possible to get an output voltage of nearly double the peak AC input voltage. This also provides a tap in the middle, which allows use of such a circuit as a split rail supply.

A variant of this is to use two capacitors in series for the output smoothing on a bridge rectifier then place a switch between the midpoint of those capacitors and one of the AC input terminals. With the switch open this circuit will act like a normal bridge rectifier with it closed it will act like a voltage doubling rectifier. In other words this makes it easy to derive a voltage of roughly 320V (+/- around 15%) DC from any mains supply in the world, this can then be fed into a relatively simple switched mode power supply.

Cascaded stages of diodes and capacitors can be added to make a voltage multiplier (Cockroft-Walton circuit). These circuits can provide a potential several times that of the peak value of the input AC, although limited in current output and regulation. Voltage multipliers are used to provide the high voltage for a CRT in a television receiver, or for powering high-voltage tubes such as image intensifiers or photo multipliers.

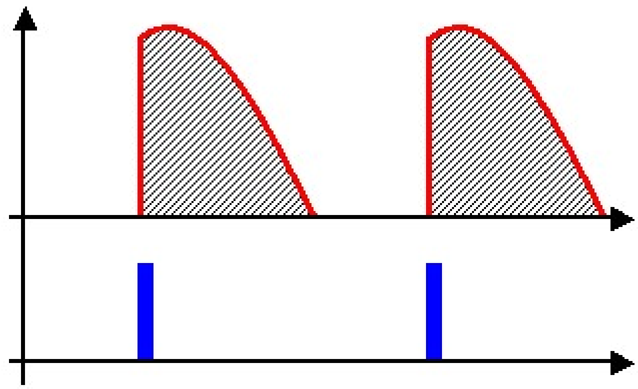
Applications

A rectifier diode (silicon controlled rectifier) and associated mounting hardware. The heavy threaded stud helps remove heat.

The primary application of rectifiers is to derive DC power from an AC supply. Virtually all electronic devices require DC, so rectifiers find uses inside the power supplies of virtually all electronic equipment.

Converting DC power from one voltage to another is much more complicated. One method of DC-to-DC conversion first converts power to AC (using a device called an inverter), then use a transformer to change the voltage, and finally rectifies power back to DC.

Rectifiers also find a use in detection of amplitude modulated radio signals. The signal may be amplified before detection, but if un-amplified, a very low voltage drop diode must be used. When using a rectifier for demodulation the capacitor and load resistance must be carefully matched. Too low a capacitance will result in the high frequency carrier passing to the output and too high will result in the capacitor just charging and staying charged.



Output voltage of a full-wave rectifier with controlled thyristors

Rectifiers are also used to supply polarised voltage for welding. In such circuits control of the output current is required and this is sometimes achieved by replacing some of the diodes in bridge rectifier with thyristors, whose voltage output can be regulated by means of phase fired controllers.

Thyristors are used in various classes of railway rolling stock systems so that fine control of the traction motors can be achieved. Gate turn-off thyristors are used to produce alternating current from a DC supply, for example on the Eurostar Trains to power the three-phase traction motors.

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Rectification technologies

Electromechanical

Early power conversion systems were purely electro-mechanical in design, since electronic devices were not available to handle significant power. Mechanical rectification systems usually rely on some form of rotation or resonant vibration in order to move quickly enough to match the frequency of the input power source, and cannot operate beyond several thousand cycles per second.

Due to the complexity of mechanical systems, they have traditionally needed a high level of maintenance to keep operating correctly. Moving parts will have friction, which requires lubrication and replacement due to wear. Opening mechanical contacts under load results in electrical arcs and sparks that heat and erode the contacts.

Synchronous rectifier

To convert AC currents into DC current in electric locomotives, a **synchronous rectifier** may be used. It consists of a synchronous motor driving a set of heavy-duty electrical contacts. The motor spins in time with the AC frequency and periodically reverses the connections to the load just when the sinusoidal current goes through a zero-crossing.

The contacts do not have to *switch* a large current, but they need to be able to *carry* a large current to supply the locomotive's DC traction motors.

Vibrator

In the past, the vibrators used in battery-to-high-voltage-DC power supplies often contained a second set of contacts that performed synchronous mechanical rectification of the stepped-up voltage.

Motor-generator set

A *motor-generator set* or the similar *rotary converter*, is not a rectifier in the sense that it doesn't actually *rectify* current, but rather *generates* DC from an AC source. In an "M-G set", the shaft of an AC motor is mechanically coupled to that of a DC generator. The DC generator produces multiphase alternating currents in its armature windings, and a commutator on the armature shaft converts these alternating currents into a direct current output; or a homopolar generator produces a direct current without the need for a commutator. M-G sets are useful for producing DC for railway traction motors, industrial motors and other high-current applications, and were common in many high power D.C. uses (for example, carbon-arc lamp projectors for outdoor theaters) before high-power semiconductors became widely available.

Electrolytic

The electrolytic rectifier was an early device from the 1900s that is no longer used. When two different metals are suspended in an electrolyte solution, it can be found that direct current flowing one way through the metals has less resistance than the other direction. These most commonly used an aluminum anode, and a lead or steel cathode, suspended in a solution of tri-ammonium ortho-phosphate.

The rectification action is due to a thin coating of aluminum hydroxide on the aluminum electrode, formed by first applying a strong current to the cell to build up the coating. The rectification process is temperature sensitive, and for best efficiency should not operate above 86 °F (30 °C). There is also a breakdown voltage where the coating is penetrated and the cell is short-circuited. Electrochemical methods are often more fragile than mechanical methods, and can be sensitive to usage variations which can drastically change or completely disrupt the rectification processes.

Similar electrolytic devices were used as lightning arresters around the same era by suspending many aluminium cones in a tank of tri-ammomium ortho-phosphate solution. Unlike the rectifier, above, only aluminium electrodes were used, and used on A.C., there was no polarization and thus no rectifier action, but the chemistry was similar.

The modern electrolytic capacitor, an essential component of most rectifier circuit configurations was also developed from the electrolytic rectifier.

Plasma type

Mercury arc

A rectifier used in high-voltage direct current power transmission systems and industrial processing between about 1909 to 1975 is a *mercury arc rectifier* or *mercury arc valve*. The device is enclosed in a bulbous glass vessel or large metal tub. One electrode, the cathode, is submerged in a pool of liquid mercury at the bottom of the vessel and one or more high purity graphite electrodes, called anodes, are suspended above the pool. There may be several auxiliary electrodes to aid in starting and maintaining the arc. When an electric arc is established between the cathode pool and suspended anodes, a stream of electrons flows from the cathode to the anodes through the ionized mercury, but not the other way. [In principle, this is a higher-power counterpart to flame rectification, which uses the same one-way current transmission properties of the plasma naturally present in a flame].

These devices can be used at power levels of hundreds of kilowatts, and may be built to handle one to six phases of AC current. Mercury arc rectifiers have been replaced by silicon semiconductor rectifiers and high power thyristor circuits, from the mid 1970s onward. The most powerful mercury arc rectifiers ever built were installed in the Manitoba Hydro Nelson River Bipole HVDC project, with a combined rating of more than one million kilowatts and 450,000 volts.

Argon gas electron tube

The General Electric Tungar rectifier was an argon gas-filled electron tube device with a tungsten filament cathode and a carbon button anode. It was useful for battery chargers and similar applications from the 1920s until low-cost solid-state rectifiers (the metal rectifiers at first) supplanted it. These were made up to a few hundred volts and a few amperes rating, and in some sizes strongly resembled an incandescent lamp with an additional electrode.

The 0Z4 was a gas-filled rectifier tube commonly used in vacuum tube car radios in the 1940s and 1950s. It was a conventional full wave rectifier tube with two anodes and one cathode, but was unique in that it had no filament (thus the "0" in its type number). The electrodes were shaped such that the reverse breakdown voltage was much higher than the forward breakdown voltage. Once the breakdown voltage was exceeded, the 0Z4 switched to a low-resistance state with a forward voltage drop of about 24 volts.

Vacuum tube (valve)

Since the discovery of the Edison effect or thermionic emission, various vacuum tube devices have been developed to rectify alternating currents. Low-power devices are used as signal detectors, first used in radio by Fleming in 1904. Many vacuum-tube devices also used vacuum rectifiers in their power supplies, for example the All American Five radio receiver. Vacuum rectifiers were made for very high voltages, such as the high voltage power supply for the cathode ray tube of television receivers, and the kenotron used for power supply in X-ray equipment. However, vacuum rectifiers generally had low current capacity owing to the maximum current density that could be obtained by electrodes heated to temperatures compatible with long life. Another limitation of the vacuum tube rectifier was that the heater power supply often required special arrangements to insulate it from the high voltages of the rectifier circuit.

Solid state

Crystal detector

The cat's-whisker detector, using a crystal such as galena, was the earliest type of solid state diode.

Selenium and copper oxide rectifiers

Once common until replaced by more compact and less costly silicon solid-state rectifiers, these units used stacks of metal plates and took advantage of the semiconductor properties of selenium or copper oxide. While selenium rectifiers were lighter in weight and used less power than comparable vacuum tube rectifiers, they had the disadvantage of finite life expectancy, increasing resistance with age, and were only suitable to use at low frequencies. Both selenium and copper oxide rectifiers have somewhat better tolerance of momentary voltage transients than silicon rectifiers.

Typically these rectifiers were made up of stacks of metal plates or washers, held together by a central bolt, with the number of stacks determined by voltage; each cell was rated for about 20 volts. An automotive battery charger rectifier might have only one cell: the high-voltage power supply for a vacuum tube might have dozens of stacked plates. Current density in an air-cooled selenium stack was about 600 mA per square inch of active area (about 90 mA per square centimeter).

Silicon and germanium diodes

In the modern world, silicon diodes are the most widely used rectifiers and have largely replaced earlier germanium diodes.

Recent developments

High-speed rectifiers

Researchers at Idaho National Laboratory (INL) have proposed high-speed rectifiers that would sit at the center of spiral nanoantennas and convert infrared frequency electricity from AC to DC. Infrared frequencies range from 0.3 to 400 terahertz.

Unimolecular rectifiers

A Unimolecular rectifier is a single organic molecule which functions as a rectifier. The technology is still in the experimental stage.

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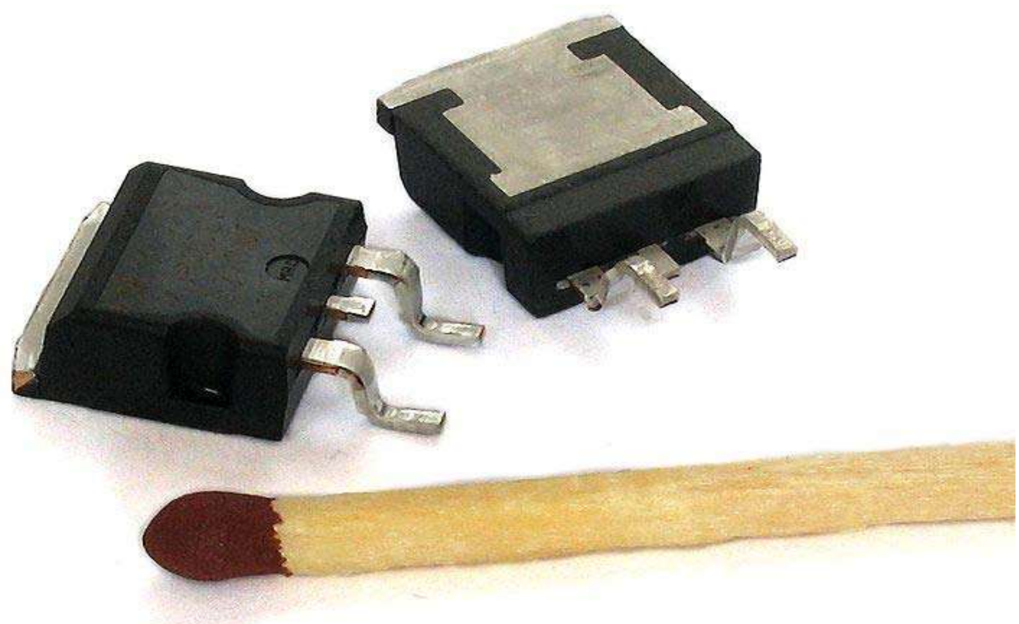
Chapter 3

Power MOSFET



Two power MOSFETs in the surface-mount package D2PAK. Each of these components can sustain a blocking voltage of 120 volts and a continuous current of 30 amperes.

A **Power MOSFET** is a specific type of metal oxide semiconductor field-effect transistor (MOSFET) designed to handle significant power levels. Compared to the other power semiconductor devices (IGBT, Thyristor...), its main advantages are high commutation speed and good efficiency at low voltages. It shares with the IGBT an isolated gate that makes it easy to drive.

It was made possible by the evolution of CMOS technology, developed for manufacturing Integrated circuits in the late 1970s. The power MOSFET shares its operating principle with its low-power counterpart, the lateral MOSFET.

The power MOSFET is the most widely used low-voltage (i.e. less than 200 V) switch. It can be found in most power supplies, DC to DC converters, and low voltage motor controllers.

Basic structure

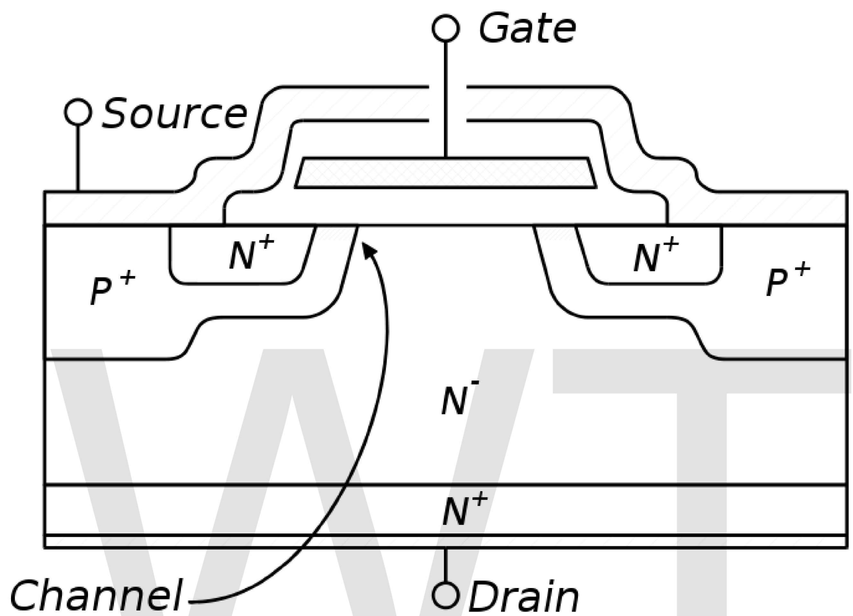


Fig. 1: Cross section of a VDMOS, showing an elementary cell. Note that a cell is very small (some micrometres to some tens of micrometres wide), and that a power MOSFET is composed of several thousand of them.

Several structures had been explored at the beginning of the 1980s, when the first Power MOSFETs were introduced. However, most of them have been abandoned (at least until recently) in favour of the Vertical Diffused MOS (VDMOS) structure (also called Double-Diffused MOS or simply DMOS).

The cross section of a VDMOS (see figure 1) shows the "verticality" of the device: It can be seen that the source electrode is placed over the drain, resulting in a current mainly vertical when the transistor is in the on-state. The "diffusion" in VDMOS refers to the manufacturing process: the P wells (see figure 1) are obtained by a diffusion process (actually a double diffusion process to get the P and N^+ regions, hence the name double diffused).

Power MOSFETs have a different structure than the lateral MOSFET: as with all power devices, their structure is vertical and not planar. In a planar structure, the current and breakdown voltage ratings are both functions of the channel dimensions (respectively width and length of the channel), resulting in inefficient use of the "silicon estate". With a vertical structure, the voltage rating of the transistor is a function of the doping and thickness of the N epitaxial layer, while the current rating is a function of the channel width. This makes possible for the transistor to sustain both high blocking voltage and high current within a compact piece of silicon.

It is worth noting that power MOSFETs with lateral structure exist. They are mainly used in high-end audio amplifiers. Their advantage is a better behaviour in the saturated region (corresponding to the linear region of a bipolar transistor) than the vertical MOSFETs. Vertical MOSFETs are designed for switching applications, so they are only used in On or Off states.

On-state characteristics

On-state resistance

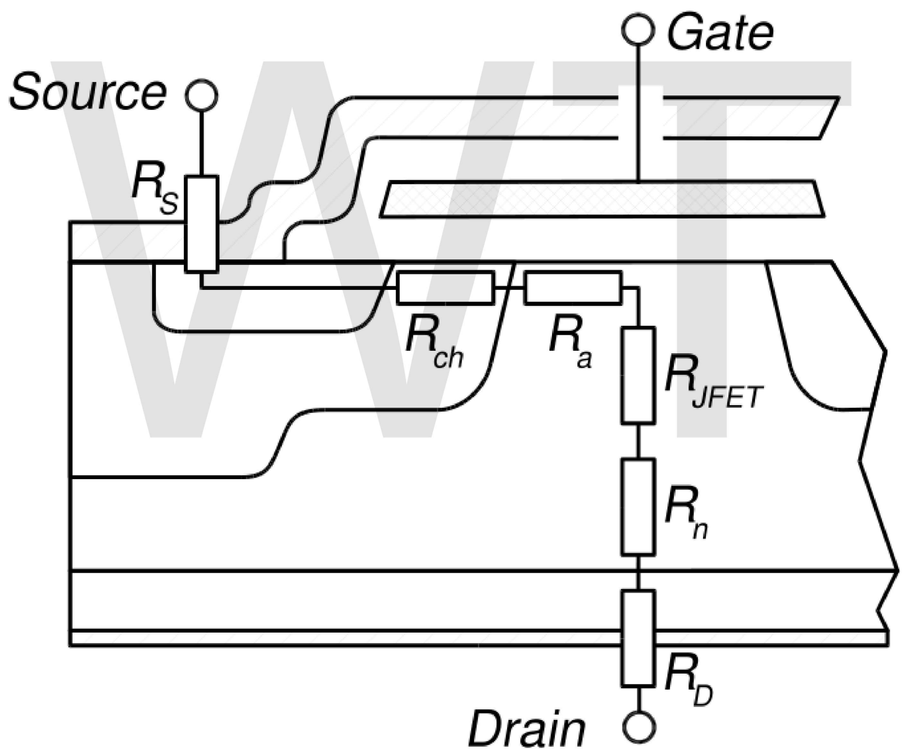


Fig.2: Contribution of the different parts of the MOSFET to the on-state resistance.

When the power MOSFET is in the on-state, it exhibits a resistive behaviour between the drain and source terminals. It can be seen in figure 2 that this resistance (called R_{DSon} for "drain to source resistance in on-state") is the sum of many elementary contributions:

- R_S is the source resistance. It represents all resistances between the source terminal of the package to the channel of the MOSFET: resistance of the wire bonds, of the source metallisation, and of the N^+ wells;

- R_{ch}. This is the channel resistance. It is inversely proportional to the channel width, and for a given die size, to the channel density. The channel resistance is one of the main contributors to the R_{DSon} of low-voltage MOSFETs, and intensive work has been carried out to reduce their cell size in order to increase the channel density;
- R_a is the *access* resistance. It represents the resistance of the epitaxial zone directly under the gate electrode, where the direction of the current changes from horizontal (in the channel) to vertical (to the drain contact);
- R_{JFET} is the detrimental effect of the cell size reduction mentioned above: the P implantations (see figure 1) form the gates of a parasitic JFET transistor that tend to reduce the width of the current flow;
- R_n is the resistance of the epitaxial layer. As the role of this layer is to sustain the blocking voltage, R_n is directly related to the voltage rating of the device. A high voltage MOSFET requires a thick, low-doped layer (i.e. highly resistive), whereas a low-voltage transistor only requires a thin layer with a higher doping level (i.e. less resistive). As a result, R_n is the main factor responsible for the resistance of high-voltage MOSFETs;
- R_D is the equivalent of R_S for the drain. It represents the resistance of the transistor substrate (note that the cross section in figure 1 is not at scale, the bottom N^+ layer is actually the thickest) and of the package connections.

Breakdown voltage/on-state resistance trade-off

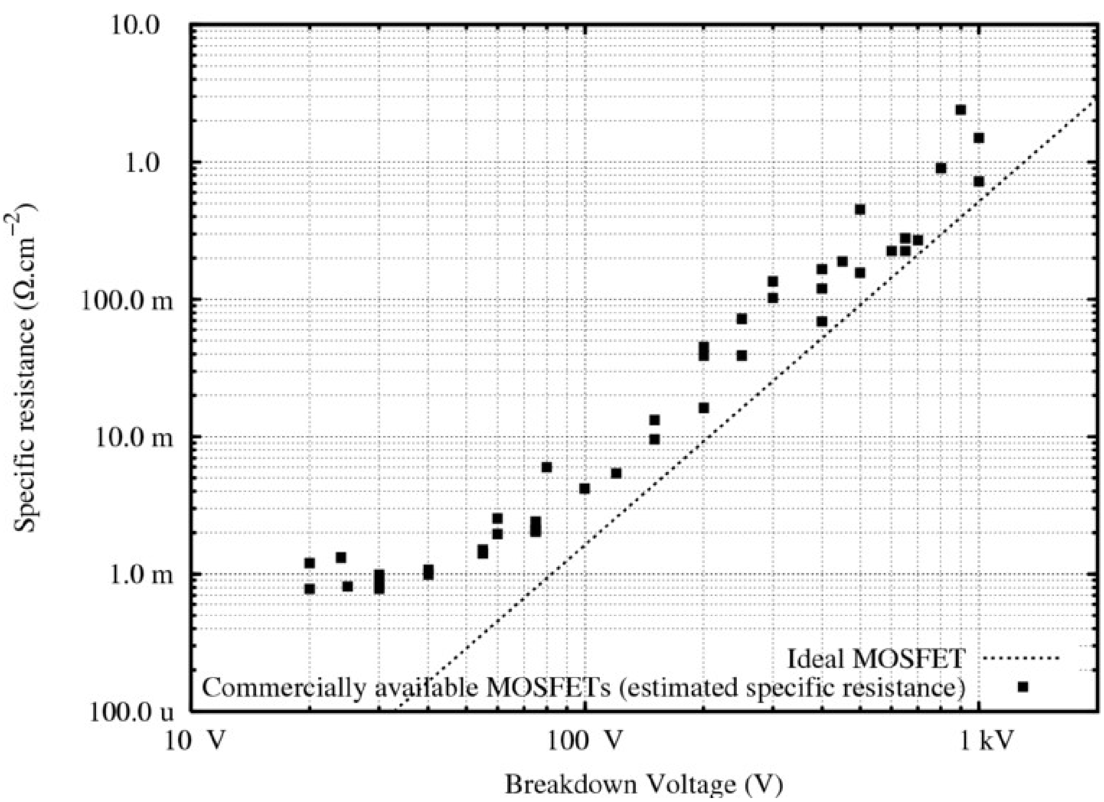


Fig. 3: The R_{DSon} of the MOSFETs increase with their Voltage rating.

When in the OFF-state, the power MOSFET is equivalent to a PIN diode (constituted by the P^+ diffusion, the N^- epitaxial layer and the N^+ substrate). When this highly non-symmetrical structure is reverse-biased, the space-charge region extends principally on the light-doped side, i.e over the N^- layer. This means that this layer has to withstand most of the MOSFET's OFF-state drain-to-source voltage.

However, when the MOSFET is in the ON-state, this N^- layer has no function. Furthermore, as it is a lightly-doped region, its intrinsic resistivity is non-negligible and adds to the MOSFET's ON-state Drain-to-Source Resistance (R_{DSon}) (this is the R_n resistance in figure 2).

Two main parameters govern both the breakdown voltage and the R_{DSon} of the transistor: the doping level and the thickness of the N^- epitaxial layer. The thicker the layer and the lower its doping level, the higher the breakdown voltage. On the contrary, the thinner the layer and the higher the doping level, the lower the R_{DSon} (and therefore the lower the conduction losses of the MOSFET). Therefore, it can be seen that there is a trade-off in the design of a MOSFET, between its voltage rating and its ON-state resistance. This is demonstrated by the plot in figure 3.

Body diode

It can be seen in figure 1 that the source metallization connects both the N^+ and P implantations, although the operating principle of the MOSFET only requires the source to be connected to the N^+ zone. However, if it were, this would result in a floating P zone between the N-doped source and drain, which is equivalent to a NPN transistor with a non-connected base. Under certain conditions (under high drain current, when the on-state drain to source voltage is in the order of some volts), this parasitic NPN transistor would be triggered, making the MOSFET uncontrollable. The connection of the P implantation to the source metallization shorts the base of the parasitic transistor to its emitter (the source of the MOSFET) and thus prevents spurious latching.

This solution, however, creates a diode between the drain (cathode) and the source (anode) of the MOSFET, making it able to block current in only one direction.

Switching operation

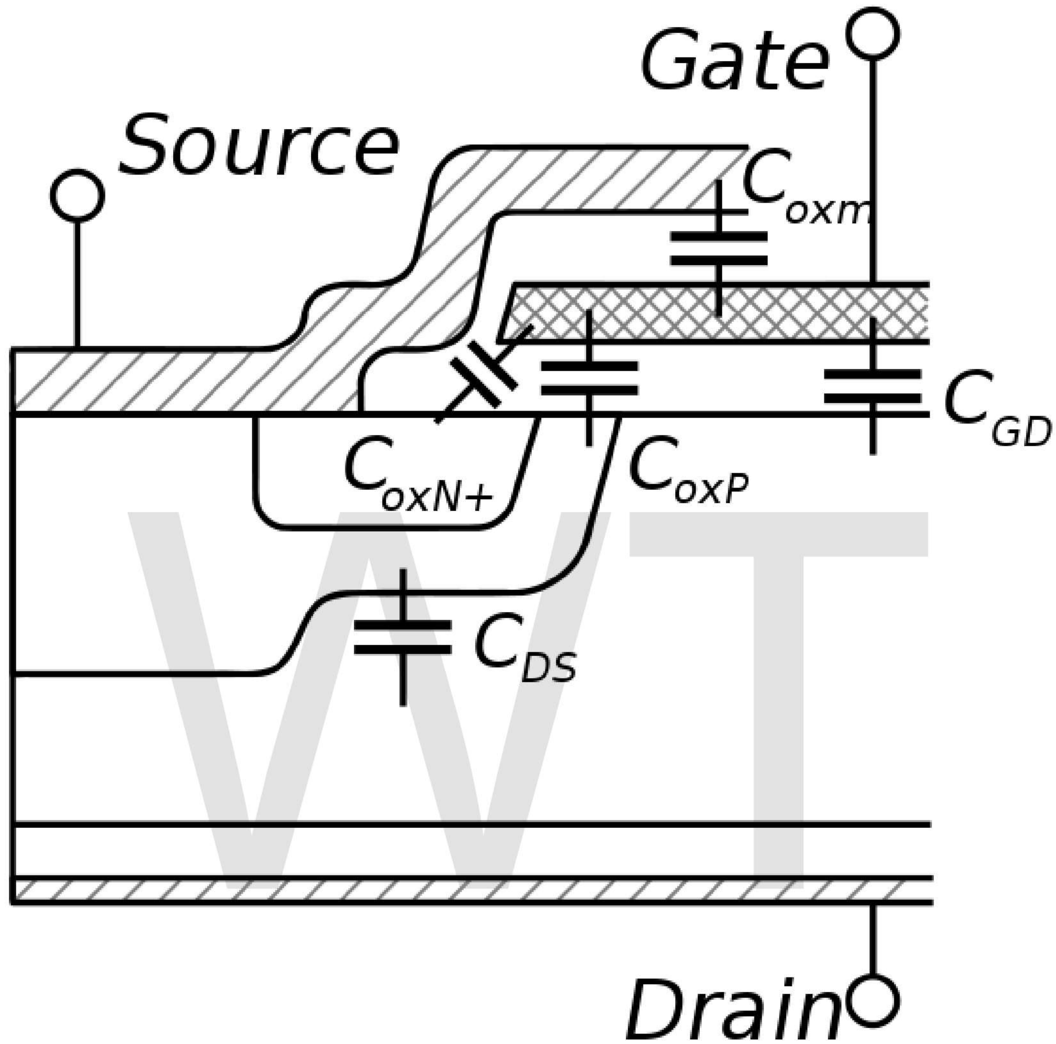


Fig. 4: Location of the intrinsic capacitances of a power MOSFET

Because of their unipolar nature, the power MOSFET can switch at very high speed. Indeed, there is no need to remove minority carriers as with bipolar devices.

The only intrinsic limitation in commutation speed is due to the internal capacitances of the MOSFET (see figure 4). These capacitances must be charged or discharged when the transistor switches. This can be a relatively slow process because the current that flows through the gate capacitances is limited by the external driver circuit. This circuit will actually dictate the commutation speed of the transistor (assuming the power circuit has sufficiently low inductance).

Capacitances

In the MOSFETs datasheets, the capacitances are often named C_{iss} (input capacitance, drain and source terminal shorted), C_{oss} (output capacitance, gate and source shorted), and C_{rss} (reverse transfer capacitance, gate and source shorted). The relationship between these capacitances and those described below is:

$$\begin{aligned} C_{iss} &= C_{GS} + C_{GD} \\ C_{oss} &= C_{GD} + C_{DS} \\ C_{rss} &= C_{GD} \end{aligned}$$

Where C_{GS}, C_{GD} and C_{DS} are respectively the gate-to-source, gate-to-drain and drain-to-source capacitances (see below). Manufacturers prefer to quote C_{iss}, C_{oss} and C_{rss} because they can be directly measured on the transistor.

Gate to source capacitance

The C_{GS} capacitance is constituted by the parallel connection of C_{oxN+}, C_{oxP} and C_{oxm} (see figure 4). As the N^+ and P regions are highly doped, the two former capacitances can be considered as constant. C_{oxm} is the capacitance between the (polysilicon) gate and the (metal) source electrode, so it is also constant. Therefore, it is common practice to consider C_{GS} as a constant capacitance, i.e its value does not depend on the transistor state.

Gate to drain capacitance

The C_{GD} capacitance can be seen as the connection in series of two elementary capacitances. The first one is the oxide capacitance (C_{oxD}), constituted by the gate electrode, the silicon dioxide and the top of the N epitaxial layer. It has a constant value. The second capacitance (C_{CDj}) is caused by the extension of the space-charge zone when the MOSFET is in off-state. Therefore, it is dependent upon the drain to source voltage. From this, the value of C_{GD} is:

$$C_{GD} = \frac{C_{oxD} \times C_{GDj}(V_{GD})}{C_{oxD} + C_{GDj}(V_{GD})}$$

The width of the space-charge region is given by

$$w_{GDj} = \sqrt{\frac{2\epsilon_{Si} V_{GD}}{qN}}$$

where ε_{Si} is the permittivity of the Silicon, q is the electron charge, and N is the doping level. The value of C_{GDj} can be approximated using the expression of the plane capacitor:

$$C_{GDj} = A_{GD}\frac{\epsilon_{Si}}{w_{GDj}}$$

Where A_{GD} is the surface area of the gate-drain overlap. Therefore, it comes:

$$C_{GDj}\left(V_{GD}\right) = A_{GD}\sqrt{\frac{q\epsilon_{Si}N}{2V_{GD}}}$$

It can be seen that C_{GDj} (and thus C_{GD}) is a capacitance which value is dependent upon the gate to drain voltage. As this voltage increases, the capacitance decreases. When the MOSFET is in on-state, C_{GDj} is shunted, so the gate to drain capacitance remains equal to C_{oxD}, a constant value.

Drain to source capacitance

As the source metallization overlaps the P-wells (see figure 1), the drain and source terminals are separated by a P-N junction. Therefore, C_{DS} is the junction capacitance. This is a non-linear capacitance, and its value can be calculated using the same equation as for C_{GDj}.

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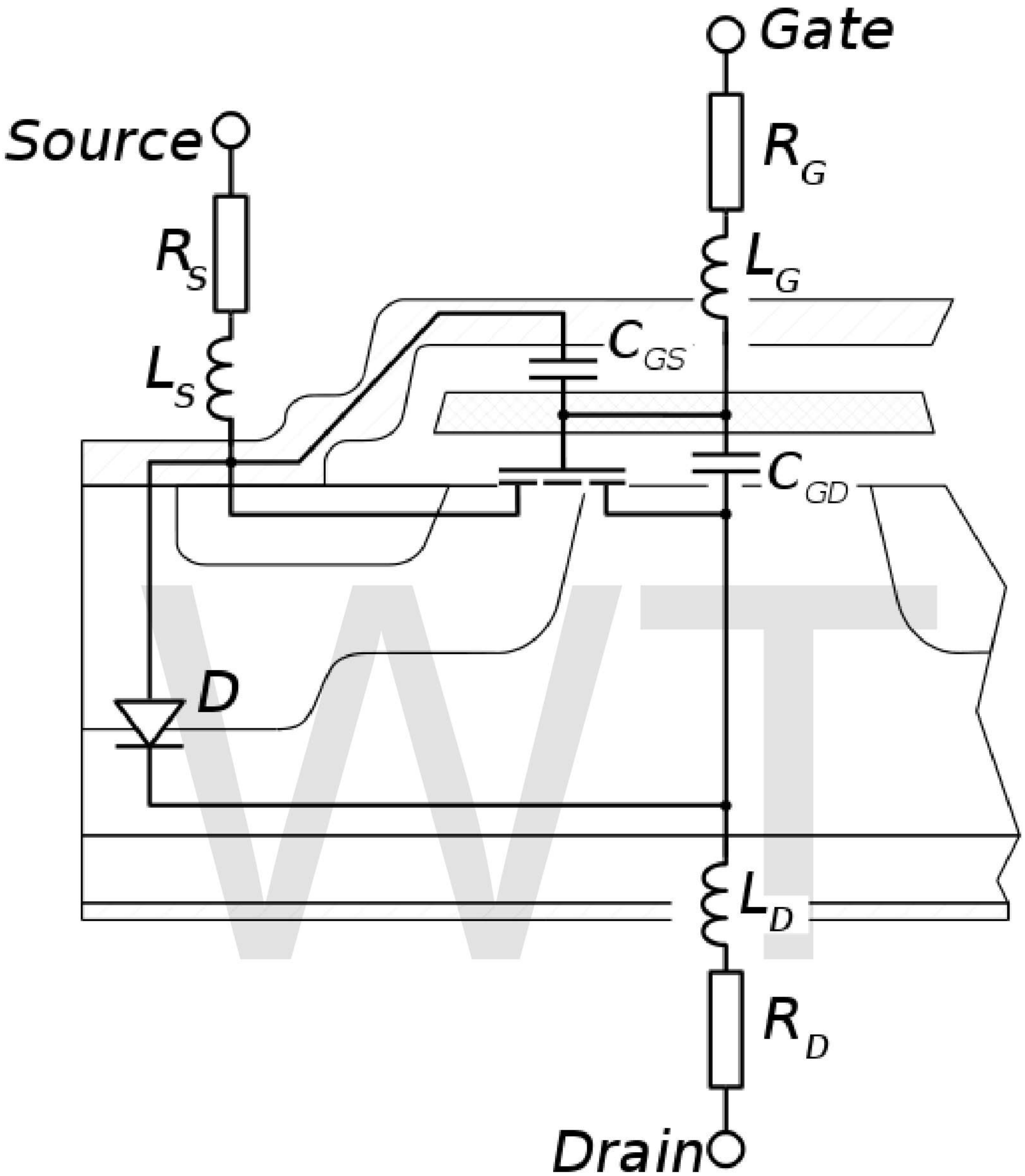
Other dynamic elements



Equivalent circuit of a power MOSFET, including the dynamic elements (capacitors, inductors), the parasitic resistors, the body diode.

Packaging inductances

To operate, the MOSFET must be connected to the external circuit, most of the time using wire bonding (although alternative techniques are investigated). These connection exhibit a parasitic inductance, which is in no way specific to the MOSFET technology, but has important effects because of its high commutation speed. Parasitic inductances tend to maintain their current constant and generate overvoltage during the transistor turn off, resulting in increasing commutation losses.

A parasitic inductance can be associated with each terminal of the MOSFET. They have different effects:

- the gate inductance has little influence (assuming it is lower than some hundreds of nanohenries), because the current gradients on the gate are relatively slow. In some cases, however, the gate inductance and the input capacitance of the transistor can constitute an oscillator. This must be avoided as it results in very high commutation losses (up to the destruction of the device). On a typical design, parasitic inductances are kept low enough to prevent this phenomenon;
- the drain inductance tends to reduce the drain voltage when the MOSFET turns on, so it reduces turn on losses. However, as it creates an overvoltage during turn-off, it increases turn-off losses;
- the source parasitic inductance has the same behaviour as the drain inductance, plus a feedback effect that makes commutation last longer, thus increasing commutation losses.
    - at the beginning of a fast turn-on, due to the source inductance, the voltage at the source (on the die) will be able to jump up as well as the gate voltage; the internal V_{GS} voltage will remain low for a longer time, therefore delaying turn-on.
    - at the beginning of a fast turn-off, as current through the source inductance decreases sharply, the resulting voltage across it goes negative (with respect to the lead outside the package) raising the internal V_{GS} voltage, keeping the MOSFET on, and therefore delaying turn-off.

Limits of operation

Gate oxide breakdown

The gate oxide is very thin (100 nm or less), so it can only sustain a limited voltage. In the datasheets, manufacturers often state a maximum gate to source voltage, around 20 V, and exceeding this limit can result in destruction of the component. Furthermore, a high gate to source voltage reduces significantly the lifetime of the MOSFET, with little to no advantage on R_{DSon} reduction.

Maximum drain to source voltage

Power MOSFETs have a maximum specified drain to source voltage, beyond which breakdown may occur. Exceeding the breakdown voltage causes the device to conduct, potentially damaging it and other circuit elements due to excessive power dissipation.

Maximum drain current

The drain current must generally stay below a certain specified value (maximum continuous drain current). It can reach higher values for very short durations of time (maximum pulsed drain current, sometimes specified for various pulse durations). The

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drain current is limited by heating due to resistive losses in internal components such as bond wires, and other phenomena such as electromigration in the metal layer.

Maximum temperature

The junction temperature of the MOSFET must stay under a specified maximum value for the device to function reliably, determined by MOSFET die layout and packaging materials. The packaging often limits the maximum junction temperature, due to the molding compound and (where used) epoxy characteristics.

The maximum operating ambient temperature is determined by the power dissipation and thermal resistance. The junction-to-case thermal resistance is intrinsic to the device and package; the case-to-ambient thermal resistance is largely dependent on the board/mounting layout, heatsinking area and air/fluid flow.

The type of power dissipation, whether continuous or pulsed, affects the maximum operating temperature, due to thermal capacitance characteristics; in general, the lower the frequency of pulses for a given power dissipation, the higher maximum operating ambient temperature, due to allowing a longer interval for the device to cool down. Models, such as a Foster Network, can be used to analyze temperature dynamics from power transients.

Safe operating area

The safe operating area defines the combined ranges of drain current and drain to source voltage the power MOSFET is able to handle without damage. It is represented graphically as an area in the plane defined by these two parameters. Both drain current and drain to source voltage must stay below their respective maximum values, but their product must also stay below the maximum power dissipation the device is able to handle. Thus the device cannot be operated at both its specified maximum drain current and maximum drain to source voltage.

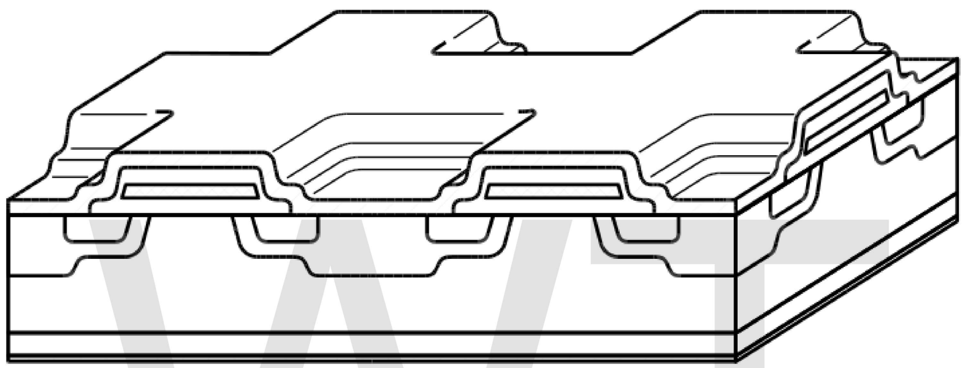
Latch-up (LU)

The equivalent circuit for a MOSFET consist of one MOSFET in parallel with a parasitic BJT (Bipolar Junction Transistor). If the BJT turns ON, it cannot be turned off since the gate has no control over it. This phenomenon is known as 'latch-up', which can lead to device destruction. The BJT can be turned on due to a voltage drop across the p-type body region. To avoid latch-up, the body and the source are typically short circuited within the device package.

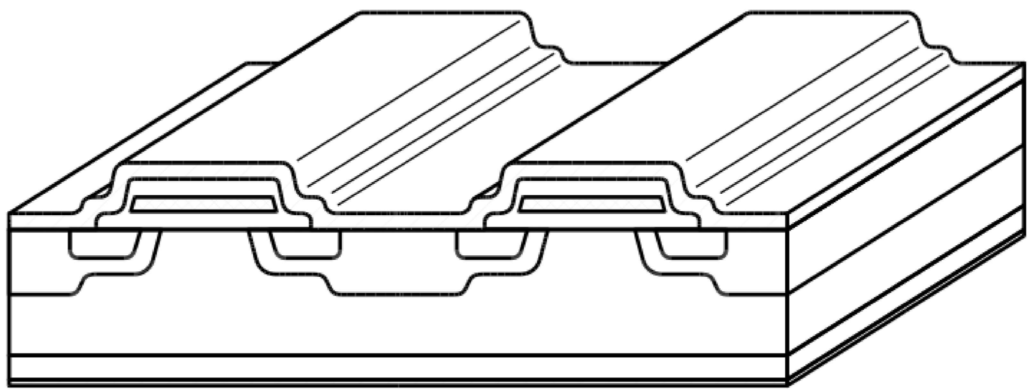
Technology

Layout

Cellular structure



This Power MOSFET has a meshed gate, with square cells



The gate layout of this MOSFET is constituted of parallel stripes

As described above, the current handling capability of a power MOSFET is determined by its gate channel width. The gate channel width is the third (Z-axis) dimension of the cross-sections pictured.

To minimize cost and size, it is valuable to keep the transistor's die area size as small as possible. Therefore, optimizations have been developed to increase the width of the channel surface area (i.e increase the "channel density"). They mainly consist of creating cellular structures repeated over the whole area of the MOSFET die. Several shapes have been proposed for these cells, the most famous being the International Rectifier's "Hexfet" (hexagonal shape).

Another way to increase the channel density is to reduce the size of the elementary structure. This allows for more cells in a given surface area, and therefore more channel width. However, as the cell size shrinks, it becomes more difficult to ensure proper contact of every cell. To overcome this, a "strip" structure is often used (see figure). It is less efficient than a cellular structure of equivalent resolution in terms of channel density, but can cope with smaller pitch.

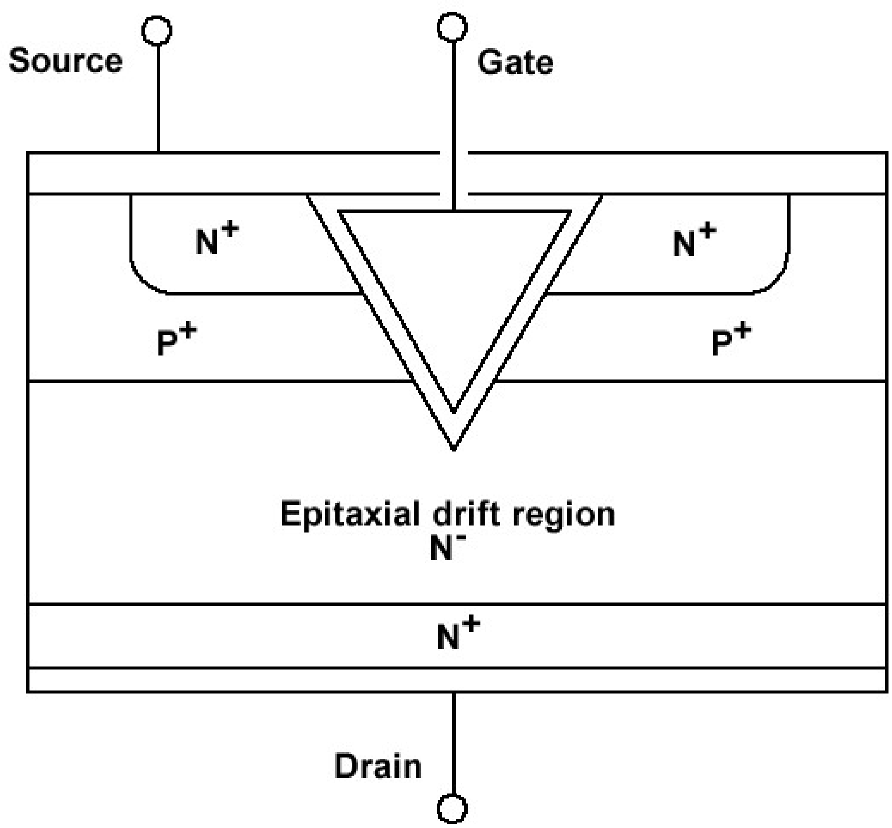
Structures

P-substrate power MOSFET

A P-substrate MOSFET (often referred to as PMOS) is a MOSFET with opposite doping types (N instead of P and P instead of N in the cross-section in figure 1). This MOSFET is made using a P-type substrate, with a P^- epitaxy. As the channel sits in a N-region, this transistor is turned on by a negative gate to source voltage. This makes it desirable in a buck converter, where one of the terminals of the switch is connected to the high side of the input voltage: with a N-MOSFET, this configuration requires to apply to the gate a voltage equal to $V_{in} + V_{GS}$, whereas no voltage over V_{in} is required with a P-MOSFET.

The main disadvantage of this type of MOSFET is the poor on-state performance: it uses holes as charge carriers, which have a much lower mobility than electrons. As resistivity is directly related to mobility, a given PMOS will have a R_{DSon} three times higher than a N-MOSFET with the same dimensions.

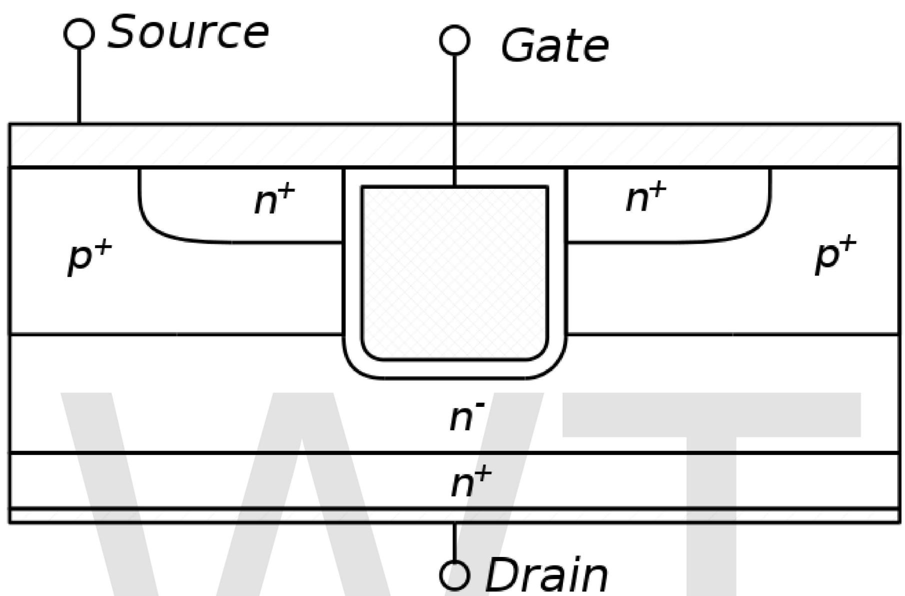
VMOS



The VMOS structure has a V-groove at the gate region

This structure has a V-groove at the gate region and was used for the first commercial devices .

UMOS (also called Trench-MOS)



The UMOS has a trench gate. It is intended to increase the channel density by making the channel vertical

In this Power MOSFET structure, the gate electrode is buried in a trench etched in the silicon. This results in a vertical channel. The main interest of the structure is the absence of the JFET effect. The name of the structure comes from the U-shape of the trench.

CoolMOS

Especially for voltages beyond 500 V some manufacturers, most notably Infineon Technologies, have begun to use a charge compensation principle. Thus the resistance in the epitaxial layer as biggest contributor in high voltage MOSFETs can be reduced by a factor >5.

Chapter 4

Power Semiconductor Device

Power semiconductor devices are semiconductor devices used as switches or rectifiers in power electronic circuits (switch mode power supplies for example). They are also called **power devices** or when used in integrated circuits, called **power ICs**.

Most power semiconductor devices are only used in commutation mode (i.e they are either on or off), and are therefore optimized for this. Most of them should not be used in linear operation.

History

Power semiconductor devices first appeared in 1952 with the introduction of the power diode by R.N. Hall. It was made of Germanium and had a voltage capability of 200 volts and a current rating of 35 amperes.

The thyristor appeared in 1957. Thyristors are able to withstand very high reverse breakdown voltage and are also capable of carrying high current. One disadvantage of the thyristor for switching circuits is that once it is 'latched-on' in the conducting state it cannot be turned off by external control. The thyristor turn-off is passive, i.e., the power must be disconnected from the device.

The first bipolar transistors devices with substantial power handling capabilities were introduced in the 1960s. These components overcame some limitations of the thyristors because they can be turned on or off with an applied signal.

With the improvements of the Metal Oxide Semiconductor technology (initially developed to produce integrated circuits), power MOSFETs became available in the late 1970s. International Rectifier introduced a 25 A, 400 V power MOSFET in 1978. These devices allow operation at higher frequency than bipolar transistors, but are limited to the low voltage applications.

The Insulated Gate Bipolar Transistor (IGBT) developed in the 1980s became widely available in the 1990s. This component has the power handling capability of the bipolar transistor, with the advantages of the isolated gate drive of the power MOSFET.

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Common power devices

Some common power devices are the power diode, thyristor, power MOSFET and IGBT. A power diode or MOSFET operates on similar principles to its low-power counterpart, but is able to carry a larger amount of current and typically is able to support a larger reverse-bias voltage in the *off-state*.

Structural changes are often made in power devices to accommodate the higher current density, higher power dissipation and/or higher reverse breakdown voltage. The vast majority of the discrete (i.e non integrated) power devices are built using a vertical structure, whereas small-signal devices employ a lateral structure. With the vertical structure, the current rating of the device is proportional to its area, and the voltage blocking capability is achieved in the height of the die. With this structure, one of the connections of the device is located on the bottom of the semiconductor die.

Common power semiconductor devices

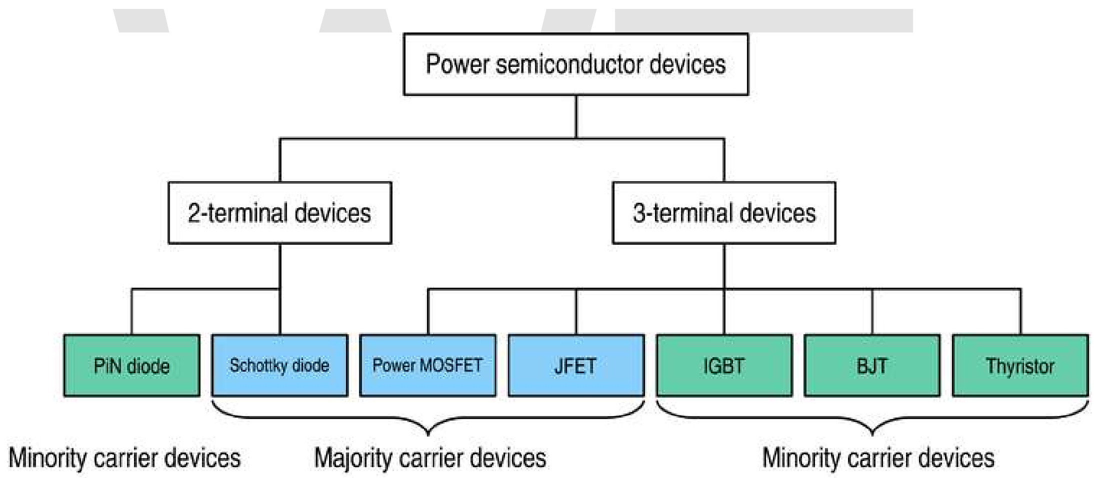

Fig. 1: The power devices family, showing the principal power switches.

The realm of power devices is divided into two main categories (see figure 1):

- The two-terminal devices (diodes), whose state is completely dependent on the external power circuit they are connected to;
- The three-terminal devices, whose state is not only dependent on their external power circuit, but also on the signal on their driving terminal (gate or base). Transistors and thyristors belong to that category.

A second classification is less obvious, but has a strong influence on device performance: Some devices are *majority carrier devices* (Schottky diode, MOSFET), while the others are *minority carrier devices* (Thyristor, bipolar transistor, IGBT). The former use only one type of charge carriers, while the latter use both (i.e electrons and holes). The majority carrier devices are faster, but the charge injection of minority carrier devices allows for better On-state performance.

Diodes

An ideal diode should have the following characteristics:

- When forward-biased, the voltage across the end terminals of the diode should be zero, whatever the current that flows through it (on-state);
- When reverse-biased, the leakage current should be zero, whatever the voltage (off-state).
- The transition between on and off states should be instantaneous.

In reality, the design of a diode is a trade-off between performance in on-state, off-state and commutation. Indeed, the same area of the device must sustain the blocking voltage in the off-state and allow current flow in the on-state. As the requirements for the two states are completely opposite, a diode has to be either optimised for one of them, or time must be allowed to switch from one state to the other (i.e slow down the commutation speed).

This trade-off between on-state/off-state and switching speed is the same for all power devices. A Schottky diode has excellent switching speed and on-state performance, but a high level of leakage current in off-state. On the other hand, PIN diodes are commercially available in different commutation speeds (so-called "fast" and "ultrafast" rectifiers), but any increase in speed is paid for by a lower performance in the on-state.

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Switches

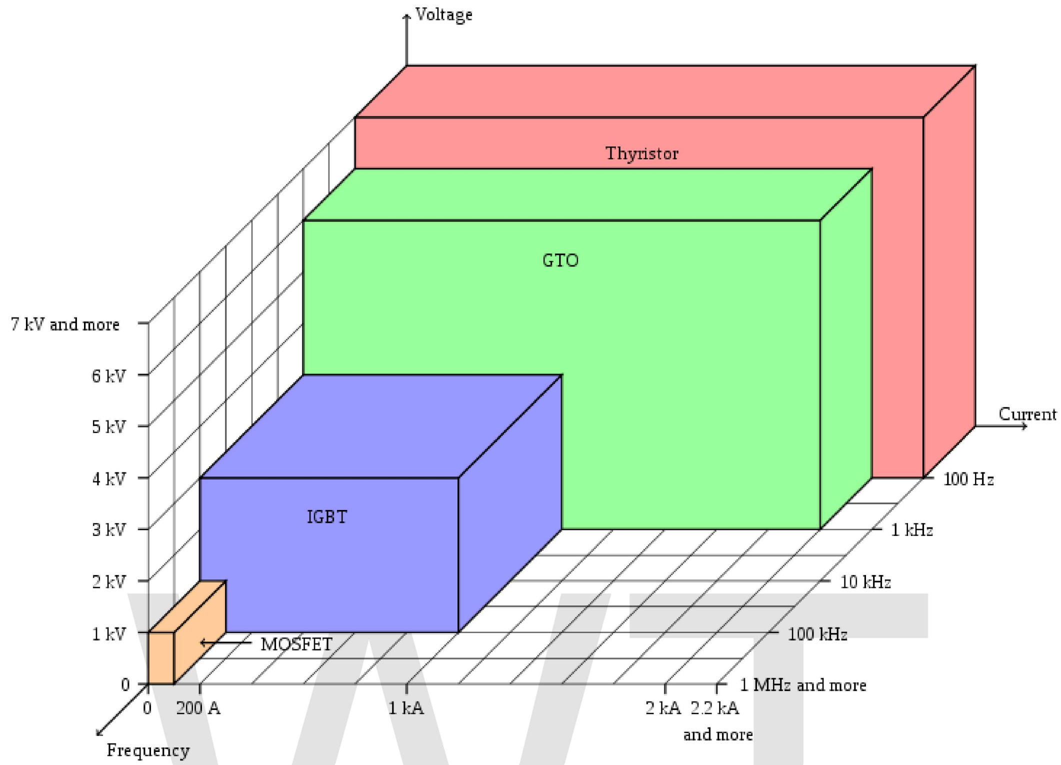


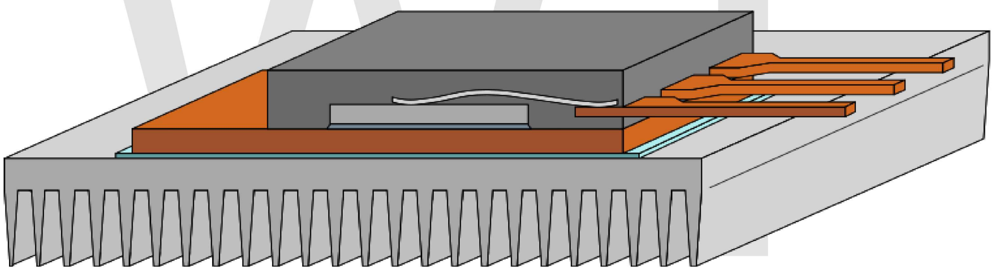
Fig.2 : Current/Voltage/switching frequency domains of the main power electronics switches.

The trade-off between voltage, current and frequency ratings also exists for the switches. Actually, all power semiconductors rely on a PIN diode structure to sustain voltage. This can be seen in figure 2. The power MOSFET has the advantages of the majority carrier devices, so it can achieve very high operating frequency, but can't be used with high voltages. As it is a physical limit, no improvement is expected from silicon MOSFETs concerning their maximum voltage ratings. However, its excellent performance in low voltage make it the device of choice (actually the only choice) for applications below 200 V. By paralleling several devices, it is possible increase the current rating of a switch. The MOSFET is particularly suited to this configuration because its positive thermal coefficient of resistance tends to balance current between individual devices.

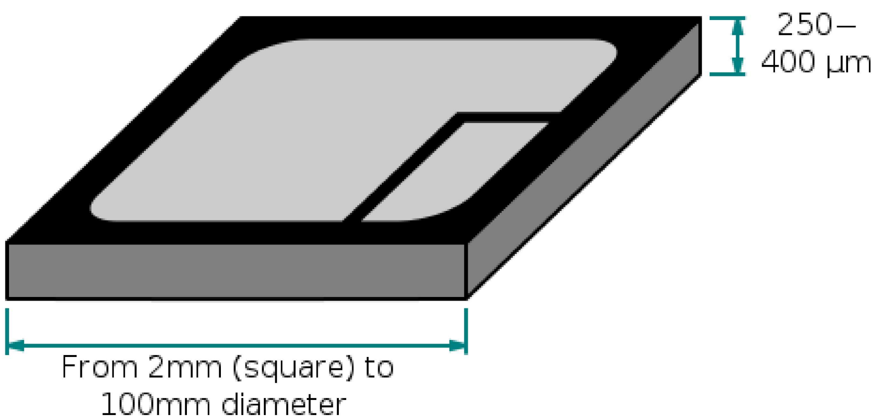
The IGBT is a recent component, so its performance improves regularly as technology evolves. It has already completely replaced the bipolar transistor in power applications, and the availability of power modules (in which several IGBT dice are connected in parallel) makes it attractive for power levels up to several megawatts, pushing further the limit where thyristors and GTOs become the only option. Basically, an IGBT is a bipolar transistor driven by a power MOSFET: it has the advantages of being a minority carrier device (good performance in on-state, even for high voltage devices), with the high input impedance of a MOSFET (it can be driven on or off with a very low amount of power). Its major limitation for low voltage applications is the high voltage drop it exhibits in on-state (2 to 4 V). Compared to the MOSFET, the operating frequency of the IGBT is relatively low (few devices are rated over 50 kHz), mainly because of a so-called 'current-tail' problem during turn-off. This problem is caused by the slow decay of the conduction current during turn-off resulting from slow recombination of large number of carriers, which flood the thick 'drift' region of the IGBT during conduction. The net result is that the turn-off switching loss of an IGBT is considerably higher than its turn-on loss. Generally, in datasheets, turn-off energy is mentioned as a measured parameter and one has to multiply that number with the switching frequency of the intended application to estimate the turn-off loss.

At very high power levels, thyristor-based devices (SCRs, GTOs, MCTs) are still the only choice. Though driving a thyristor is somewhat complicated, as this device can only be turned on. It turns off by itself as soon as no more current flows through it. This requires a circuit with the means to divert current, or specific applications where current is known to cancel regularly (i.e. Alternating Current). MCTs and GTOs have been developed to overcome this limitation; these components are widely used in power distribution applications.

Parameters of power semiconductor devices



A power device is usually attached to a heatsink to remove the heat caused by operation losses.



The power semiconductor die of a three-terminal device (IGBT, MOSFET or BJT). Two contacts are on top of the die, the remaining one is on the back.

1. **Breakdown voltage**: Often there is a trade-off between breakdown voltage rating and on-resistance, because increasing the breakdown voltage by incorporating a thicker and lower doped drift region leads to higher on-resistance.
2. **On-resistance**: Higher current rating lowers the on-resistance due to greater numbers of parallel cells. This increases overall capacitance and slows down the speed.
3. **Rise and fall times** for switching between on and off states.
4. **Safe-operating area** (from thermal dissipation and "latch-up" consideration)
5. **Thermal resistance**: This is an often ignored but extremely important parameter from practical design point of view. Semiconductors do not perform well at elevated temperature but due to large current conduction, all power semiconductor devices heat up. Therefore they need to be cooled by removing that heat continuously. Packaging and heatsinks provide a means of removing heat from the semiconductor device by conducting it to the external environment. Generally, large current devices have large die and packaging surface areas and lower thermal resistance.

Research and development

Packaging

The role of packaging is to:

- connect a die to the external circuit;
- provide a way to remove the heat generated by the device;
- protect the die from the external environment (moisture, dust);

Many of the reliability issues of power device are either related to excessive temperature of fatigue due to thermal cycling. Research is currently carried out on the following topics:

- improve the cooling performance.
- improve the resistance to thermal cycling by closely matching the Coefficient of thermal expansion of the packaging to that of the silicon.
- increase the maximum operating temperature of the packaging material.

Research is also ongoing on electrical issues such as reducing the parasitic inductance of packaging. This inductance limits the operating frequency as it generates losses in the devices during commutation.

Low-voltage MOSFETs are also limited by the parasitic resistance of the packages, as their intrinsic on-state resistance can be as low as one or two milliohms.

Some of the most common type of power semiconductor packages include TO-220, TO-247, TO-262, TO-3, D^2Pak, etc.

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Improvement of structures

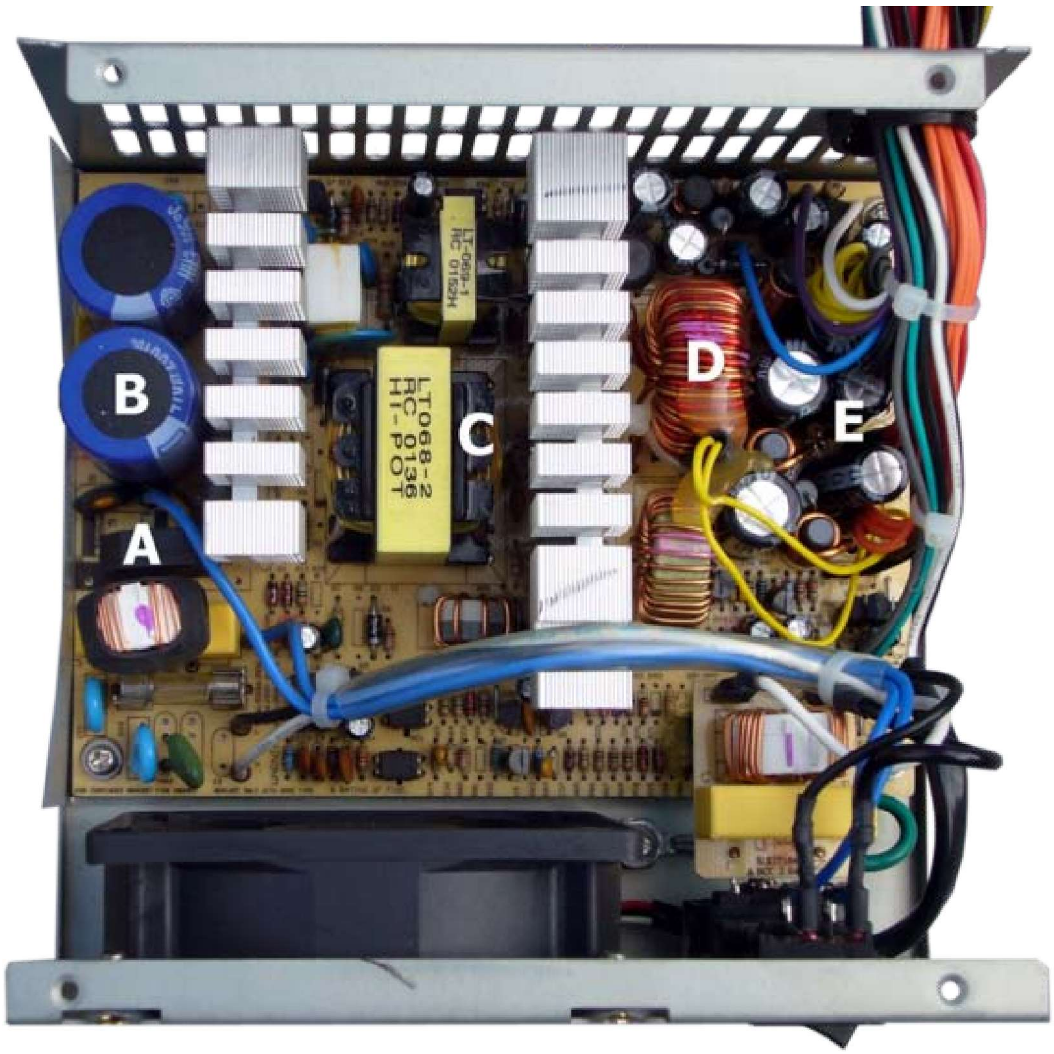
IGBTs are still under development and we can expect increased operating voltages in the future. At the high-power end of the range, MOS-Controlled Thyristor are promising devices. A major improvement over conventional MOSFET structure is achieved by employing superjunction charge-balance principle to the design. Essentially, it allows the thick drift region of a power MOSFET to be heavily doped (thereby reducing the electrical resistance for electron flow) without compromising the breakdown voltage. An adjacent region of similarly doped (but of opposite carrier polarity - *holes*) is created within the structure. These two similar but opposite doped regions effectively cancel out their mobile charge and develop a 'depleted region' which supports the high voltage during off-state. On the other hand, during conducting state, the higher doping of the drift region allows easier flow of carrier thereby reducing on-resistance. Commercial devices, based on this principle, have been developed by International Rectifier and Infineon in the name of CoolMOS™.

Wide band-gap semiconductors

The major breakthrough in power semiconductor devices is expected from the replacement of silicon by a wide band-gap semiconductor. At the moment, silicon carbide (SiC) is considered to be the most promising. SiC Schottky diodes with a breakdown voltage of 1200 V are commercially available, as are 1200 V JFETs. As both are majority carrier devices, they can operate at high speed. Bipolar devices are being developed for higher voltages, up to 20 kV. Among its advantages, silicon carbide can operate at higher temperature (up to 400°C) and has a lower thermal resistance than silicon, allowing better cooling.

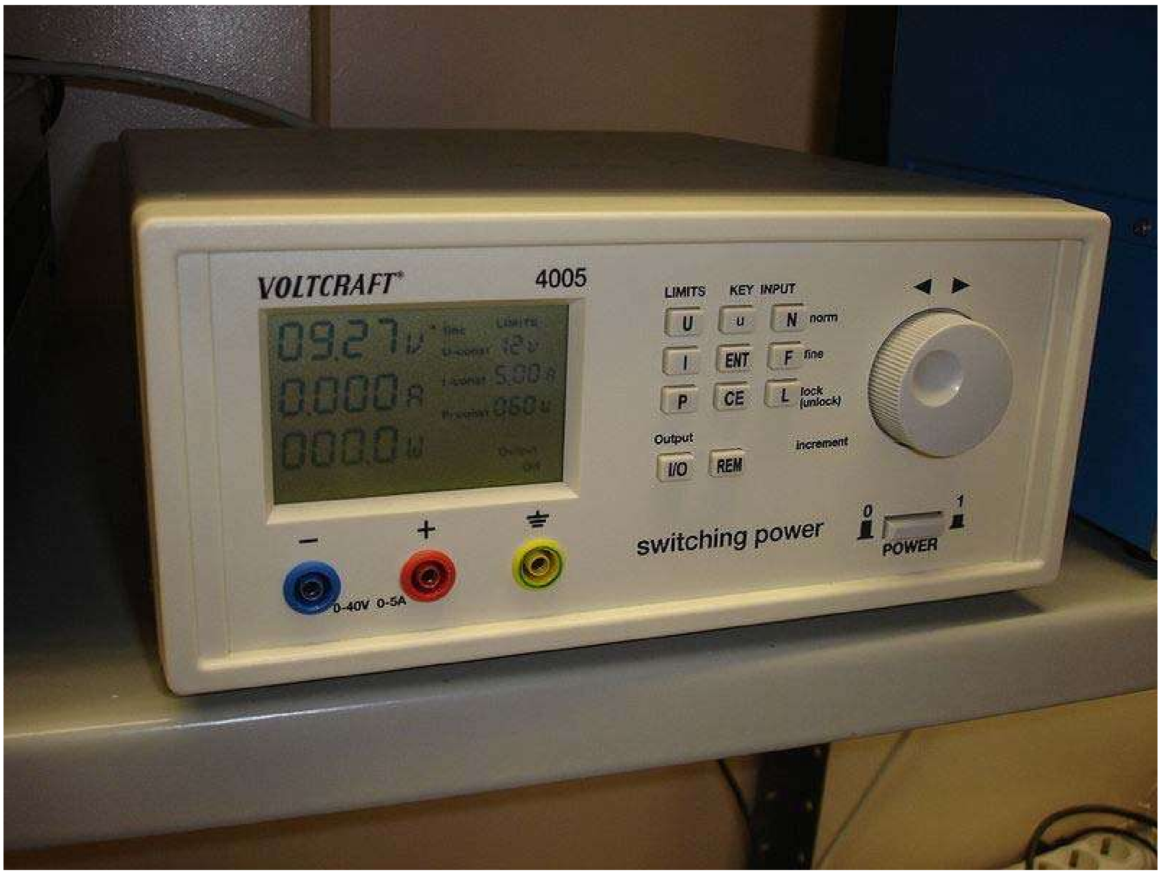
Chapter 5

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

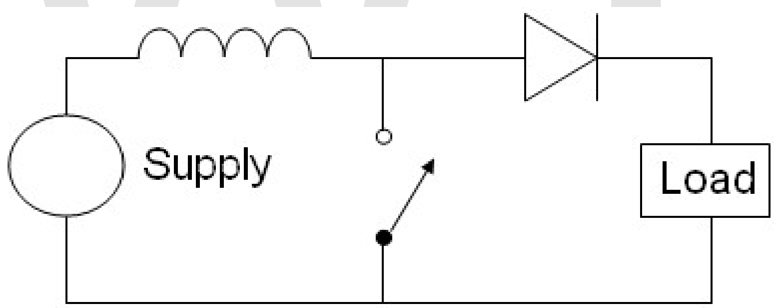
A **switched-mode power supply** (**switching-mode power supply**, **SMPS**, or simply **switcher**) is an electronic power supply that incorporates a switching regulator in order to be highly efficient in the conversion of electrical power. Like other types of power supplies, an SMPS transfers power 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 so-called 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.

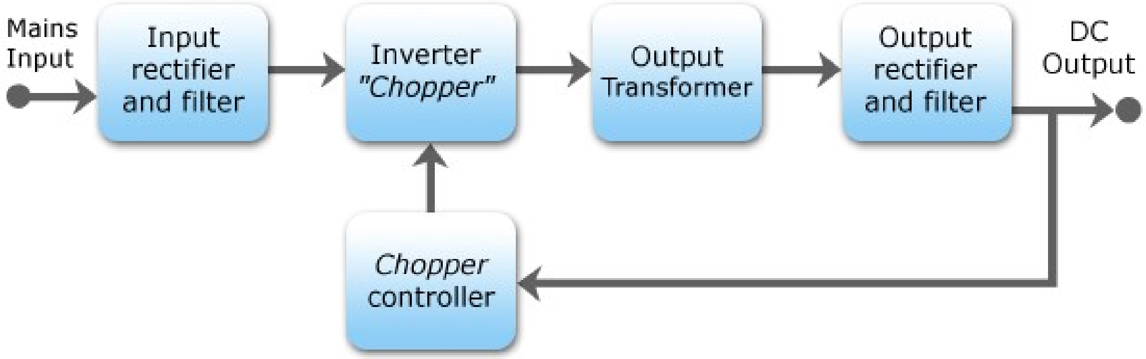
Very low cost SMPSs may couple electrical switching noise back onto the mains power line, causing interference with A/V equipment connected to the same phase. Non-power-factor-corrected SMPSs also cause harmonic distortion.

Classification

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

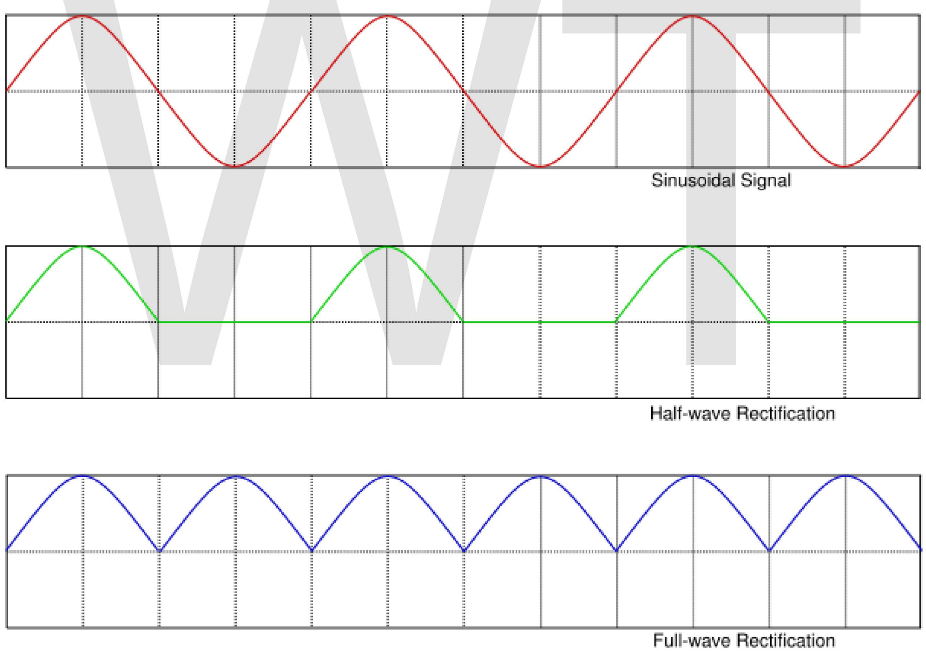
- AC in, DC out: rectifier, off-line converter input stage
- DC in, DC out: voltage converter, or current converter, or DC to DC converter
- AC in, AC out: frequency changer, cycloconverter, transformer, phase converter
- DC in, AC out: inverter

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 so called *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.

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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 ≤ Out ≤ In, $V_2 = DV_1$	Current is continuous at output.
Boost	0–150	70%	1.0	Single inductor	Out ≥ In, $V_2 = \frac{1}{1-D} V_1$	Current is continuous at input.
Buck-boost	0–150	78%	1.0	Single inductor	Out ≤ 0, $V_2 = -\frac{D}{1-D} V_1$	Current is dis-continuous 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 *and* 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
Resonant forward	0–60	87%	1.0	60–400	Inductor and capacitor	Single rail input, unregulated output, high efficiency, low EMI.
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			

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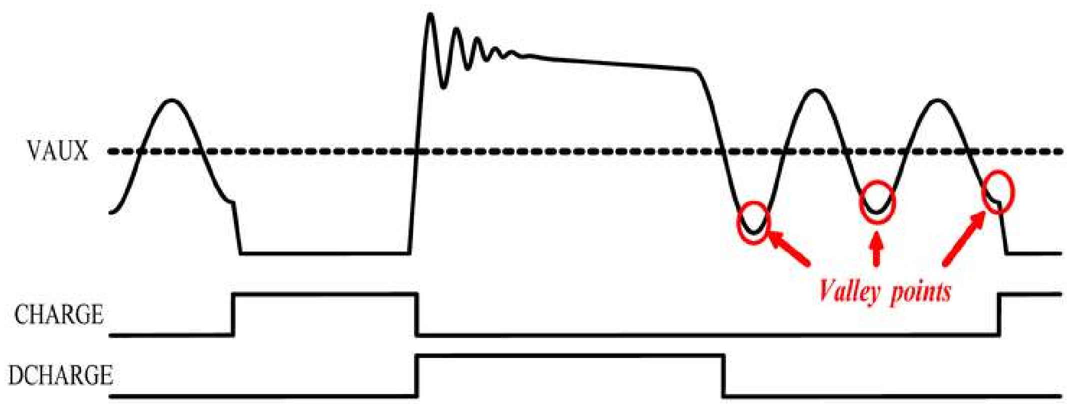
Isolated Ćuk	Two capacitors and two inductors

- **^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 ciruit, 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 μA for IT equipment.

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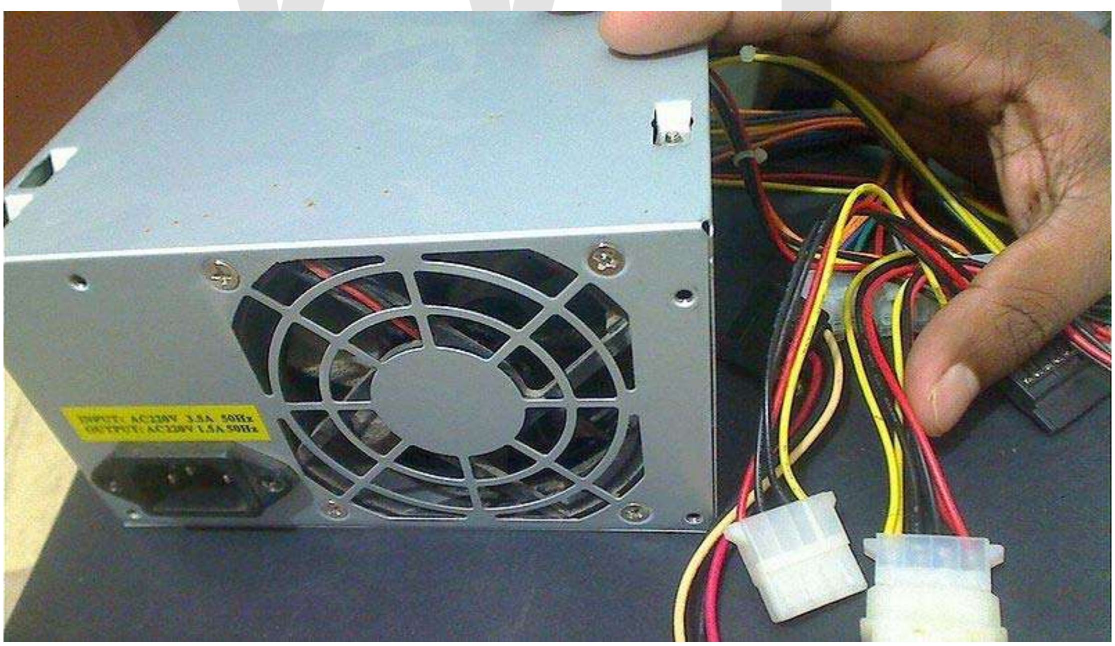
Applications

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 6

Inverter

An **inverter** is an electrical device that converts direct current (DC) to alternating current (AC); the converted AC can be at any required voltage and frequency with the use of appropriate transformers, switching, and control circuits.

Solid-state inverters have no moving parts and are used in a wide range of applications, from small switching power supplies in computers, to large electric utility high-voltage direct current applications that transport bulk power. Inverters are commonly used to supply AC power from DC sources such as solar panels or batteries.

There are two main types of inverter. The output of a **modified sine wave** inverter is similar to a square wave output except that the output goes to zero volts for a time before switching positive or negative. It is simple and low cost (~$0.10USD/Watt) and is compatible with most electronic devices, except for sensitive or specialized equipment, for example certain laser printers. A **pure sine wave** inverter produces a nearly perfect sine wave output (<3% total harmonic distortion) that is essentially the same as utility-supplied grid power. Thus it is compatible with all AC electronic devices. This is the type used in grid-tie inverters. Its design is more complex, and costs 5 or 10 times more per unit power (~$0.50 to $1.00USD/Watt). The electrical inverter is a high-power electronic oscillator. It is so named because early mechanical AC to DC converters were made to work in reverse, and thus were "inverted", to convert DC to AC.

The inverter performs the opposite function of a rectifier.

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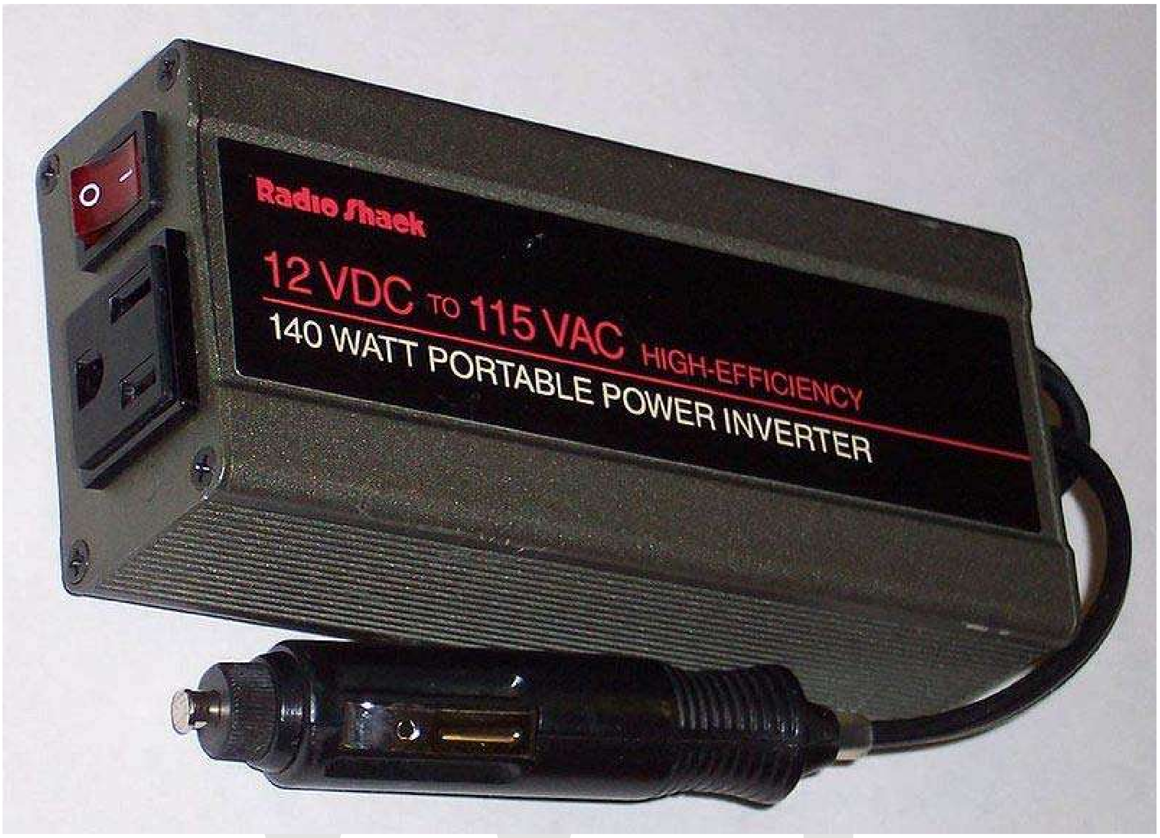
Applications

DC power source utilization



Inverter designed to provide 115 VAC from the 12 VDC source provided in an automobile. The unit shown provides up to 1.2 amperes of alternating current, or enough to power two sixty watt light bulbs.

An inverter converts the DC electricity from sources such as batteries, solar panels, or fuel cells to AC electricity. The electricity can be at any required voltage; in particular it can operate AC equipment designed for mains operation, or rectified to produce DC at any desired voltage.

Grid tie inverters can feed energy back into the distribution network because they produce alternating current with the same wave shape and frequency as supplied by the distribution system. They can also switch off automatically in the event of a blackout.

Micro-inverters convert direct current from individual solar panels into alternating current for the electric grid. They are grid tie designs by default.

Uninterruptible power supplies

An uninterruptible power supply (UPS) uses batteries and an inverter to supply AC power when main power is not available. When main power is restored, a rectifier supplies DC power to recharge the batteries.

Induction heating

Inverters convert low frequency main AC power to a higher frequency for use in induction heating. To do this, AC power is first rectified to provide DC power. The inverter then changes the DC power to high frequency AC power.

HVDC power transmission

With HVDC power transmission, AC power is rectified and high voltage DC power is transmitted to another location. At the receiving location, an inverter in a static inverter plant converts the power back to AC.

Variable-frequency drives

A variable-frequency drive controls the operating speed of an AC motor by controlling the frequency and voltage of the power supplied to the motor. An inverter provides the controlled power. In most cases, the variable-frequency drive includes a rectifier so that DC power for the inverter can be provided from main AC power. Since an inverter is the key component, variable-frequency drives are sometimes called inverter drives or just inverters.

Electric vehicle drives

Adjustable speed motor control inverters are currently used to power the traction motors in some electric and diesel-electric rail vehicles as well as some battery electric vehicles and hybrid electric highway vehicles such as the Toyota Prius and Fisker Karma. Various improvements in inverter technology are being developed specifically for electric vehicle applications. In vehicles with regenerative braking, the inverter also takes power from the motor (now acting as a generator) and stores it in the batteries.

Air conditioning

An air conditioner bearing the inverter tag uses a variable-frequency drive to control the speed of the motor and thus the compressor.

The general case

A transformer allows AC power to be converted to any desired voltage, but at the same frequency. Inverters, plus rectifiers for DC, can be designed to convert from any voltage, AC or DC, to any other voltage, also AC or DC, at any desired frequency. The output

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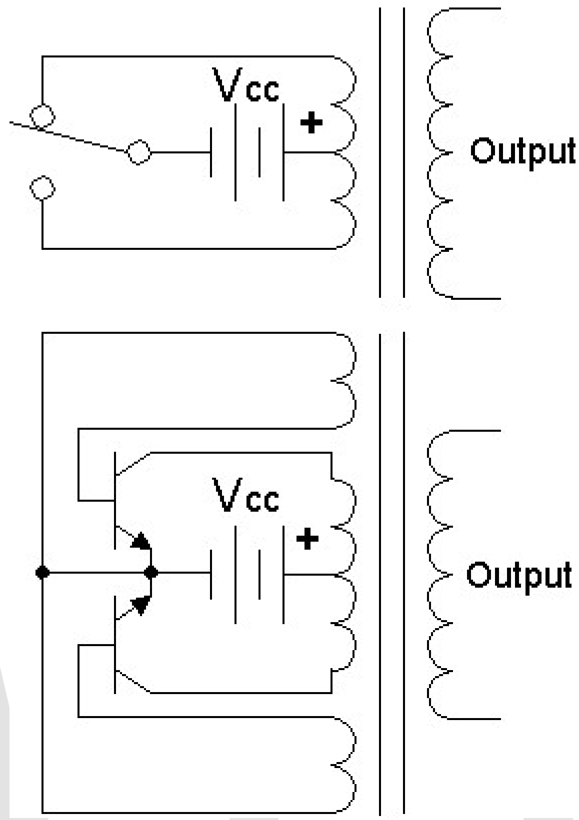
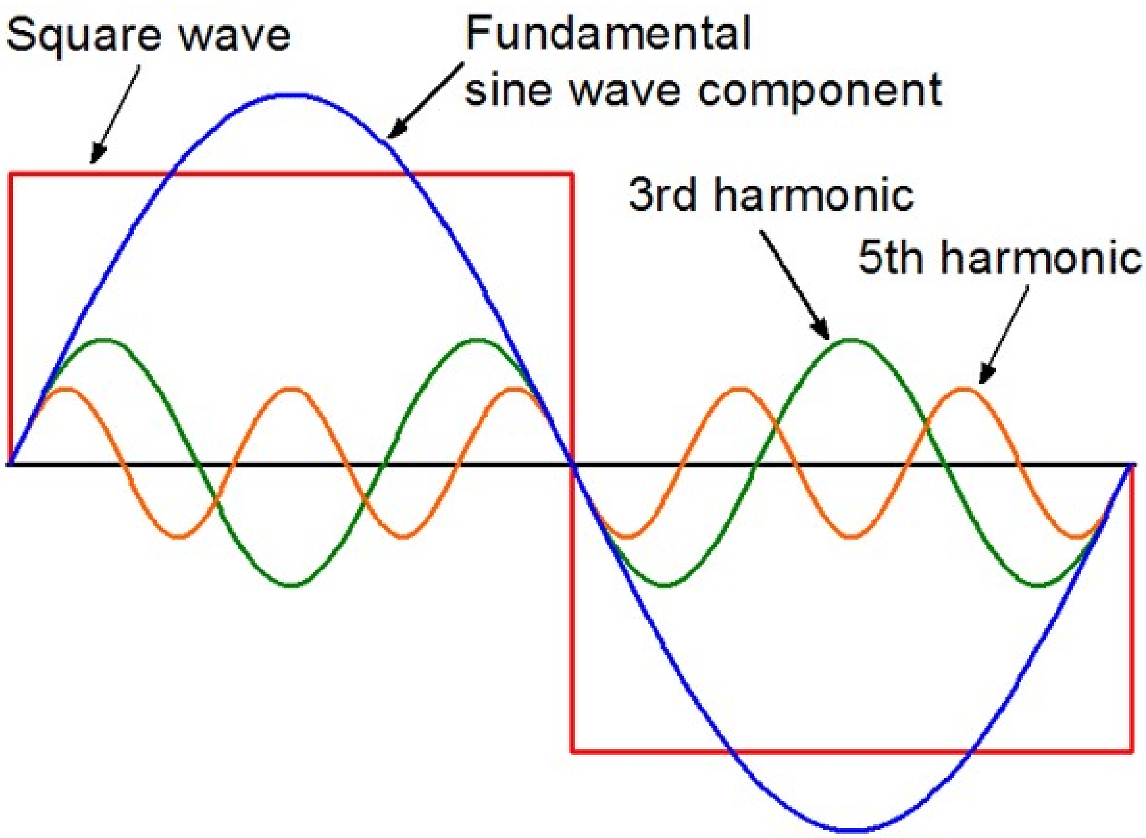
power can never exceed the input power, but efficiencies can be high, with a small proportion of the power dissipated as waste heat.

Circuit description



Top: Simple inverter circuit shown with an electromechanical switch
and automatic equivalent
auto-switching device implemented with two transistors and split winding auto-transformer in place of the mechanical switch.



Square waveform with fundamental sine wave component, 3rd harmonic and 5th harmonic

Basic designs

In one simple inverter circuit, DC power is connected to a transformer through the centre tap of the primary winding. A switch is rapidly switched back and forth to allow current to flow back to the DC source following two alternate paths through one end of the primary winding and then the other. The alternation of the direction of current in the primary winding of the transformer produces alternating current (AC) in the secondary circuit.

The electromechanical version of the switching device includes two stationary contacts and a spring supported moving contact. The spring holds the movable contact against one of the stationary contacts and an electromagnet pulls the movable contact to the opposite stationary contact. The current in the electromagnet is interrupted by the action of the switch so that the switch continually switches rapidly back and forth. This type of electromechanical inverter switch, called a vibrator or buzzer, was once used in vacuum tube automobile radios. A similar mechanism has been used in door bells, buzzers and tattoo guns.

As they became available with adequate power ratings, transistors and various other types of semiconductor switches have been incorporated into inverter circuit designs.

Output waveforms

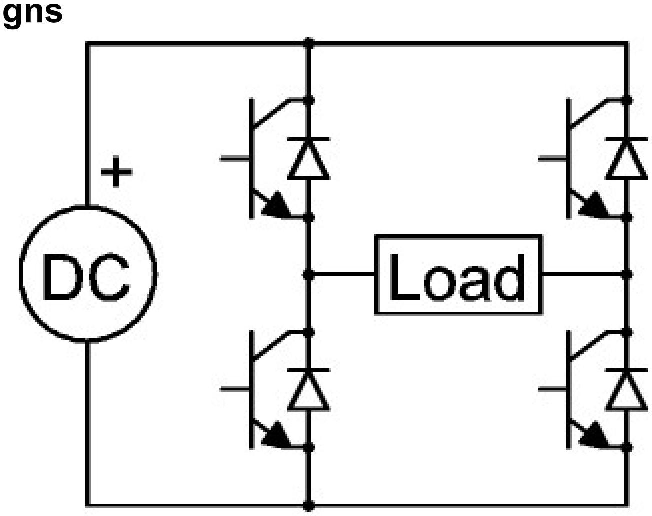
The switch in the simple inverter described above, when not coupled to an output transformer, produces a square voltage waveform due to its simple off and on nature as opposed to the sinusoidal waveform that is the usual waveform of an AC power supply. Using Fourier analysis, periodic waveforms are represented as the sum of an infinite series of sine waves. The sine wave that has the same frequency as the original waveform is called the fundamental component. The other sine waves, called *harmonics*, that are included in the series have frequencies that are integral multiples of the fundamental frequency.

The quality of the inverter output waveform can be expressed by using the Fourier analysis data to calculate the total harmonic distortion (THD). The total harmonic distortion is the square root of the sum of the squares of the harmonic voltages divided by the fundamental voltage:

$$\mathrm{THD} = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \cdots + V_n^2}}{V_1}$$

The quality of output waveform that is needed from an inverter depends on the characteristics of the connected load. Some loads need a nearly perfect sine wave voltage supply in order to work properly. Other loads may work quite well with a square wave voltage.

Advanced designs

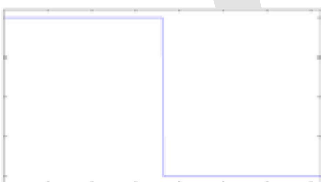
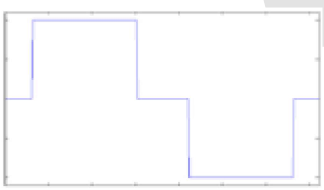
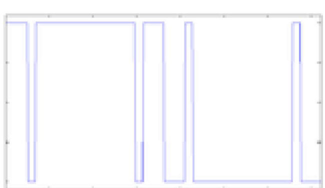
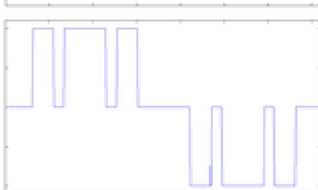


H-bridge inverter circuit with transistor switches and antiparallel diodes

There are many different power circuit topologies and control strategies used in inverter designs. Different design approaches address various issues that may be more or less important depending on the way that the inverter is intended to be used.

The issue of waveform quality can be addressed in many ways. Capacitors and inductors can be used to filter the waveform. If the design includes a transformer, filtering can be applied to the primary or the secondary side of the transformer or to both sides. Low-pass filters are applied to allow the fundamental component of the waveform to pass to the output while limiting the passage of the harmonic components. If the inverter is designed to provide power at a fixed frequency, a resonant filter can be used. For an adjustable frequency inverter, the filter must be tuned to a frequency that is above the maximum fundamental frequency.

Since most loads contain inductance, feedback rectifiers or antiparallel diodes are often connected across each semiconductor switch to provide a path for the peak inductive load current when the switch is turned off. The antiparallel diodes are somewhat similar to the *freewheeling diodes* used in AC/DC converter circuits.

waveform	**signal transitions per period**	**harmonics eliminated**	**harmonics amplified**	**System Description**	**THD**
	2	-	-	2-level square wave	~45%
	4	3, 9, 27,...	-	3-level "modified square wave"	> 23.8%
	8			5-level "modified square wave"	> 6.5%
	10	3, 5, 9, 27	7, 11,...	2-level very slow PWM	
	12	3, 5, 9, 27	7, 11,...	3-level very slow PWM	

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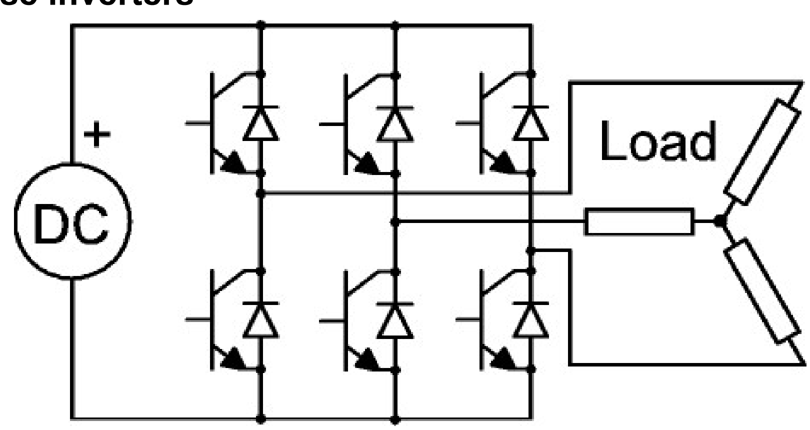
Fourier analysis reveals that a waveform, like a square wave, that is anti-symmetrical about the 180 degree point contains only odd harmonics, the 3rd, 5th, 7th, etc. Waveforms that have steps of certain widths and heights can attenuate certain lower harmonics at the expense of amplifying higher harmonics. For example, by inserting a zero-voltage step between the positive and negative sections of the square-wave, all of the harmonics that are divisible by three (3rd and 9th, etc.) can be eliminated. That leaves only the 5th, 7th, 11th, 13th etc. The required width of the steps is one third of the period for each of the positive and negative steps and one sixth of the period for each of the zero-voltage steps.

Changing the square wave as described above is an example of pulse-width modulation (PWM). Modulating, or regulating the width of a square-wave pulse is often used as a method of regulating or adjusting an inverter's output voltage. When voltage control is not required, a fixed pulse width can be selected to reduce or eliminate selected harmonics. Harmonic elimination techniques are generally applied to the lowest harmonics because filtering is much more practical at high frequencies, where the filter components can be much smaller and less expensive. *Multiple pulse-width* or *carrier based* PWM control schemes produce waveforms that are composed of many narrow pulses. The frequency represented by the number of narrow pulses per second is called the *switching frequency* or *carrier frequency*. These control schemes are often used in variable-frequency motor control inverters because they allow a wide range of output voltage and frequency adjustment while also improving the quality of the waveform.

Multilevel inverters provide another approach to harmonic cancellation. Multilevel inverters provide an output waveform that exhibits multiple steps at several voltage levels. For example, it is possible to produce a more sinusoidal wave by having split-rail direct current inputs at two voltages, or positive and negative inputs with a central ground. By connecting the inverter output terminals in sequence between the positive rail and ground, the positive rail and the negative rail, the ground rail and the negative rail, then both to the ground rail, a stepped waveform is generated at the inverter output. This is an example of a three level inverter: the two voltages and ground.

Three phase inverters



3-phase inverter with wye connected load

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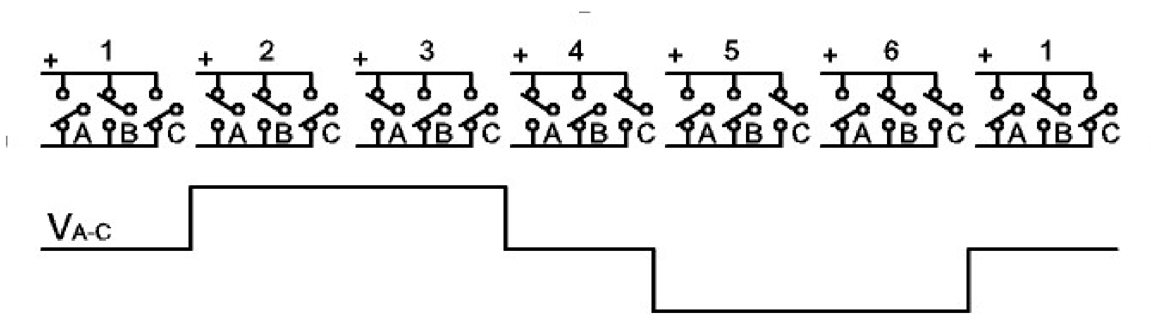
Three-phase inverters are used for variable-frequency drive applications and for high power applications such as HVDC power transmission. A basic three-phase inverter consists of three single-phase inverter switches each connected to one of the three load terminals. For the most basic control scheme, the operation of the three switches is coordinated so that one switch operates at each 60 degree point of the fundamental output waveform. This creates a line-to-line output waveform that has six steps. The six-step waveform has a zero-voltage step between the positive and negative sections of the square-wave such that the harmonics that are multiples of three are eliminated as described above. When carrier-based PWM techniques are applied to six-step waveforms, the basic overall shape, or *envelope*, of the waveform is retained so that the 3rd harmonic and its multiples are cancelled.



3-phase inverter switching circuit showing 6-step switching sequence and waveform of voltage between terminals A and C

To construct inverters with higher power ratings, two six-step three-phase inverters can be connected in parallel for a higher current rating or in series for a higher voltage rating. In either case, the output waveforms are phase shifted to obtain a 12-step waveform. If additional inverters are combined, an 18-step inverter is obtained with three inverters etc. Although inverters are usually combined for the purpose of achieving increased voltage or current ratings, the quality of the waveform is improved as well.

History

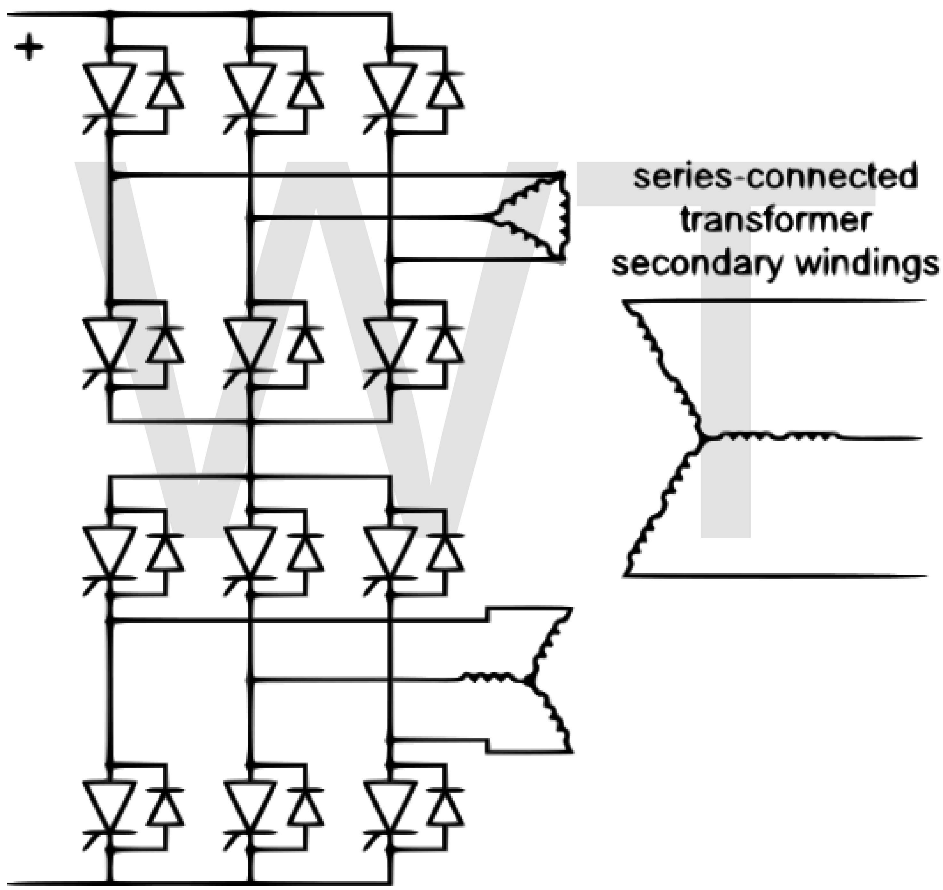
Early inverters

From the late nineteenth century through the middle of the twentieth century, DC-to-AC power conversion was accomplished using rotary converters or motor-generator sets (M-G sets). In the early twentieth century, vacuum tubes and gas filled tubes began to be used as switches in inverter circuits. The most widely used type of tube was the thyratron.

The origins of electromechanical inverters explain the source of the term *inverter*. Early AC-to-DC converters used an induction or synchronous AC motor direct-connected to a generator (dynamo) so that the generator's commutator reversed its connections at exactly the right moments to produce DC. A later development is the synchronous converter, in which the motor and generator windings are combined into one armature, with slip rings at one end and a commutator at the other and only one field frame. The result with either is AC-in, DC-out. With an M-G set, the DC can be considered to be separately generated from the AC; with a synchronous converter, in a certain sense it can be considered to be "mechanically rectified AC". Given the right auxiliary and control equipment, an M-G set or rotary converter can be "run backwards", converting DC to AC. Hence an inverter is an inverted converter.

Controlled rectifier inverters

Since early transistors were not available with sufficient voltage and current ratings for most inverter applications, it was the 1957 introduction of the thyristor or silicon-controlled rectifier (SCR) that initiated the transition to solid state inverter circuits.



12-pulse line-commutated inverter circuit

The *commutation* requirements of SCRs are a key consideration in SCR circuit designs. SCRs do not turn off or *commutate* automatically when the gate control signal is shut off. They only turn off when the forward current is reduced to below the minimum holding current, which varies with each kind of SCR, through some external process. For SCRs connected to an AC power source, commutation occurs naturally every time the polarity of the source voltage reverses. SCRs connected to a DC power source usually require a means of forced commutation that forces the current to zero when commutation is required. The least complicated SCR circuits employ natural commutation rather than forced commutation. With the addition of forced commutation circuits, SCRs have been used in the types of inverter circuits described above.

In applications where inverters transfer power from a DC power source to an AC power source, it is possible to use AC-to-DC controlled rectifier circuits operating in the inversion mode. In the inversion mode, a controlled rectifier circuit operates as a line commutated inverter. This type of operation can be used in HVDC power transmission systems and in regenerative braking operation of motor control systems.

Another type of SCR inverter circuit is the current source input (CSI) inverter. A CSI inverter is the dual of a six-step voltage source inverter. With a current source inverter, the DC power supply is configured as a current source rather than a voltage source. The inverter SCRs are switched in a six-step sequence to direct the current to a three-phase AC load as a stepped current waveform. CSI inverter commutation methods include load commutation and parallel capacitor commutation. With both methods, the input current regulation assists the commutation. With load commutation, the load is a synchronous motor operated at a leading power factor.

As they have become available in higher voltage and current ratings, semiconductors such as transistors or IGBTs that can be turned off by means of control signals have become the preferred switching components for use in inverter circuits.

Rectifier and inverter pulse numbers

Rectifier circuits are often classified by the number of current pulses that flow to the DC side of the rectifier per cycle of AC input voltage. A single-phase half-wave rectifier is a one-pulse circuit and a single-phase full-wave rectifier is a two-pulse circuit. A three-phase half-wave rectifier is a three-pulse circuit and a three-phase full-wave rectifier is a six-pulse circuit.

With three-phase rectifiers, two or more rectifiers are sometimes connected in series or parallel to obtain higher voltage or current ratings. The rectifier inputs are supplied from special transformers that provide phase shifted outputs. This has the effect of phase multiplication. Six phases are obtained from two transformers, twelve phases from three transformers and so on. The associated rectifier circuits are 12-pulse rectifiers, 18-pulse rectifiers and so on.

When controlled rectifier circuits are operated in the inversion mode, they would be classified by pulse number also. Rectifier circuits that have a higher pulse number have reduced harmonic content in the AC input current and reduced ripple in the DC output voltage. In the inversion mode, circuits that have a higher pulse number have lower harmonic content in the AC output voltage waveform.

Chapter 7

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.

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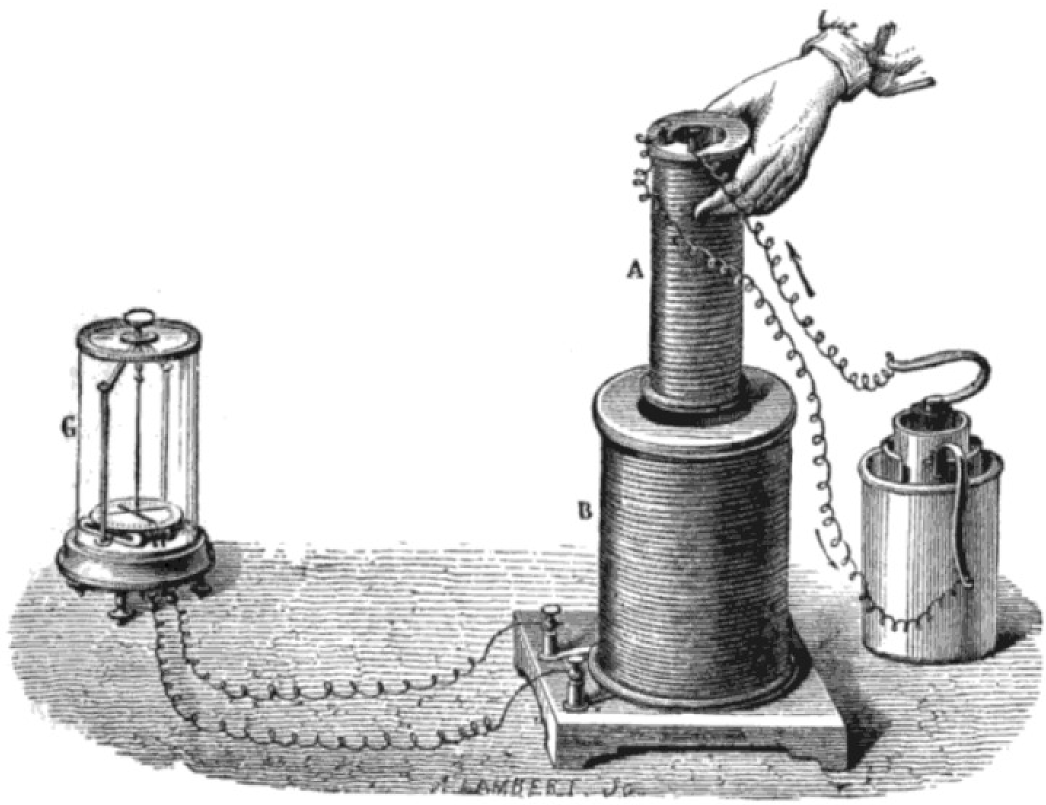
History

Discovery



Faraday's experiment with induction between coils of wire

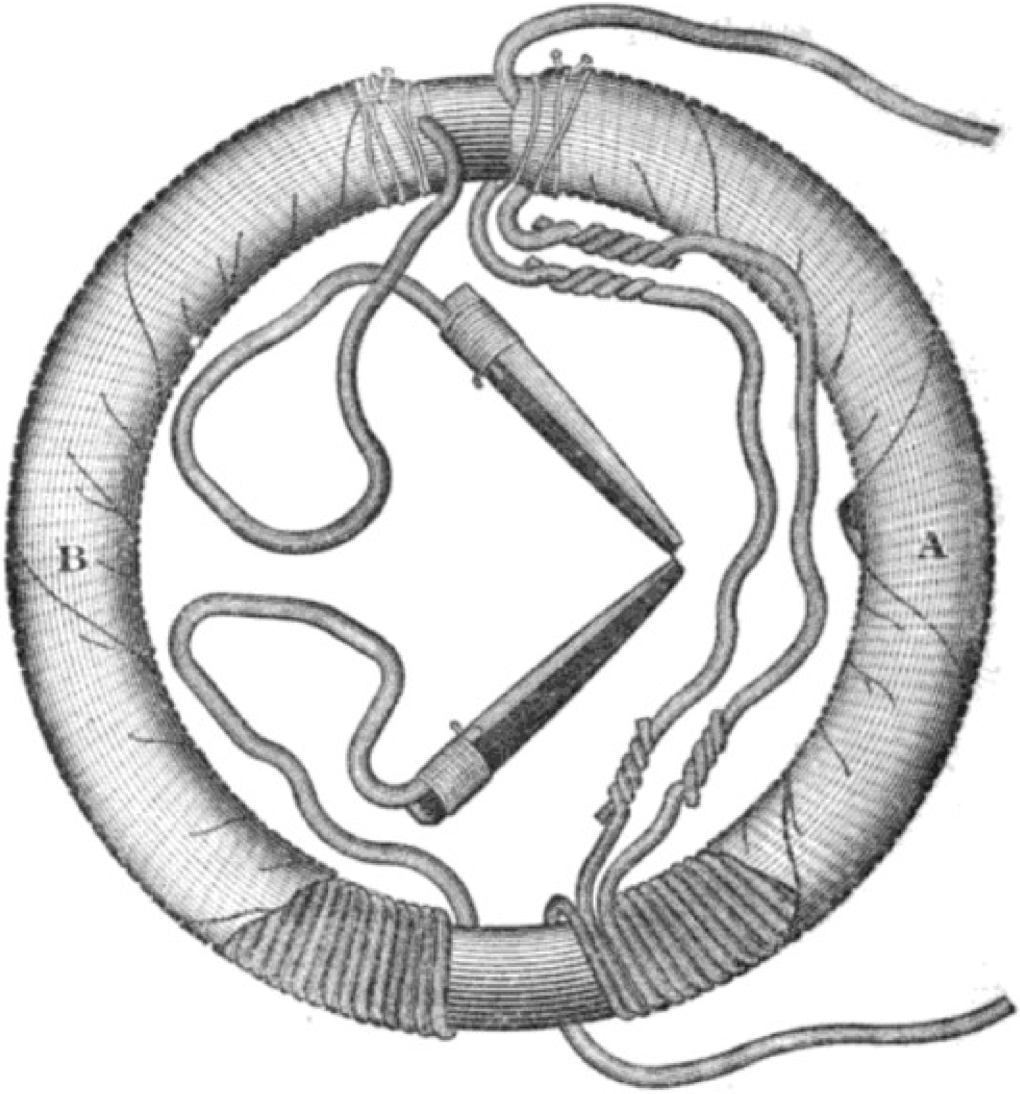
The phenomenon of electromagnetic induction was discovered independently by Michael Faraday and Joseph Henry in 1831. However, Faraday was the first to publish the results of his experiments and thus receive credit for the discovery. The relationship between electromotive force (EMF) or "voltage" and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

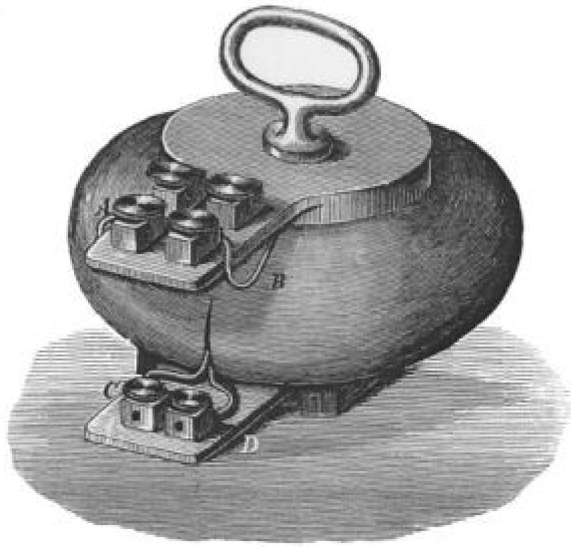
In 1878, the Ganz Company in Hungary began manufacturing equipment for electric lighting and, by 1883, had installed over fifty systems in Austria-Hungary. Their systems used alternating current exclusively and included those comprising both arc and incandescent lamps, along with generators and other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

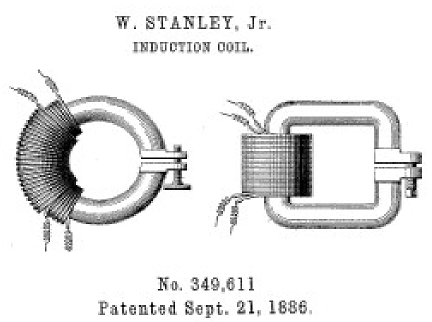
Closed-core transformers and the introduction of parallel connection



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 Gibs. When they employed it in parallel connected electric distribution systems, closed-core transformers finally made it technically and economically feasible to provide electric power for lighting in homes, businesses and public spaces. Bláthy had suggested the use of closed-cores, Zipernowsky the use of shunt connections, and Déri had performed the experiments; Bláthy also discovered the transformer formula, $V_s/V_p = N_s/N_p$. 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

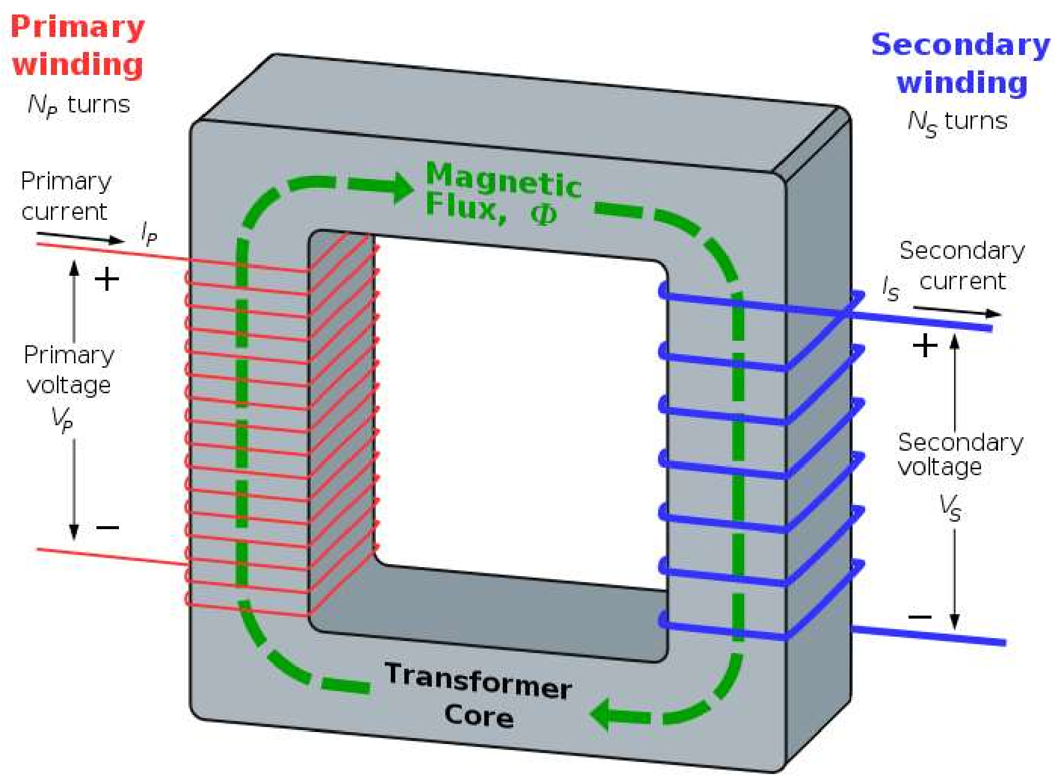
In 1889, Russian-born engineer Mikhail Dolivo-Dobrovolsky developed the first three-phase transformer at the Allgemeine Elektricitäts-Gesellschaft ("General Electricity Company") in Germany.

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

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

Basic principles

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



An ideal transformer

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

Induction law

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

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

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

$$V_p = N_p \frac{d\Phi}{dt}.$$

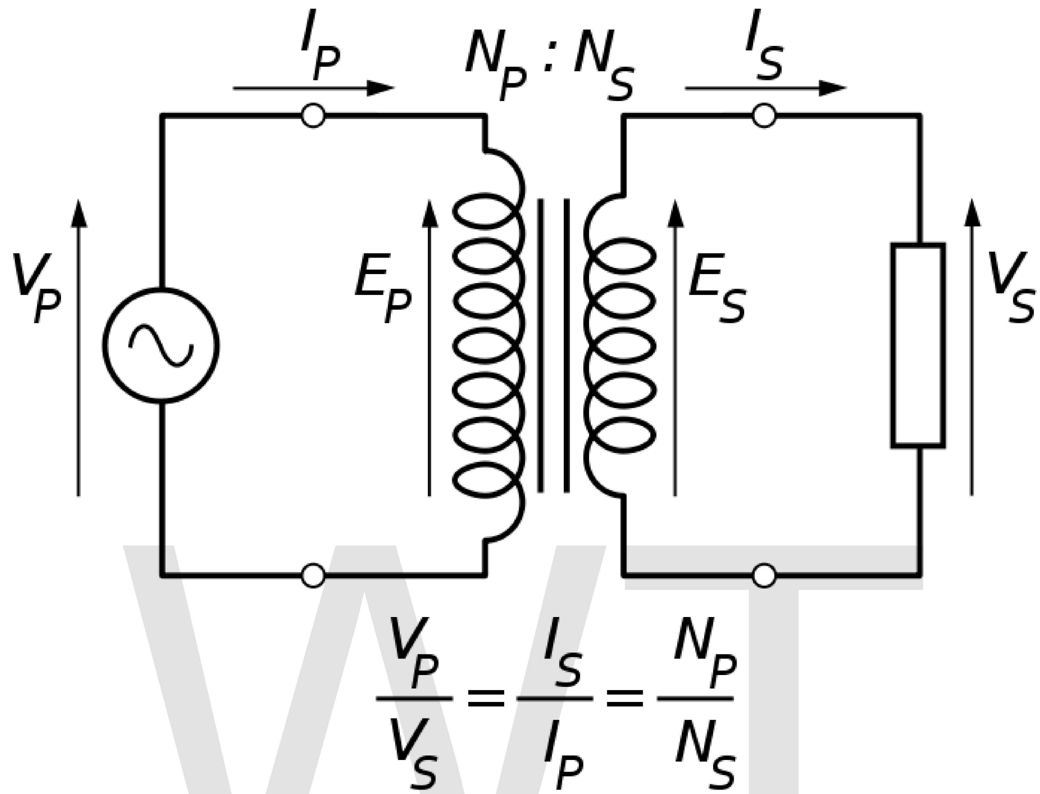
Taking the ratio of the two equations for V_s and V_p gives the basic equation for stepping up or stepping down the voltage

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

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.

VT

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:

$$P_{\text{incoming}} = I_{\text{p}} V_{\text{p}} = P_{\text{outgoing}} = I_{\text{s}} V_{\text{s}},$$

giving the ideal transformer equation

$$\frac{V_{\text{s}}}{V_{\text{p}}} = \frac{N_{\text{s}}}{N_{\text{p}}} = \frac{I_{\text{p}}}{I_{\text{s}}}.$$

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

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

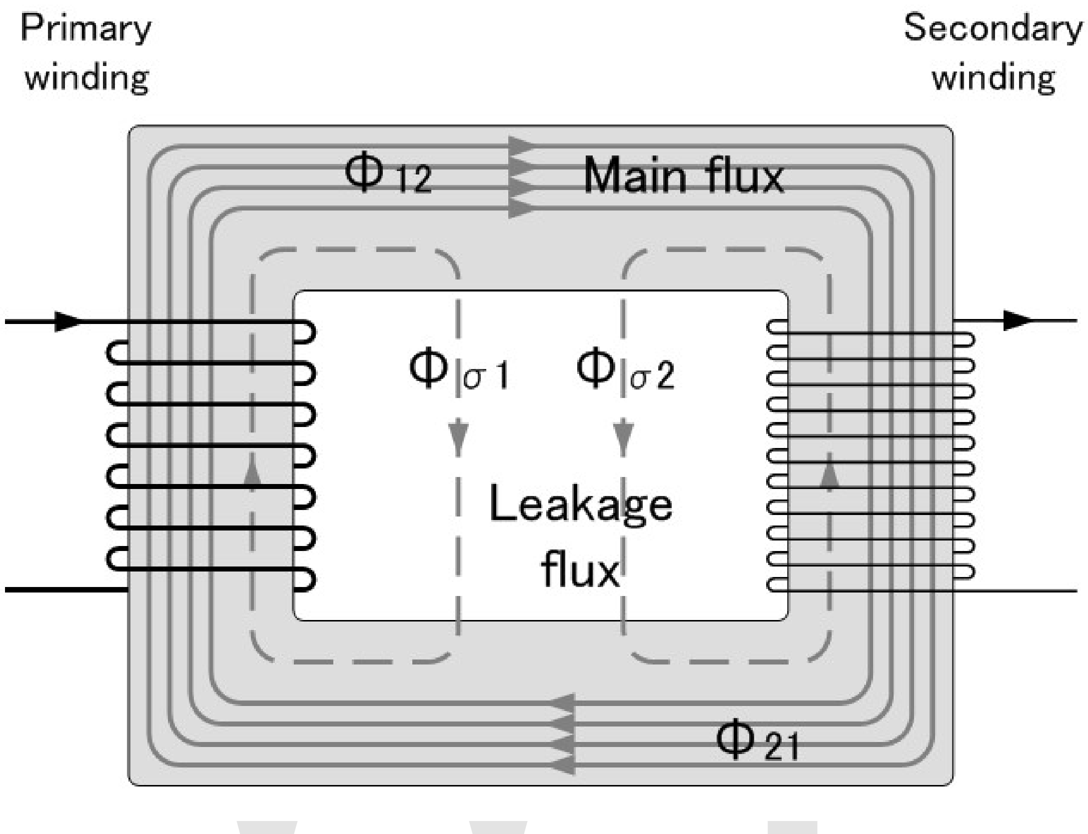
The simplified description above neglects several practical factors, in particular the primary current required to establish a magnetic field in the core, and the contribution to the field due to current in the secondary circuit.

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:

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

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

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

The time-derivative term in Faraday's Law shows that the flux in the core is the integral with respect to time of the applied voltage. 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.

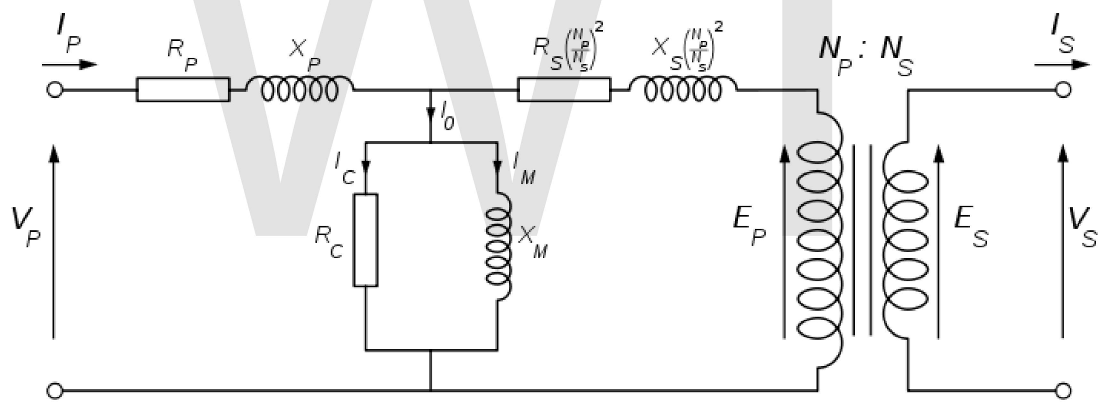
Equivalent circuit

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

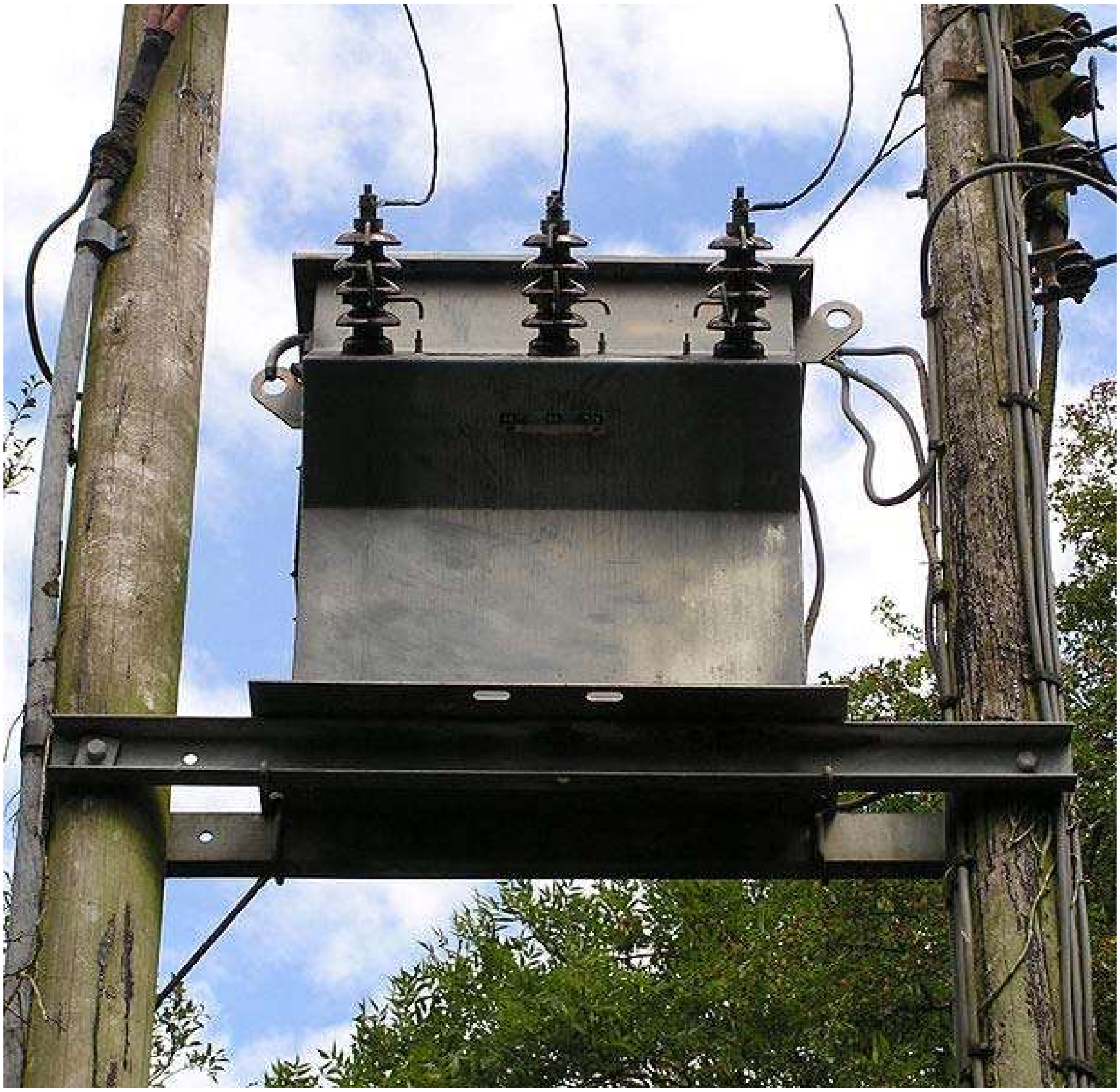
A variable autotransformer

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.

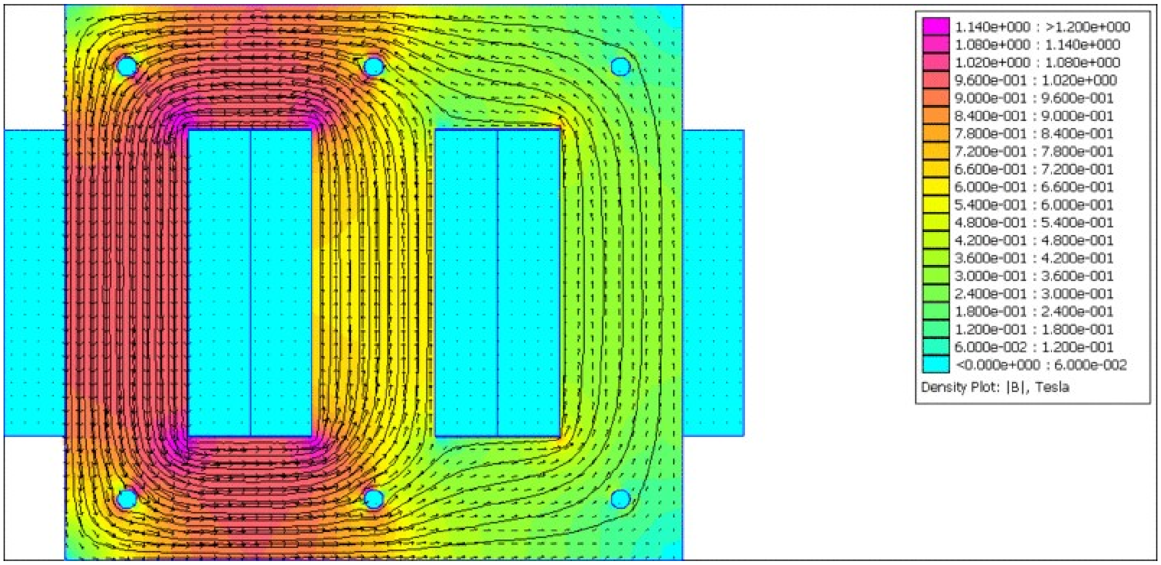
A variable autotransformer is made by exposing part of the winding coils and making the secondary connection through a sliding brush, giving a variable turns ratio. Such a device is often referred to by the trademark name *variac*.

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.

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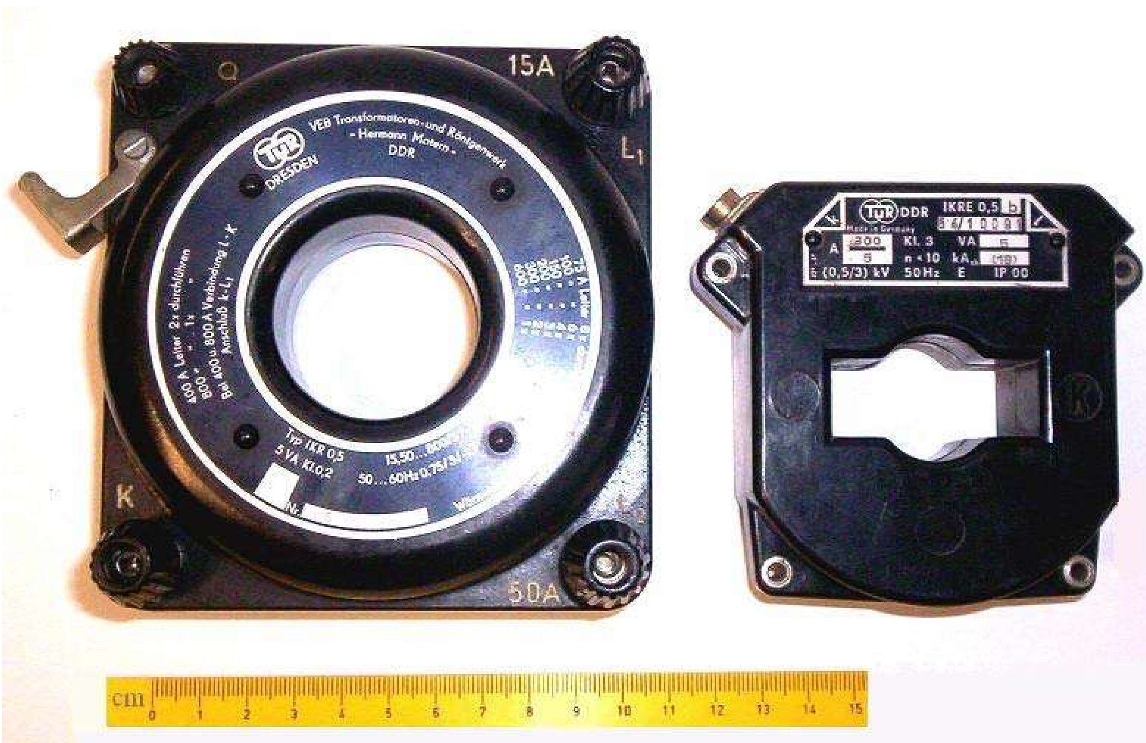
Instrument transformers

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.

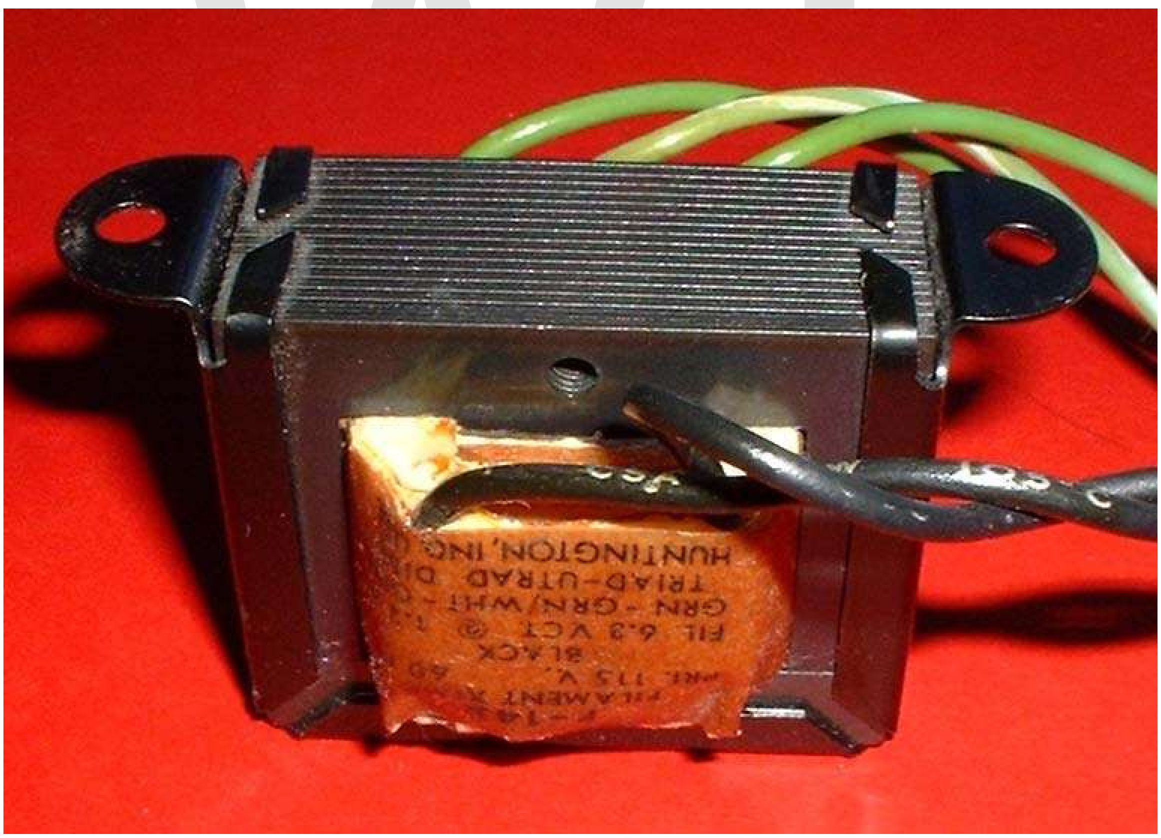
Classification

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

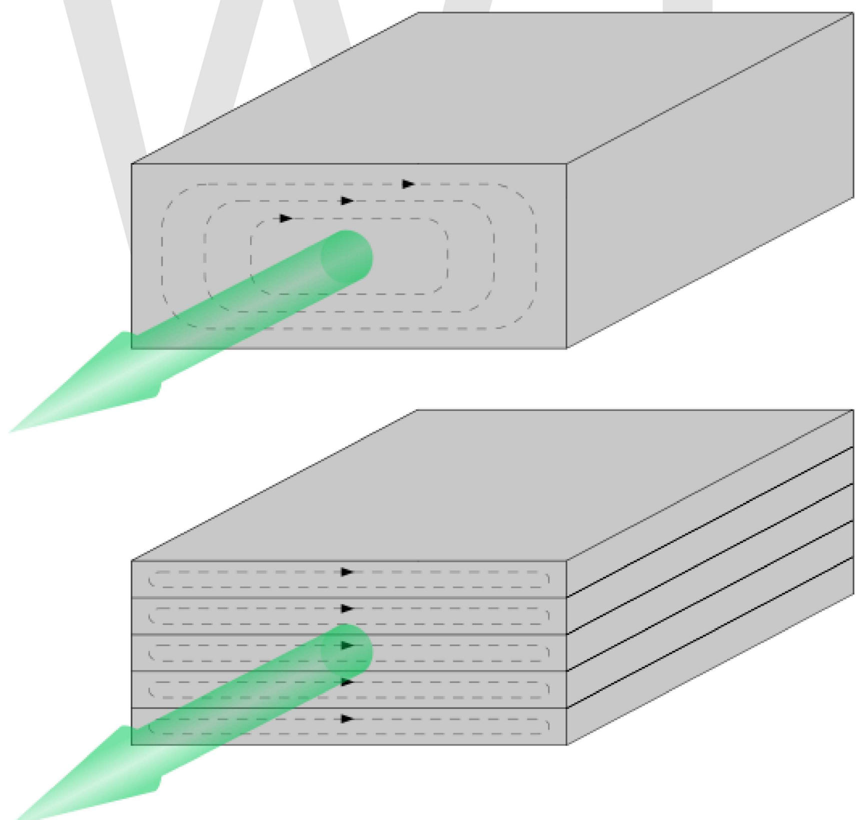


Laminated core transformer showing edge of laminations at top of photo

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.

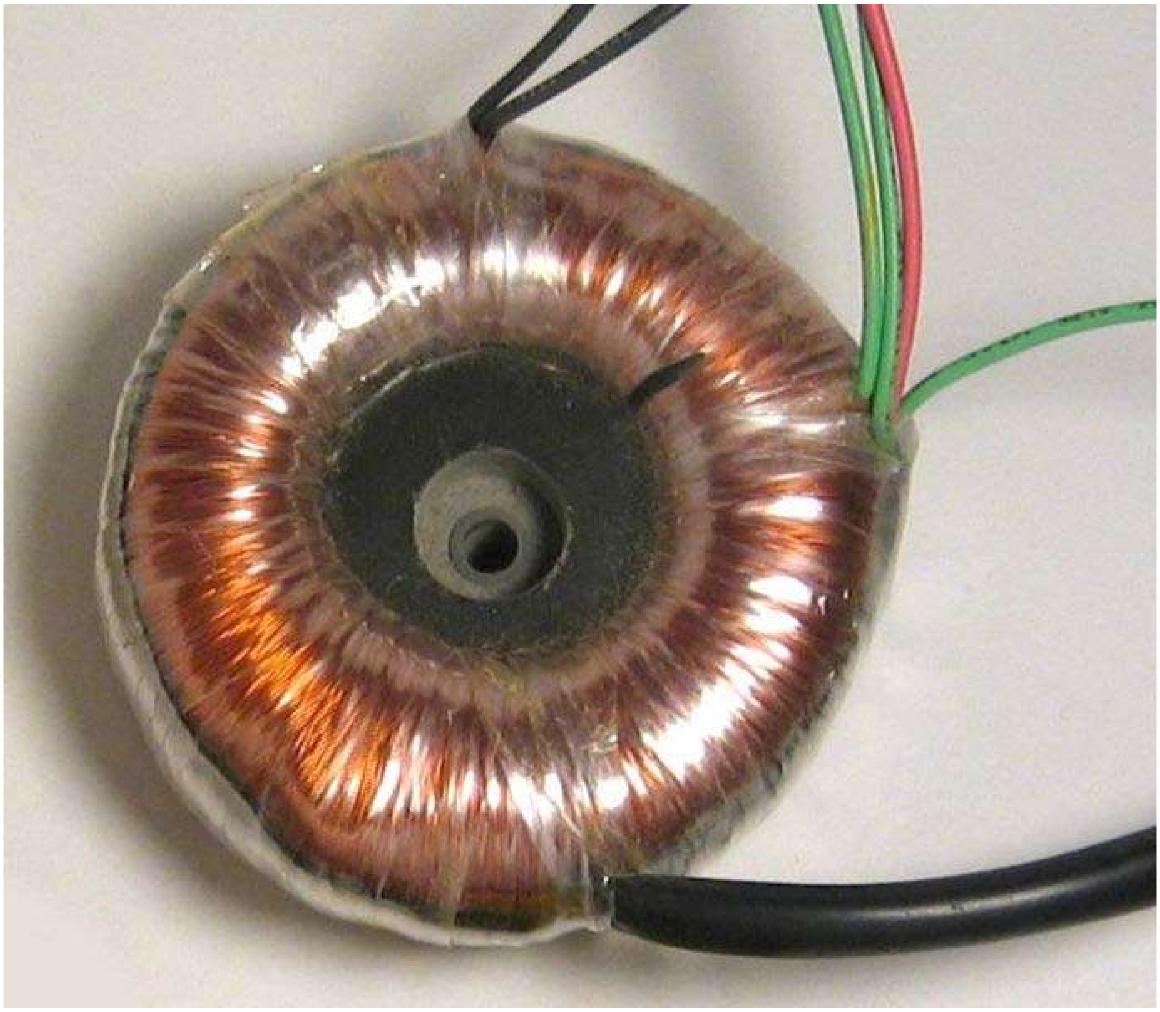
A steel core's remanence means that it retains a static magnetic field when power is removed. When power is then reapplied, the residual field will cause a high inrush current until the effect of the remaining magnetism is reduced, usually after a few cycles of the applied alternating current. Overcurrent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

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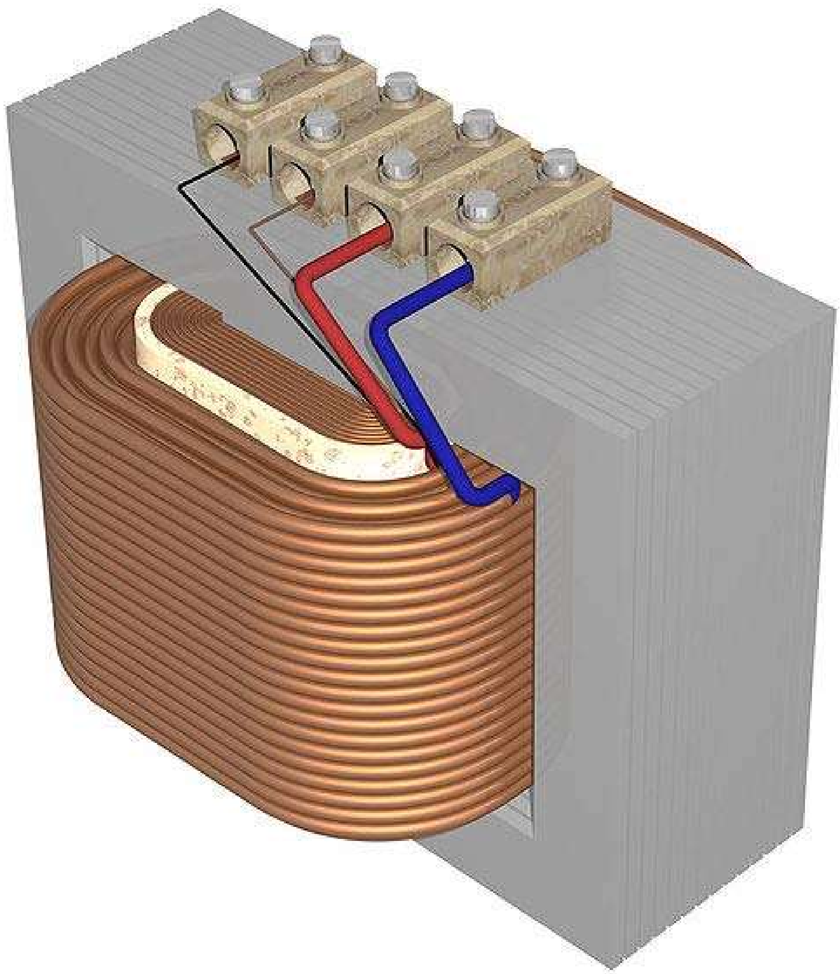
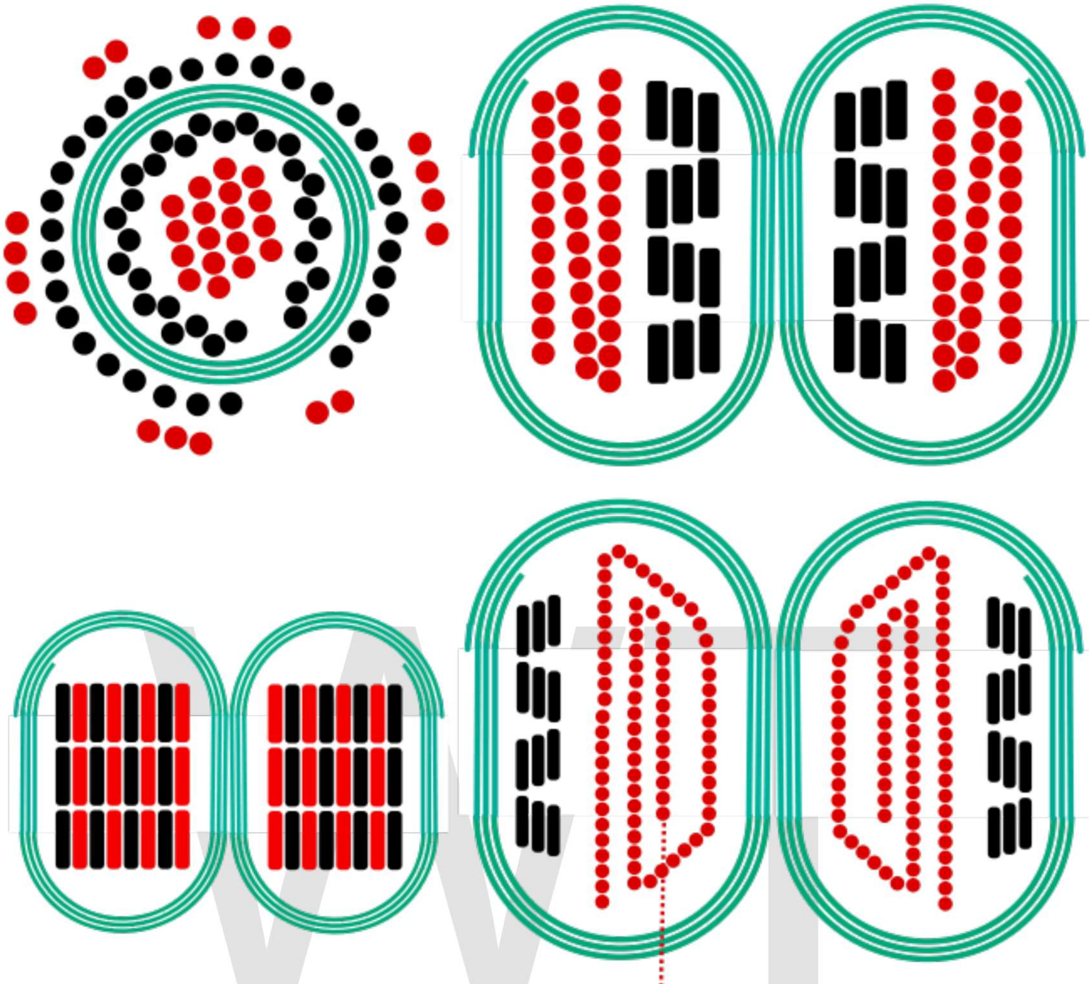
Windings



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.

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Chapter 8

Sparse Matrix Converter and Braking Chopper

Sparse matrix converter

The **Sparse Matrix Converter** is an AC/AC converter which offers a reduced number of components, a low-complexity modulation scheme, and low realization effort . Invented in 2001 by Prof Johann W. Kolar , sparse matrix converters avoid the multi step commutation procedure of the conventional matrix converter, improving system reliability in industrial operations. Its principal application is in highly compact integrated AC drives.

Characteristics

- Quasi-Direct AC-AC conversion with no DC link energy storage elements
- Sinusoidal input current in phase with mains voltage
- Zero DC link current commutation scheme resulting in lower modulation complexity and very high reliability
- Low complexity of power circuit / power modules available
- Ultra-Sparse Matrix Converter, does show very low realization effort, in case unidirectional power flow can be accepted (admissible displacement of 30° the input current fundamental and input voltage, as well as for the output voltage fundamental and output current), accordingly, a possible application area would be variable speed PSM drives of low dynamics.

Topologies

Sparse Matrix Converter

Characteristics of the Sparse Matrix Converter topology are 15 Transistors, 18 Diodes, and 7 Isolated Driver Potentials. Compared to the Direct Matrix Converter this topology provides identical functionality, but with a reduced number of power switches and the option of employing an improved zero DC-link current commutation scheme, which provides lower control complexity and higher safety and reliability.

Very Sparse Matrix Converter

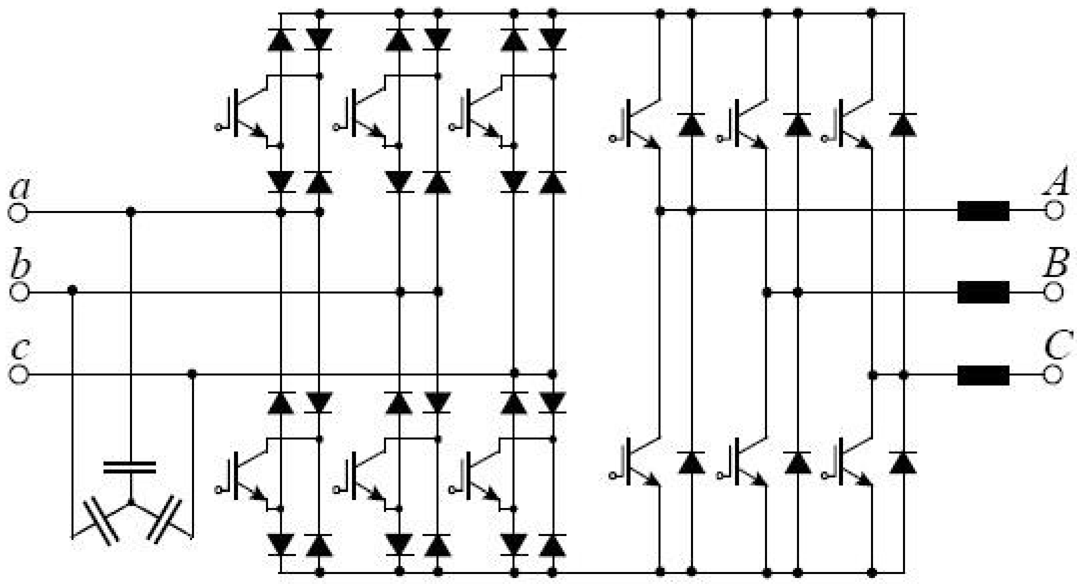

Fig 2: Topology of the very-sparse matrix.

Characteristics of the Very Sparse Matrix Converter topology are 12 Transistors, 30 Diodes, and 10 Isolated Driver Potentials. There are no limitations in functionality compared to the Direct Matrix Converter and Sparse Matrix Converter. Compared to the Sparse Matrix Converter there are fewer transistors but higher conduction losses due to the increased number of diodes in the conduction paths.

Ultra Sparse Matrix Converter

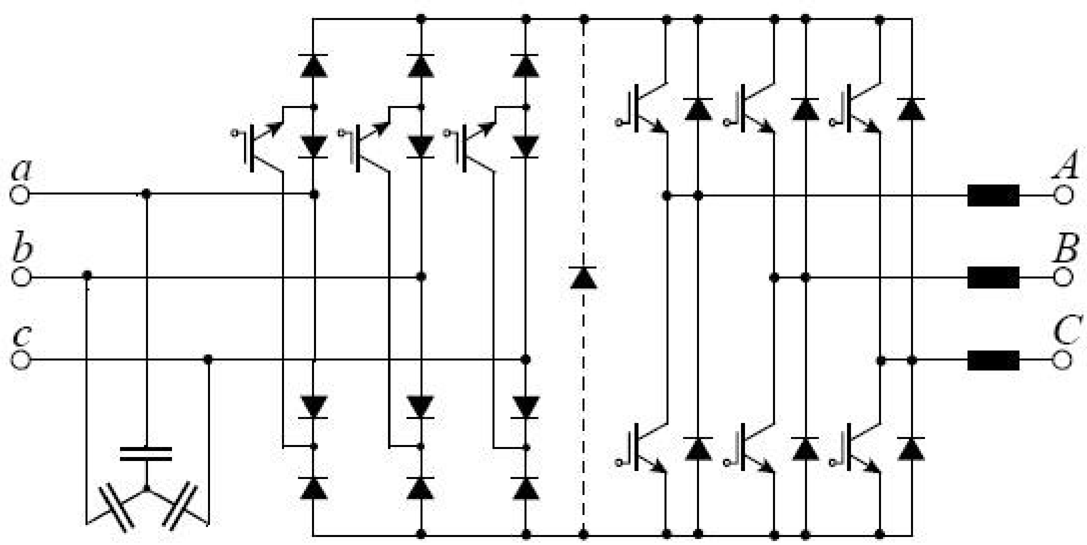

Fig 3: Topology of the ultra-sparse matrix.

Characteristics of the Ultra Sparse Matrix Converter topology are 9 Transistors, 18 Diodes, and 7 Isolated Driver Potentials. The significant limitation of this converter topology compared to the Sparse Matrix Converter is the restriction of its maximal phase displacement between input voltage and input current which is restricted to ± 30°.

Multi-Step Commutation

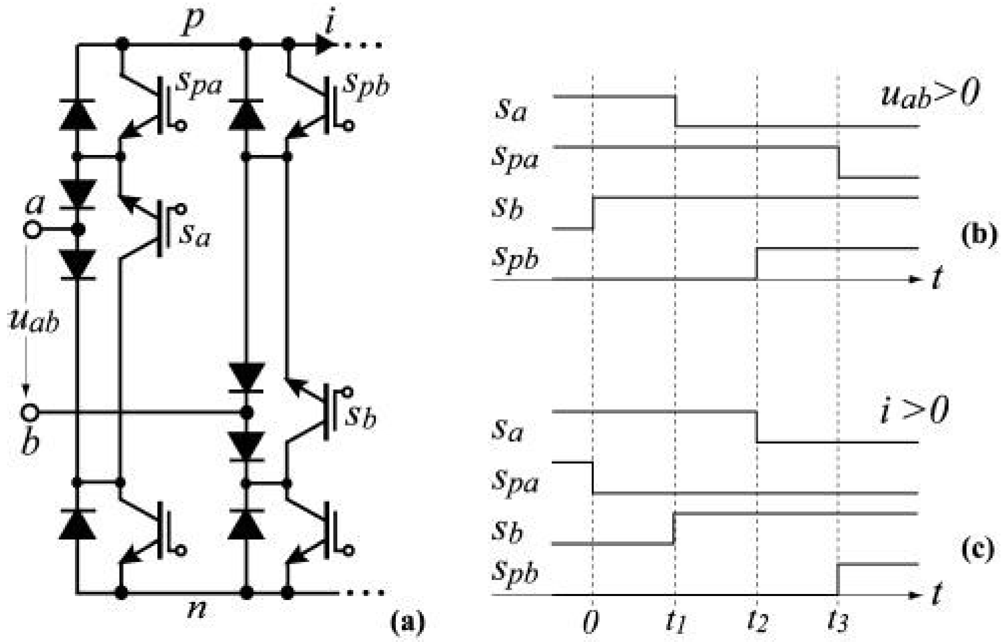

Fig 4: Multistep commutation of the Sparse Matrix Converter rectifier input stage.

This is a commutation scheme, depicted in Fig. 4. For a given switching state of the rectifier input stage, the commutation of the inverter output stage has to be performed in an identical manner to the commutation of a conventional voltage dc-link converter. The basic structure of the commutating bridge legs of the Sparse Matrix Converter is shown in Fig. 4(a). The switch sequence to change the connection of the positive dc-link voltage bus p from input a to input b is shown in Fig. 4(b) and Fig. 4(c). In Fig. 4(b) the assumption is current-independent commutation with uab > 0. In Fig. 4(c) the assumption is voltage-independent commutation with i > 0.

A dead time between the turn-off and turn-on of the power transistors of a bridge leg has to be implemented in order to avoid a short circuit of the dc-link voltage. To change the switching state of the Sparse Matrix Converter rectifier input stage for a given inverter switching state, one has to make sure that there is no bidirectional connection between any two input lines. This guarantees that no short-circuiting of an input line-to-line voltage can occur. Additionally a current path must be continuously provided. Therefore multistep commutation schemes, using voltage independent and current independent commutation as known for the Conventional Direct Matrix Converter, can be employed.

Zero DC Link Current Commutation

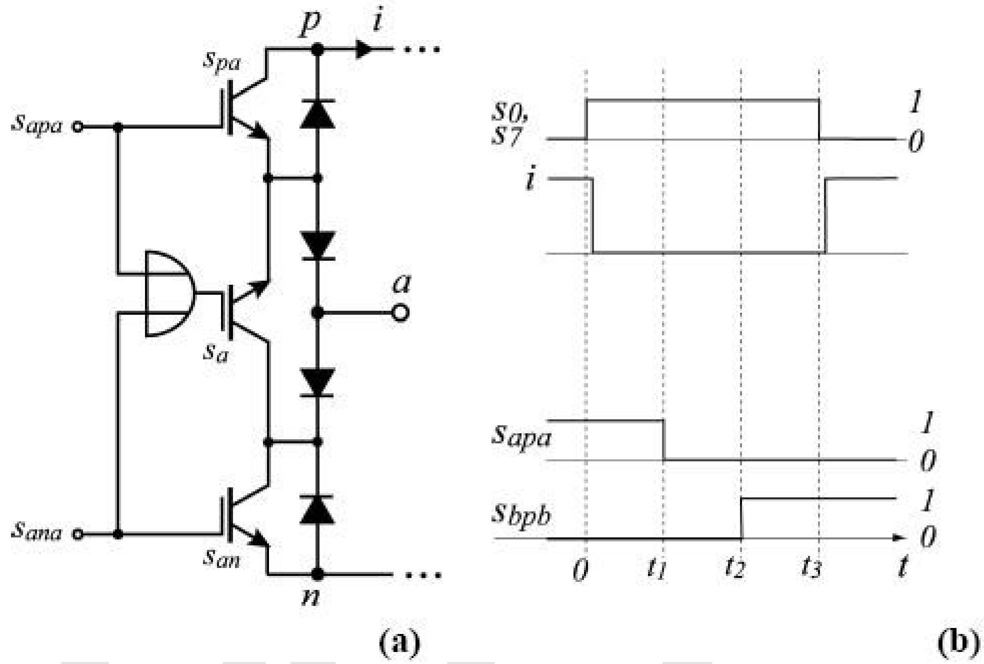

Fig 5: Zero DC link current commutation shown for the Sparse Matrix Converter.

The drawback of the multistep commutation describe before is its complexity. Indirect matrix converters like the Sparse Matrix Converter provide a degree of control freedom that is not available for the Conventional Direct Matrix Converter. This can be used to simplify the complex commutation problem. It has been proposed to switch the inverter stage into a free-wheeling state, and then to commutate the rectifier stage with zero dc-link current. This is shown in Fig. 5.

Fig. 5(a) shows the control of the power transistors in one bridge leg of the Sparse Matrix Converter. Fig. 5(b) shows the switching state sequence where s0; s7 = 1 indicates free-wheeling operation of the inverter stage. Furthermore, the dc-link current i is shown.

The zero DC link current commutation scheme gives the additional benefit of a reduction in the switching losses of the input stage. One only has to ensure that no overlapping of turn-on intervals of power transistors in a bridge half occurs, because this would result in a short circuit of an input line-to-line voltage.

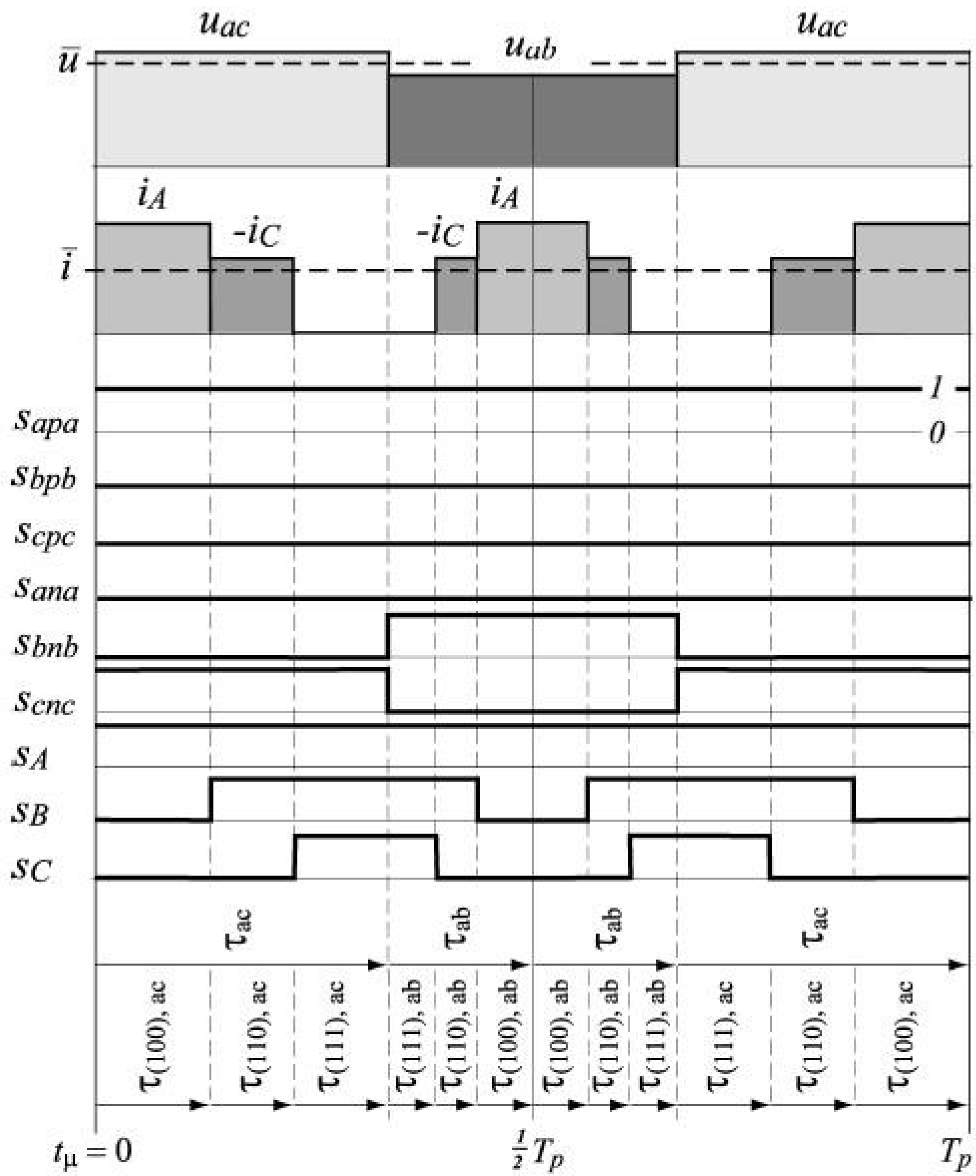

Fig 6: Characteristic voltages and currents and switching states of the Sparse Matrix Converter during on-switching period.

Fig 6 shows the formation of the dc-link voltage u and dc-link current i within one switching period Furthermore, it shows as an example the switching functions of the rectifier and inverter stage for φ_1 in interval (0...π / 6)and φ_2 in interval (0...π / 6). Input stage switching occurs at zero dc-link current. The dc-link current has a constant average value $\bar{i}$ within τ_{ac} and τ_{ab}. The switching state functions are given as s_A,s_B, and s_C. The switching frequency ripple of u_{ac},u_{ab},i_A and i_C is neglected

Braking chopper

A sample of a Braking chopper

Brake choppers are used in the DC voltage intermediate circuits of frequency converters to control voltage when the load feeds energy back to the intermediate circuit. This arises, for example, when a magnetized motor is being roatated by an overhauling load and so functions as a generator feeding power to the DC voltage intermediate circuit.

The concept of flux braking

Flux braking is a method based on motor losses. When braking in the drive system is needed, the motor flux and thus also the magnetizing current component used in the motor are increased. The control of flux can be easily achieved through the direct torque control principle. With DTC the inverter is directly controlled to achieve the desired torque and flux for the motor. During flux braking the motor is under DTC control which guarantees that braking can be made according to the specified speed ramp.This is very different to the DC injection braking typically used in drives. In the DC injection method

DC current is injected to the motor so that control of the motor flux is lost during braking. The flux braking method based on DTC enables the motor to shift quickly from braking to motoring power when requested.

In flux braking the increased current means increased losses inside the motor. The braking power is therefore also increased although the braking power delivered to the frequency converter is not increased. The increased current generates increased losses in motor resistances. The higher the resistance value the higher the braking energy dissipation inside the motor. Typically, in low power motors(below 5 kW) the resistance value of the motor is relatively large in respect to the nominal current of the motor. The higher the power or the voltage of the motor the less the resistance value of the motor in respect to motor current. In other words, flux braking is most effective in a low power motor.

Functioning of braking chopper

A large Braking chopper being put to use

The other possibility to limit DC bus voltage is to lead the braking energy to a resistor through a braking chopper. The braking chopper is an electrical switch that connects DC bus voltage to a resistor where the braking energy is converted to heat. The braking choppers are automatically activated when the actual DC bus voltage exceeds a specified level depending on the nominal voltage of the Variable-frequency drive

Benefits of the braking chopper and resistor solutions

1. Simple electrical construction and well-known technology.
2. Low fundamental investment for chopper and resistor.
3. The chopper works even if AC supply is lost. Braking during main power loss may be required. E.g. in elevator or other safety related applications.

Drawbacks of the Braking chopper and resistor

1. The braking energy is wasted if the heated air can not be utilised.
2. The braking chopper and resistors require additional space.
3. May require extra investments in the cooling and heat recovery system.
4. Braking choppers are typically dimensioned for a certain cycle, e.g. 100 % power 1/10 minutes, long braking times require more accurate dimensioning of the braking chopper.
5. Increased risk of fire due to hot resistor and possible dust and chemical components in the ambient air space.
6. The increased DC bus voltage level during braking causes additional voltage stress on motor insulation.

When to apply a braking chopper

1. The braking cycle is needed occasionally.
2. The amount of braking energy with respect to motoring energy is extremely small.
3. Braking operation is needed during main power loss.

When not to use Braking Chopper Resistor

1. The braking is continuous or regularly repeated.
2. The total amount of braking energy is high in respect to the motoring energy needed.
3. The instantaneous braking power is high, e.g. several hundred kW for several minutes.
4. The ambient air includes substantial amounts of dust or other potentially combustible or explosive or metallic components.

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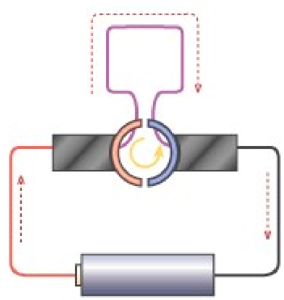
Chapter 9

Commutator

A **commutator** is a rotary electrical switch in certain types of electric motors or electrical generators that periodically reverses the current direction between the rotor and the external circuit. In a motor, it applies power to the best location on the rotor, and in a generator, picks off power similarly. As a switch, it has exceptionally long life, considering the number of circuit makes and breaks that occur in normal operation.

A commutator is a common feature of direct current rotating machines. By reversing the current direction in the moving coil of a motor's armature, a steady rotating force (torque) is produced. Similarly, in a generator, reversing of the coil's connection to the external circuit provides unidirectional—direct—current to the external circuit. The first commutator-type direct current machine was built by Hippolyte Pixii in 1832, based on a suggestion by André-Marie Ampère.

Principle of Operation



As the rotor turns, the current in the winding reverses every time the commutator makes half a turn. This reversal of the winding current compensates for the fact that the winding has also rotated half a turn relative to the fixed magnetic field (not shown). The current in the winding causes the fixed magnetic field to exert a rotational force (a torque) on the winding, making it turn. As the rotor's field comes close to aligning itself with that of the stator, the commutator switches the rotor's polarity, so the motor is perpetually trying to settle, so to speak.

Note that all practical commutators have at least three segments, and in some instances (such as the N.Y. City transit system's old rotary AC-to-DC converters), up to several hundred. In these elementary diagrams, there is a dead position where the motor will not start.

For the image to the right, when the brushes make contact across both commutator segments, the commutator is short-circuited and current passes directly from one brush to the other across the commutator, doing no work in the rotor windings, and drawing a destructive fault current from the power source. As well, practical rotors have more turns in their windings. For the image to the left, there is a dead spot when the brushes cross the insulation between the two segments and no current flows. In either case, in a motor, the rotor cannot begin to spin if it is stopped in this position.

Simplest practical commutator

This has three segments, and the rotor has three poles. The left image shows the three rotor poles with their windings. The commutator is near the end of the shaft, as it points up and to the left. It is a metal cylinder (note the yellowish reflection) with three equally spaced cuts parallel to the shaft, and has white plastic discs on both ends. Each segment connects to the nearest junction between two of the three rotor coils.

In the middle illustration, the brushes (in this instance, flat metal springs; carbon brushes are not needed at the low voltages used by such motors as these) are the two straight horizontal pieces; when assembled, the brushes are under tension, slightly away from each other, to stay in contact with the commutator. Power connects to two solder terminals on the outside of the end disc shown in this image. Those terminals are likely to be the same pieces of metal as the brushes themselves.

Inside the exterior metal cylinder is a hollow cylindrical permanent magnet with its south pole opposite its north pole. Interaction between the rotor and that magnet's field is what makes the motor spin. This motor's diameter is greater than its length, something uncommon in motors of this sort. In other sorts of motors, it is typical. Considering that it was used to spin the disc in a CD drive, short length was quite important.

This type of motor is widely used in small toys, models, and electromechanical/electronic devices.

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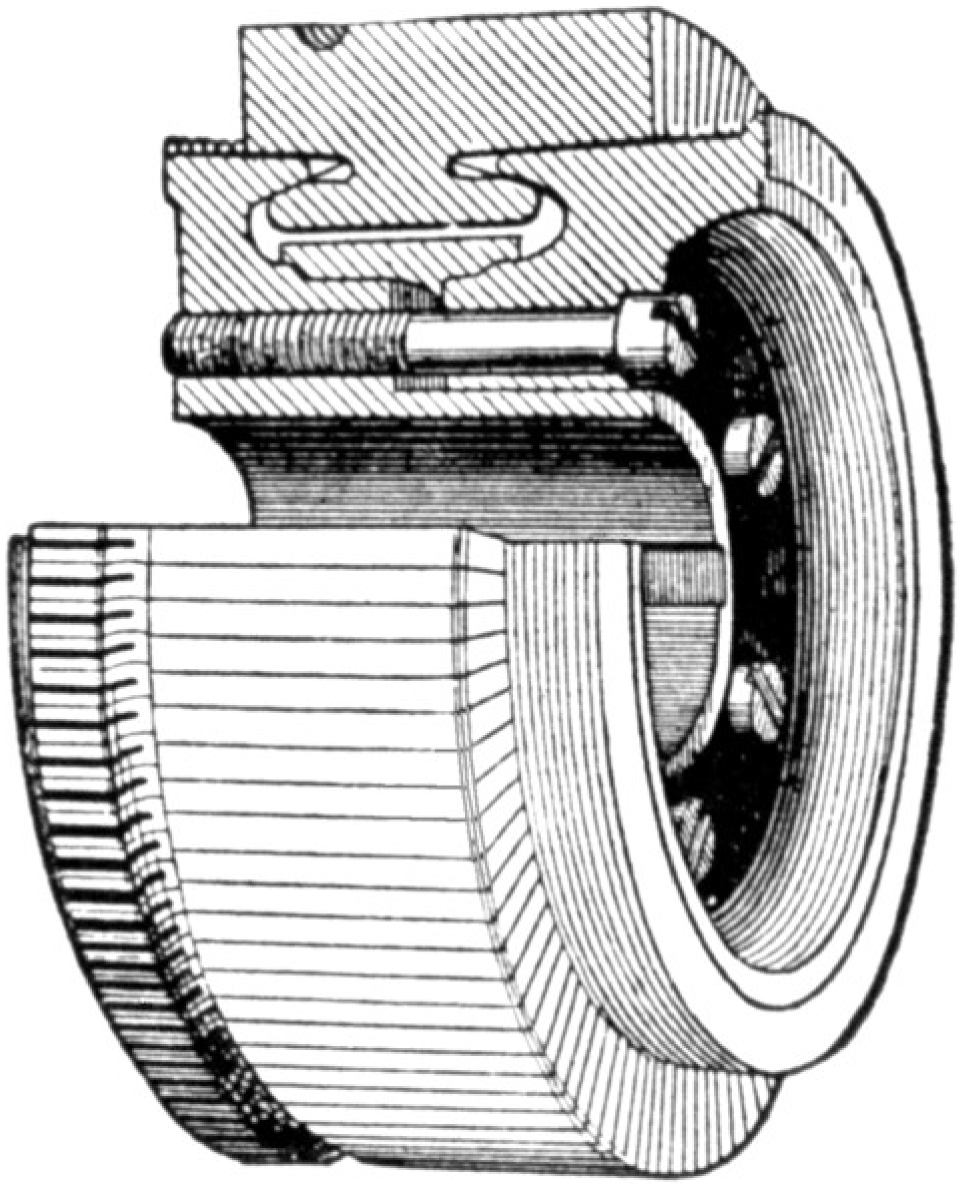
Although the rotor can potentially stop in a position where two commutator segments touch one brush, this only de-energizes one of the three rotor arms while the other two are correctly powered. The motor produces sufficient torque with the two powered rotor arms to begin spinning the rotor, and no direct shorting can occur between the commutator brushes.

Although, so far, this explanation has assumed a permanent-magnet field (or a wound field with the electromagnet fed by DC), so-called universal motors in appliances such as vacuum cleaners have wound fields, and operate well on AC. Power goes to both the field and the brushes, so the magnetic fields of both rotor and stator reverse together. These motors also operate on DC, hence the term "universal".

Ring/Segment Construction



Cross-section of a commutator that can be disassembled for repair

A commutator typically consists of a set of copper segments, fixed around part of the circumference of the rotating part of the machine (the *rotor*), and a set of spring-loaded brushes fixed to the stationary frame of the machine. The external source of current (for a motor) or electrical load (for a generator) is connected to the brushes. For small equipment the commutator segments can be stamped from sheet metal. For very large equipment the segments are made from a copper casting that is then machined into the final shape.

Each conducting segment on the armature of the commutator is insulated from adjacent segments. Initially when the technology was first developed, mica was used as an insulator between commutation segments. Later materials research into polymers brought the development of plastic spacers which are more durable and less prone to cracking, and have a higher and more uniform breakdown voltage than mica.

The segments are held onto the shaft using a dovetail shape on the edges or underside of each segment, using insulating wedges around the perimeter of each commutation segment. Due to the high cost of repairs, for small appliance and tool motors the segments are typically crimped permanently in place and cannot be removed; when the motor fails it is simply discarded and replaced. On very large industrial motors it is economical to be able to replace individual damaged segments, and so the end-wedge can be unscrewed and individual segments removed and replaced.

Commutator segments are connected to the coils of the armature, with the number of coils (and commutator segments) depending on the speed and voltage of the machine. Large motors may have hundreds of segments.

Friction between the segments and the brushes eventually causes wear to both surfaces. Carbon brushes, being made of a softer material, wear faster and may be designed to be replaced easily without dismantling the machine. Older copper brushes caused more wear to the commutator, causing deep grooving and notching of the surface over time. The commutator on small motors (say, less than a kilowatt rating) is not designed to be repaired through the life of the device. On large industrial equipment, the commutator may be re-surfaced with abrasives, or the rotor may be removed from the frame, mounted in a large metal lathe, and the commutator resurfaced by cutting it down to a smaller diameter. The largest of equipment can include a lathe turning attachment directly over the commutator.

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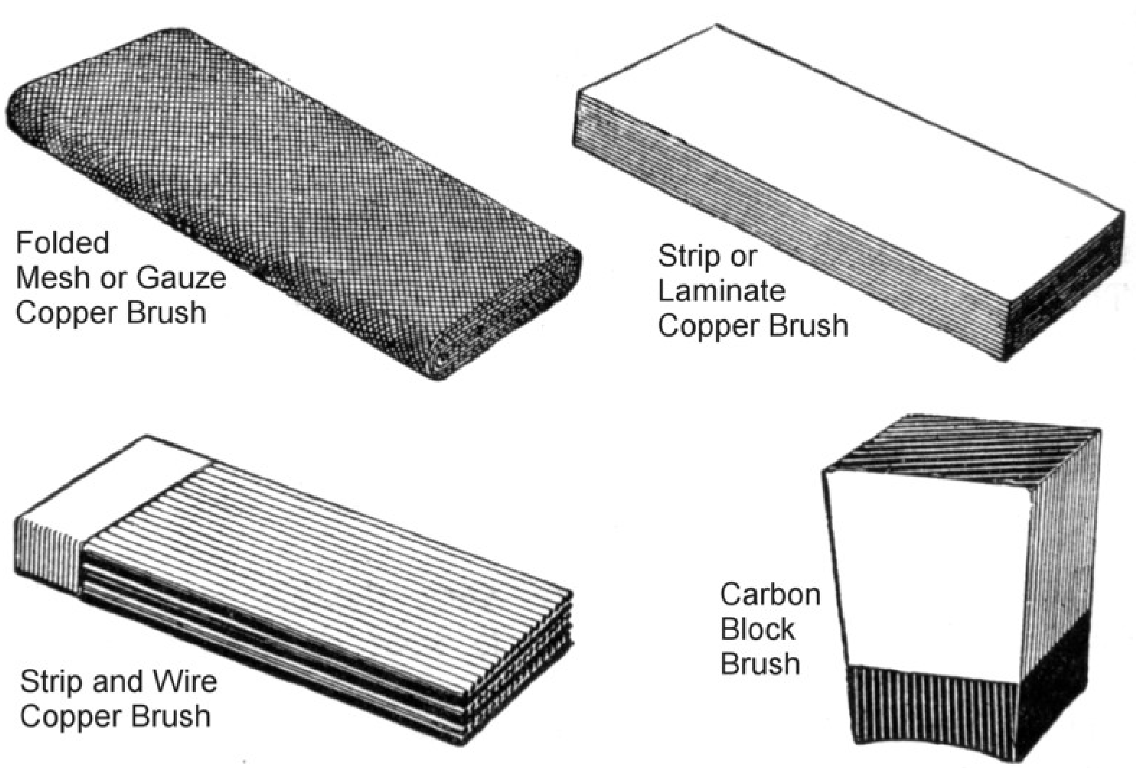
Brush Construction



Various types of copper and carbon brushes

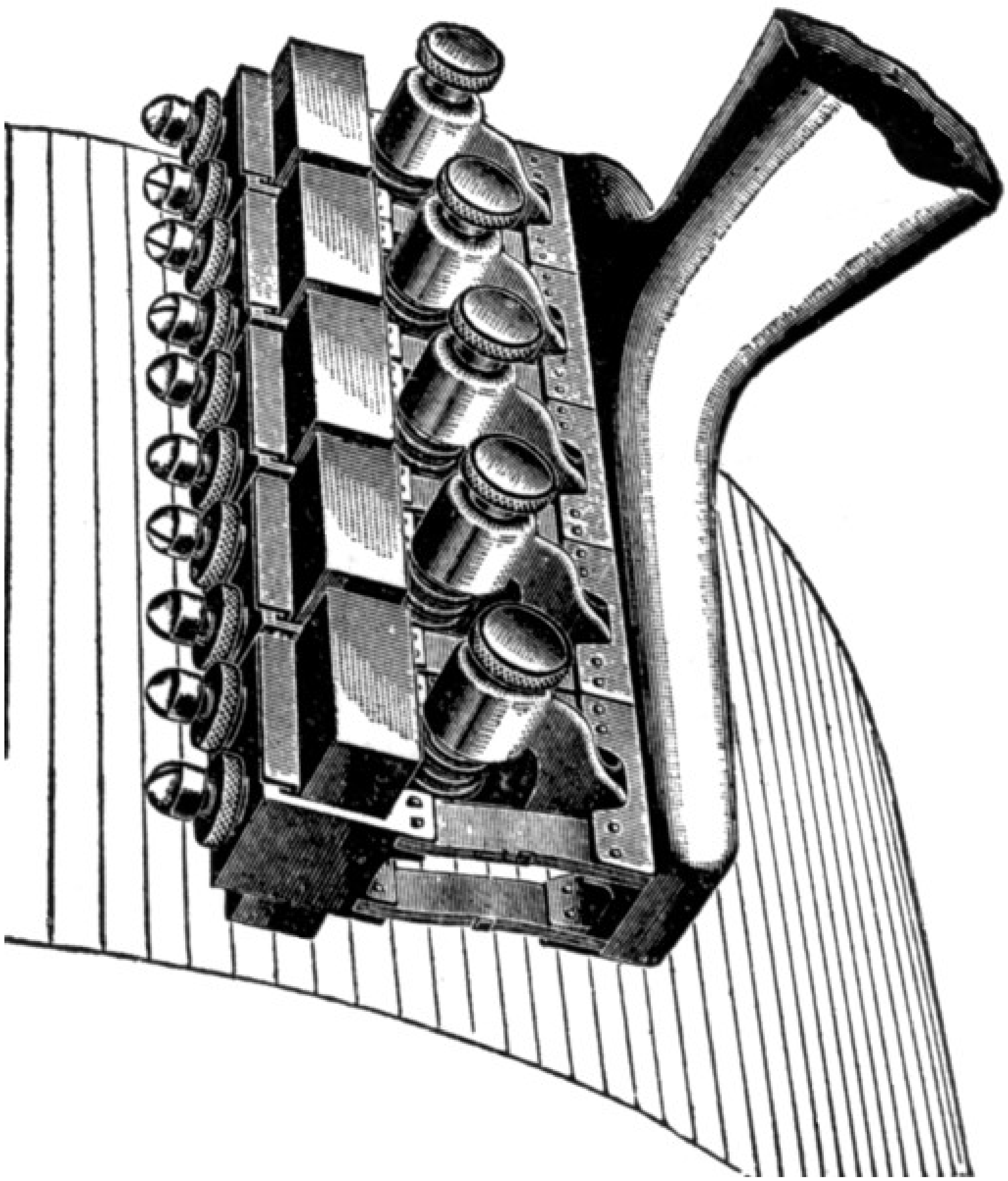
Early in the development of dynamos and motors, copper brushes were used to contact the surface of the commutator. However, these hard metal brushes tended to scratch and groove the smooth commutator segments, eventually requiring resurfacing of the commutator. As the copper brushes wear away, the dust and pieces of the brush could wedge between commutator segments, shorting them and reducing the efficiency of the device. Fine copper wire mesh or gauze provided better surface contact with less segment wear, but gauze brushes were more expensive than strip or wire copper brushes. The copper brush was eventually replaced by the carbon brush.

Carbon brushes tend to wear more evenly than copper brushes, and the soft carbon causes far less damage to the commutator segments. There is less sparking with carbon as compared to copper, and as the carbon wears away, the higher resistance of carbon results in fewer problems from the dust collecting on the commutator segments.

Copper and carbon are each better suited for a particular purpose. Copper brushes perform better with very low voltages and high current, while carbon brushes are better for high voltage and low current. Copper brushes typically carry 150 to 200 amperes per square inch of contact surface, while carbon only carries 40 to 70 amperes per square inch. The higher resistance of carbon also results in a greater voltage drop of 0.8 to 1.0 volts per contact, or 1.6 to 2.0 volts across the commutator.

Modern rotating machines with commutators now use carbon brushes, which may have copper powder mixed in to improve conductivity. Metallic copper brushes would only be found in toy or very small motors, such as the one illustrated above.

Brush Holders



Compound carbon brush holder, with individual clamps and tension adjustments for each block of carbon.

A spring is typically used with the brush, to maintain constant contact with the commutator. As the brush and commutator wear down, the spring steadily pushes the brush downwards towards the commutator. Eventually the brush wears small and thin enough that steady contact is no longer possible or it is no longer securely held in the brush holder, and so the brush must be replaced.

It is common for a flexible power cable to be directly attached to the brush, because current flowing through the support spring causes heating, which may lead to a loss of metal temper and a loss of the spring tension.

When a commutated motor or generator uses more power than a single brush is capable of conducting, an assembly of several brush holders is mounted in parallel across the surface of the very large commutator.

This parallel holder distributes current evenly across all the brushes, and permits a careful operator to remove a bad brush and replace it with a new one, even as the machine continues to spin fully powered and under load.

High power, high current commutated equipment is now uncommon, due to the less complex design of alternating current generators that permits a low current, high voltage spinning field coil to energize high current fixed-position stator coils. This permits the use of very small singular brushes in the alternator design. In this instance, the rotating contacts are continuous rings, called slip rings, and, of course, no switching happens.

Modern devices using carbon brushes usually have a maintenance-free design that requires no adjustment throughout the life of the device, using a fixed-position brush holder slot and a combined brush-spring-cable assembly that fits into the slot. Replacement simply involves pulling out the old brush and inserting a new one.

Older commutator motors sometimes had all brushes mounted on movable frames so that the position of the brushes in relation to the magnetic fields of the stator poles could be adjusted manually.

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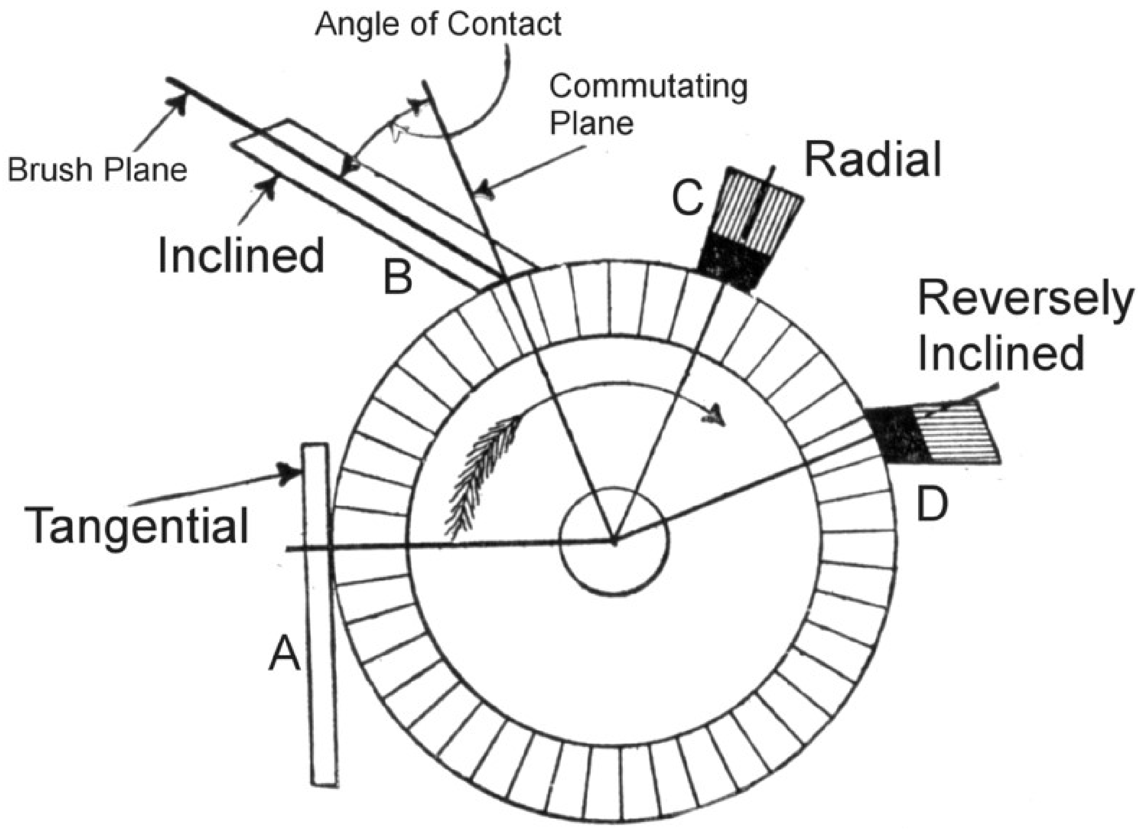
Brush Contact Angle

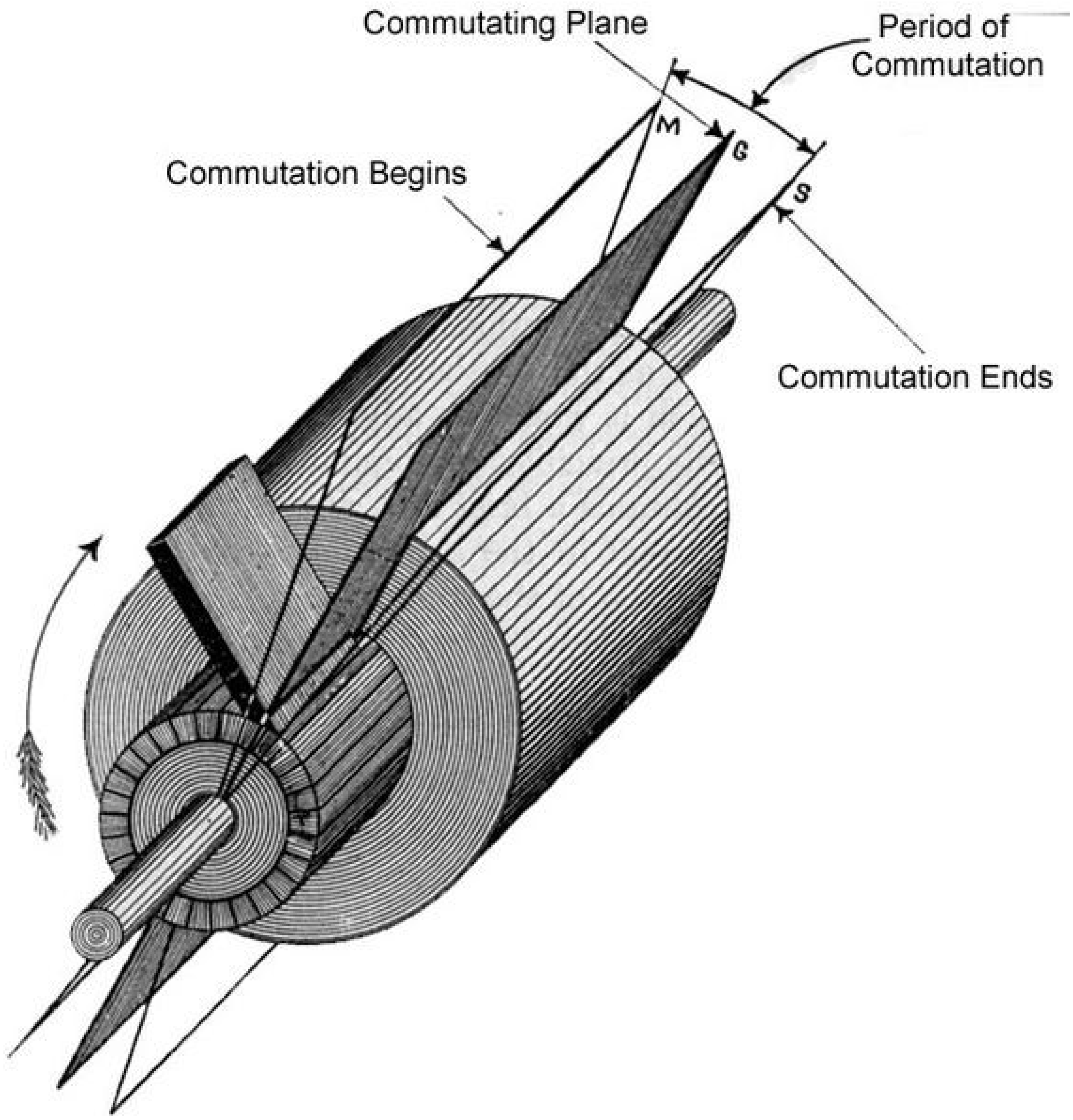


Brush angle definitions

The different brush types make contact with the commutator in different ways. Because copper brushes have the same hardness as the commutator segments, the rotor cannot be spun backwards against the ends of copper brushes without the copper digging into the segments and causing severe damage. Consequently strip/laminate copper brushes only make tangential contact with the commutator, while copper mesh and wire brushes use an inclined contact angle touching their edge across the segments of a commutator that can spin in only one direction.

The softness of carbon brushes permits direct radial end-contact with the commutator without damage to the segments, permitting easy reversal of rotor direction, without the need to reorient the brush holders for operation in the opposite direction. Although never reversed, common appliance motors that use wound rotors, commutators and brushes have radial-contact brushes. In the case of a reaction-type carbon brush holder, carbon brushes may be reversely inclined with the commutator so that the commutator tends to push against the carbon for firm contact.

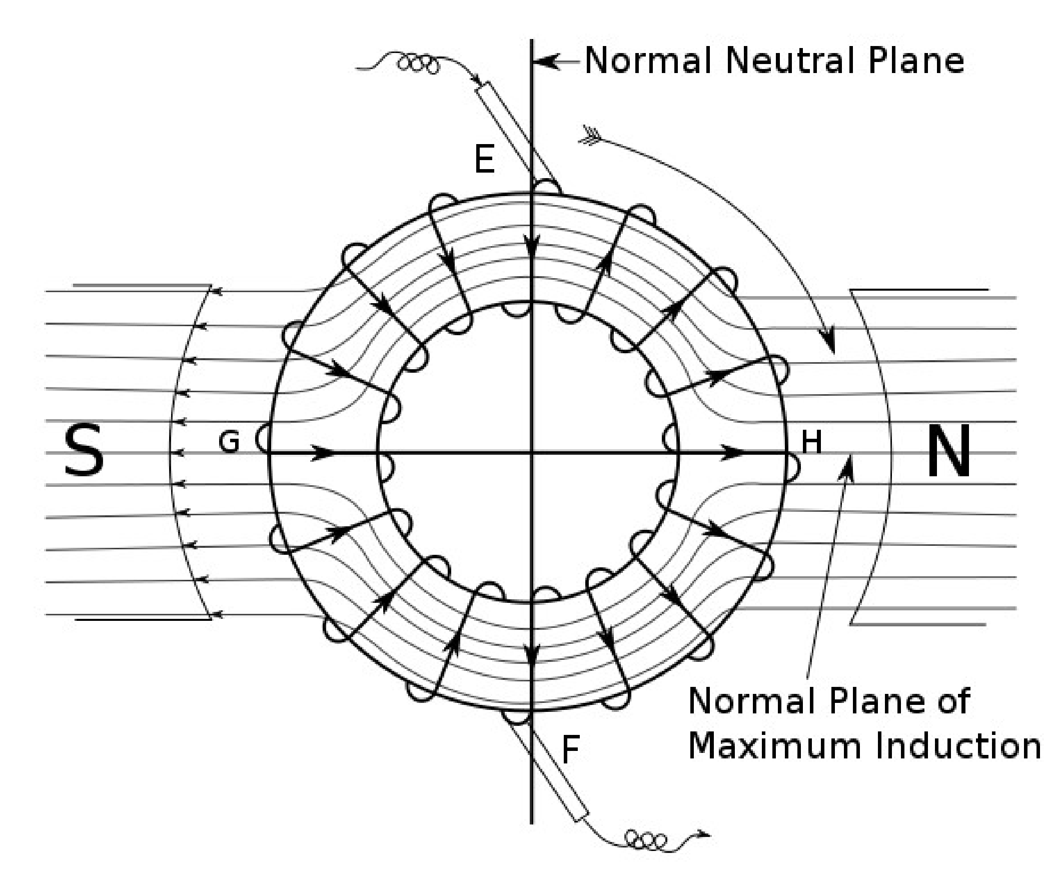
The Commutating Plane



Commutating plane definitions

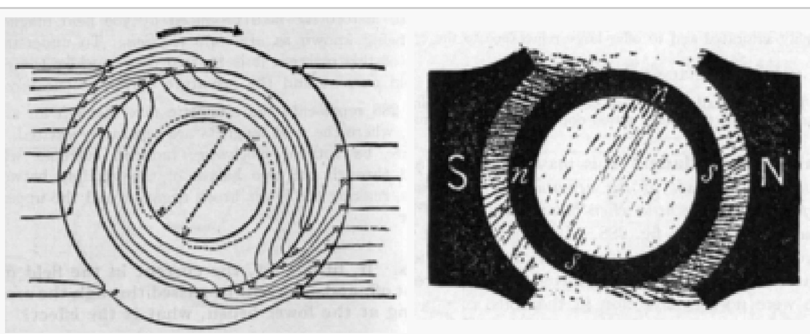
The contact point where a brush touches the commutator is referred to as the *commutating plane*. In order to conduct sufficient current to or from the commutator, the brush contact area is not a thin line but instead a rectangular patch across the segments. Typically the brush is wide enough to span 2.5 commutator segments. This means that two adjacent segments are electrically connected by the brush when it contacts both.

Compensation for stator field distortion



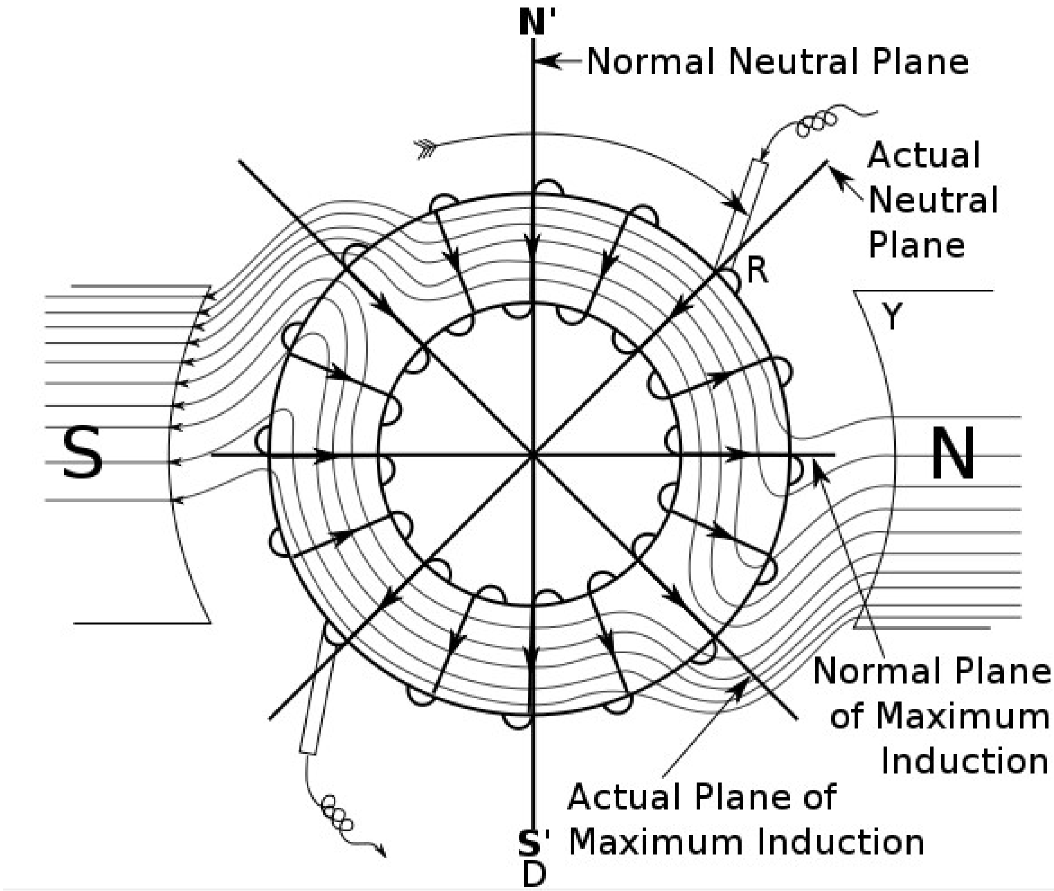
Centered position of the commutating plane if there were no field distortion effects

Most introductions to motor and generator design start with a simple two-pole device with the brushes arranged at a perfect 90-degree angle from the field. This ideal is useful as a starting point for understanding how the fields interact but it is not how a motor or generator functions in actual practice.



On the left is an exaggerated example of how the field is distorted by the rotor. On the right, iron filings show the distorted field across the rotor.

In a real motor or generator, the field around the rotor is never perfectly uniform. Instead, the rotation of the rotor induces field effects which drag and distort the magnetic lines of the outer non-rotating stator.



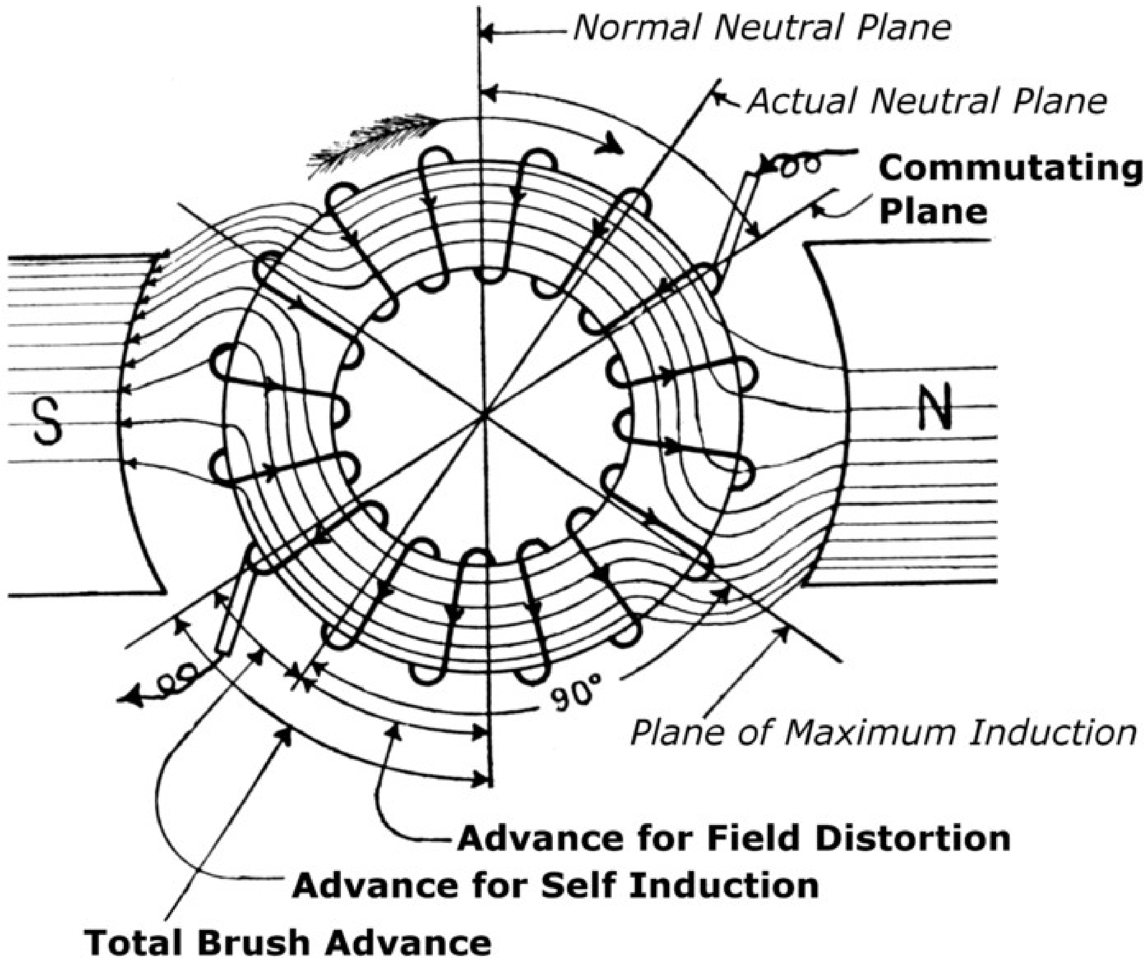
Actual position of the commutating plane to compensate for field distortion

The faster the rotor spins, the further this degree of field distortion. Because a motor or generator operates most efficiently with the rotor field at right angles to the stator field, it is necessary to either retard or advance the brush position to put the rotor's field into the correct position to be at a right angle to the distorted field.

These field effects are reversed when the direction of spin is reversed. It is therefore difficult to build an efficient reversible commutated dynamo, since for highest field strength it is necessary to move the brushes to the opposite side of the normal neutral plane.

The effect can be considered to be analogous to timing advance in an internal combustion engine. Generally a dynamo that has been designed to run at a certain fixed speed will have its brushes permanently fixed to align the field for highest efficiency at that speed.

Further Compensation for Self-Induction



Brush advance for Self-Induction

In a coil of wire, the magnetic field of each wire compounds together to form a magnetic field that tends to resist changes in current, as if the current had inertia. This is known as *self-induction*.

In the coils of the rotor, there is a tendency for current to continue to flow for a brief moment after the brush has been reached. This energy is wasted as heat due to the brush spanning across several commutator segments and the current short-circuiting across the segments.

Spurious resistance is an apparent increase in the resistance in the armature winding, which is proportional to the speed of the armature, and is due to the lagging of the current.

In order to minimize sparking at the brushes due to this short-circuiting, the brushes are advanced a few degrees further yet, beyond the advance for field distortions. This moves the rotor winding undergoing commutation slightly forward into the stator field which has magnetic lines in the opposite direction and which oppose the field in the stator. This opposing field helps to reverse the lagging self-inducting current in the stator.

So even for a rotor which is at rest and initially requires no compensation for spinning field distortions, the brushes should still be advanced beyond the perfect 90-degree angle as taught in so many beginners textbooks, in order to compensate for self-induction.

Limitations and alternatives

While commutators are widely applied in direct current machines, up to several thousand kilowatts in rating, they have limitations.

Brushes and copper segments wear. On small machines the brushes may last as long as the product (small power tools, appliances, etc.) but larger machines will require regular replacement of brushes and occasional resurfacing of the commutator. Brush-type motors may not be suitable for long service on aerospace equipment where maintenance is not possible.

The efficiency of direct current machines is limited by the "brush drop" due to the resistance of the sliding contact. This may be several volts, making low-voltage direct-current machines very inefficient. The friction of the brush on the commutator also absorbs some of the energy of the machine.

Lastly, the current density in the brush is limited and the maximum voltage on each segment of the commutator is also limited. Very large direct current machines, say, more than several megawatts rating, cannot be built with commutators. The largest motors and generators, of hundreds of megawatt ratings, are all alternating-current machines.

With the widespread availability of power semiconductors, it is now economical to provide electronic switching of the current in the motor windings. These "brushless direct current" motors eliminate the commutator; these can be likened to AC machines with a built-in DC to AC inverter. In these motors, rotor position determines when the stator windings switch polarity. Operating life is limited only by bearing wear, if other factors are not adverse.

Repulsion induction motors

These are single-phase AC-only motors with higher starting torque than can be obtained with split-phase starting windings, and before high-capacitance (non-polar, relatively high-current electrolytic) starting capacitors became practical. They have a conventional wound stator as with any induction motor, but the wire-wound rotor is much like that with a conventional commutator. Brushes opposite each other are connected to each other (not to an external circuit), and transformer action induces currents into the rotor that develop torque by repulsion.

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One variety, notable for having an adjustable speed, runs continuously with brushes in contact, while another uses repulsion only for high starting torque and in some cases lifts the brushes once the motor is running fast enough. In the latter case, all commutator segments are connected together as well, before the motor attains running speed.

Once at speed, the rotor windings become functionally equivalent to the squirrel-cage structure of a conventional induction motor, and the motor runs as such.

Web ref. gives a nice, concise description

Laboratory commutators

Commutators were used as simple forward-off-reverse switches for electrical experiments in physics laboratories. There are two well-known historical types :

Ruhmkorff commutator

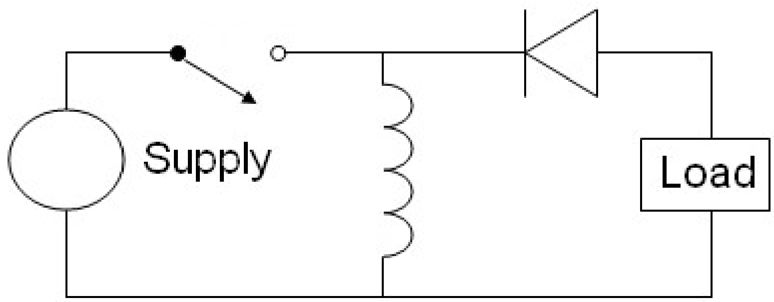
This is similar in design to the commutators used in motors and dynamos. It was usually constructed of brass and ivory (later ebonite).

Pohl commutator

This consisted of a block of wood or ebonite with four wells, containing mercury, which were cross-connected by copper wires. The output was taken from a pair of curved copper wires which were moved to dip into one or other pair of mercury wells.

Chapter 10

Buck–boost Converter



The basic schematic of a buck–boost converter

Two different topologies are called **buck–boost converter**. Both of them can produce an output voltage much larger (in absolute magnitude) than the input voltage. Both of them can produce a wide range of output voltage from that maximum output voltage to almost zero.

- The inverting topology – The output voltage is of the opposite polarity as the input
- A buck (step-down) converter followed by a boost (step-up) converter – The output voltage is of the same polarity as the input, and can be lower or higher than the input. Such a non-inverting buck-boost converter may use a single inductor that is used as both the buck inductor and the boost inductor.

This page describes the inverting topology.

The **buck–boost converter** is a type of DC-to-DC converter that has an output voltage magnitude that is either greater than or less than the input voltage magnitude. It is a switched-mode power supply with a similar circuit topology to the boost converter and the buck converter. The output voltage is adjustable based on the duty cycle of the switching transistor. One possible drawback of this converter is that the switch does not have a terminal at ground; this complicates the driving circuitry. Also, the polarity of the output voltage is opposite the input voltage. Neither drawback is of any consequence if the power supply is isolated from the load circuit (if, for example, the supply is a battery) as the supply and diode polarity can simply be reversed. The switch can be on either the ground side or the supply side.

Principle of operation

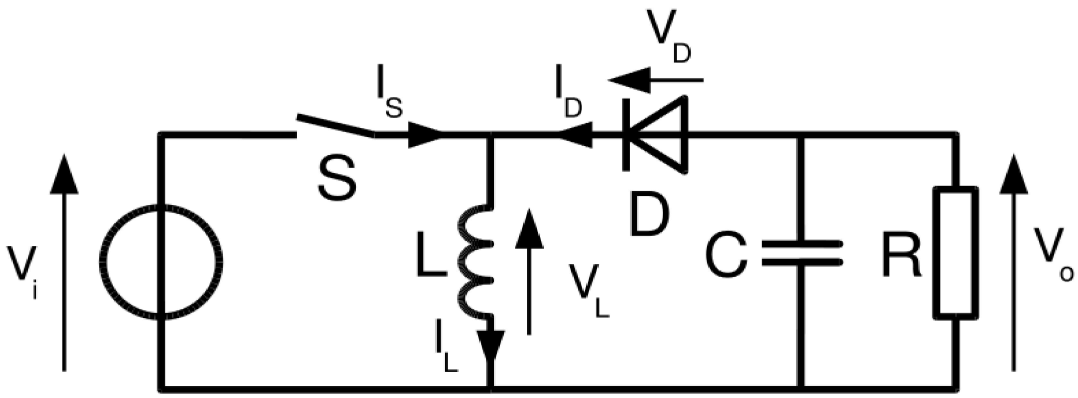


Fig. 1: Schematic of a buck–boost converter

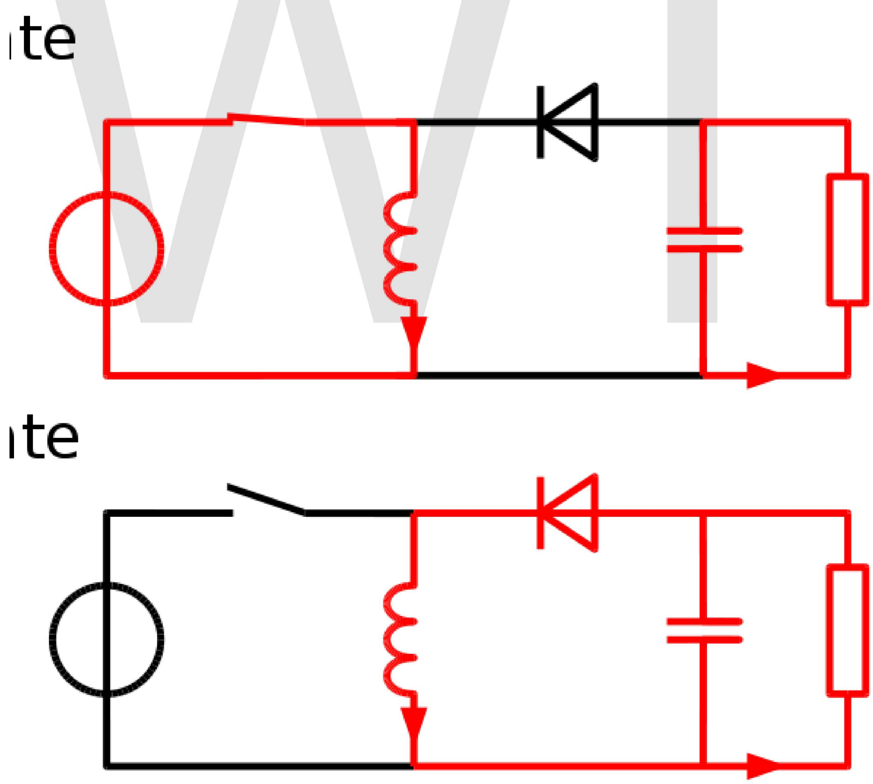


Fig. 2: The two operating states of a buck–boost converter: When the switch is turned-on, the input voltage source supplies current to the inductor and the capacitor supplies current to the resistor (output load). When the switch is opened (providing energy is stored into the inductor), the inductor supplies current to the load via the diode D.

The basic principle of the buck–boost converter is fairly simple (see figure 2):

- while in the On-state, the input voltage source is directly connected to the inductor (L). This results in accumulating energy in L. In this stage, the capacitor supplies energy to the output load.
- while in the Off-state, the inductor is connected to the output load and capacitor, so energy is transferred from L to C and R.

Compared to the buck and boost converters, the characteristics of the buck–boost converter are mainly:

- polarity of the output voltage is opposite to that of the input;
- the output voltage can vary continuously from 0 to $-\infty$ (for an ideal converter). The output voltage ranges for a buck and a boost converter are respectively 0 to V_i and V_i to ∞.

Continuous Mode

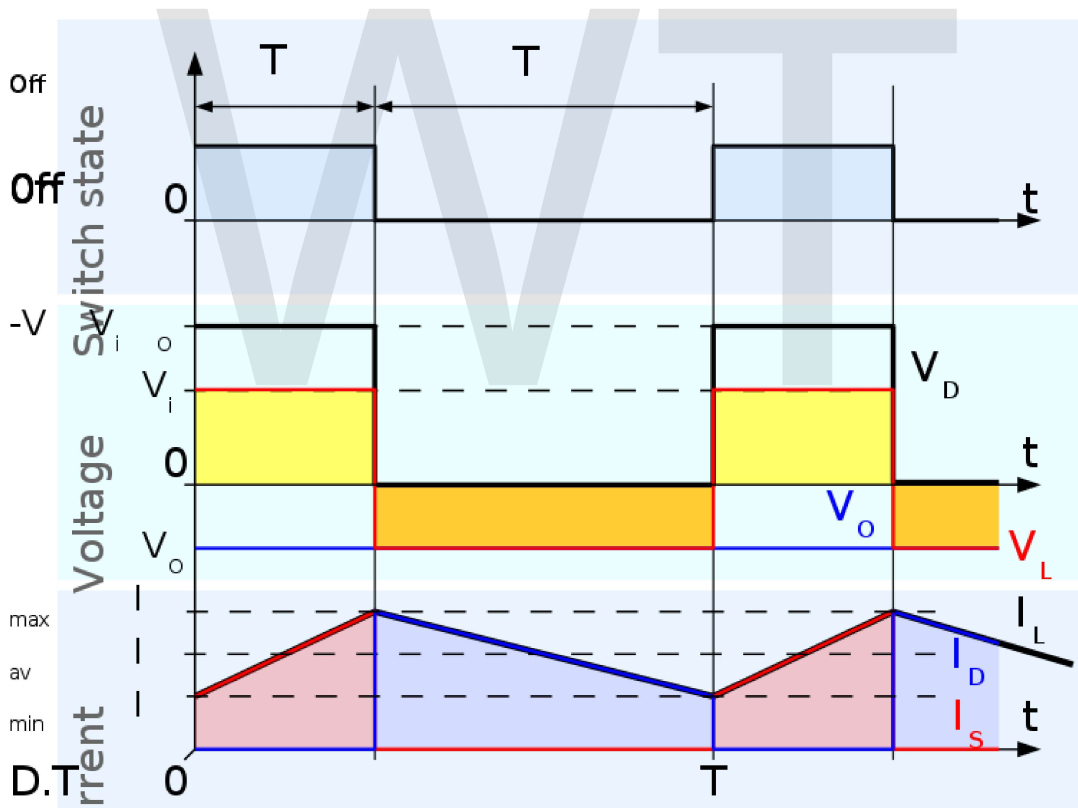


Fig 3: Waveforms of current and voltage in a buck–boost converter operating in continuous mode.

If the current through the inductor *L* never falls to zero during a commutation cycle, the converter is said to operate in continuous mode. The current and voltage waveforms in an ideal converter can be seen in Figure 3.

From $t=0$to $t=D\,T$, the converter is in On-State, so the switch *S* is closed. The rate of change in the inductor current (I_L) is therefore given by

$$\frac{\mathrm{d}I_\mathrm{L}}{\mathrm{d}t}=\frac{V_i}{L}$$

At the end of the On-state, the increase of I_L is therefore:

$$\Delta I_{\mathrm{L_{On}}}=\int_0^{D\,T}\mathrm{d}I_\mathrm{L}=\int_0^{D\,T}\frac{V_i}{L}\,\mathrm{d}t=\frac{V_i\,D\,T}{L}$$

D is the duty cycle. It represents the fraction of the commutation period *T* during which the switch is On. Therefore *D* ranges between 0 (*S* is never on) and 1 (*S* is always on).

During the Off-state, the switch *S* is open, so the inductor current flows through the load. If we assume zero voltage drop in the diode, and a capacitor large enough for its voltage to remain constant, the evolution of I_L is:

$$\frac{\mathrm{d}I_\mathrm{L}}{\mathrm{d}t}=\frac{V_o}{L}$$

Therefore, the variation of I_L during the Off-period is:

$$\Delta I_{\mathrm{L_{Off}}}=\int_0^{(1-D)T}\mathrm{d}I_\mathrm{L}=\int_0^{(1-D)T}\frac{V_o\,\mathrm{d}t}{L}=\frac{V_o\,(1-D)\,T}{L}$$

As we consider that the converter operates in steady-state conditions, the amount of energy stored in each of its components has to be the same at the beginning and at the end of a commutation cycle. As the energy in an inductor is given by:

$$E=\frac{1}{2}L\,I_\mathrm{L}^2$$

it is obvious that the value of I_L at the end of the Off state must be the same as the value of I_L at the beginning of the On-state, i.e. the sum of the variations of I_L during the on and the off states must be zero:

$$\Delta I_{\mathrm{L_{On}}}+\Delta I_{\mathrm{L_{Off}}}=0$$

Substituting $\Delta I_{\mathrm{L_{On}}}$and $\Delta I_{\mathrm{L_{Off}}}$by their expressions yields:

$$\Delta I_{\mathrm{L_{On}}}+\Delta I_{\mathrm{L_{Off}}}=\frac{V_i\,D\,T}{L}+\frac{V_o\,(1-D)T}{L}=0$$

This can be written as:

$$\frac{V_o}{V_i} = \left(\frac{-D}{1-D}\right)$$

This in return yields that:

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

From the above expression it can be seen that the polarity of the output voltage is always negative (as the duty cycle goes from 0 to 1), and that its absolute value increases with D, theoretically up to minus infinity as *D* approaches 1. Apart from the polarity, this converter is either step-up (as a boost converter) or step-down (as a buck converter). This is why it is referred to as a buck–boost converter.

Discontinuous Mode

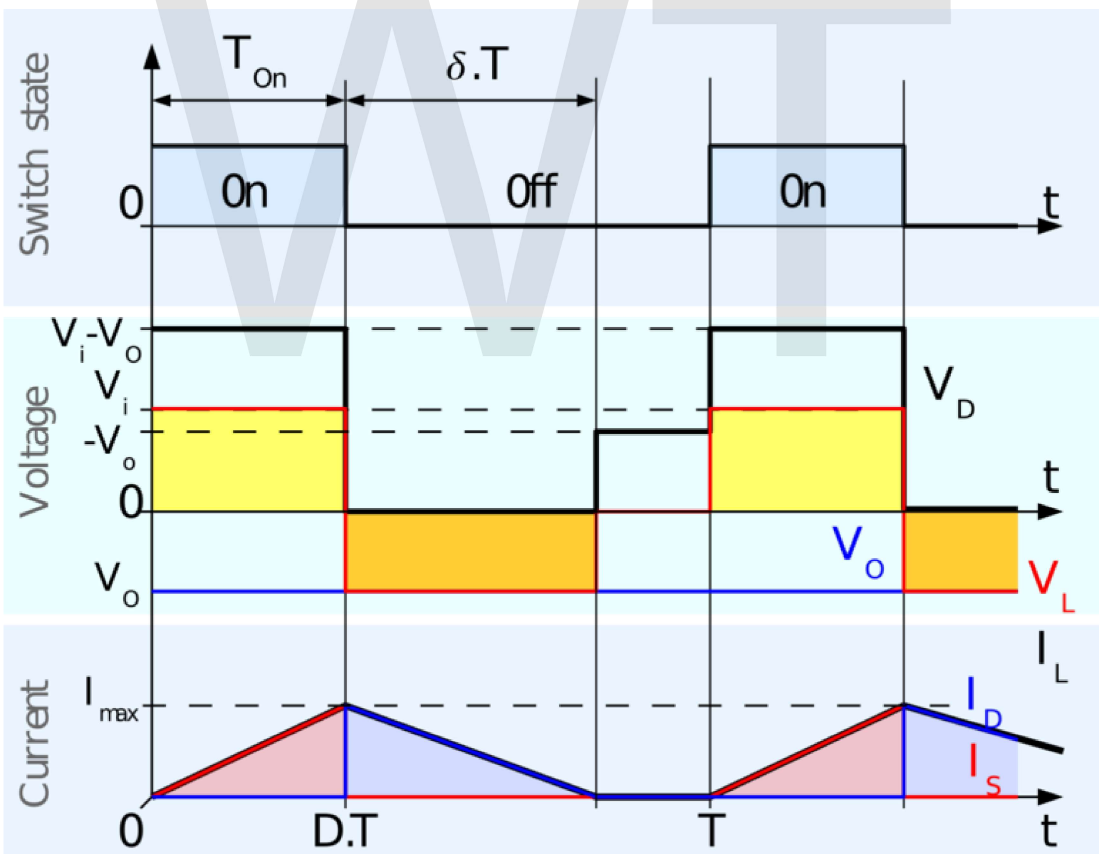


Fig 4: Waveforms of current and voltage in a buck–boost converter operating in discontinuous mode.

In some cases, the amount of energy required by the load is small enough to be transferred in a time smaller than the whole commutation period. In this case, the current through the inductor falls to zero during part of the period. The only difference in the principle described above is that the inductor is completely discharged at the end of the commutation cycle (see waveforms in figure 4). Although slight, the difference has a strong effect on the output voltage equation. It can be calculated as follows:

As the inductor current at the beginning of the cycle is zero, its maximum value $I_{L_{\max}}$(at $t = DT$) is

$$I_{L_{\max}} = \frac{V_i\,D\,T}{L}$$

During the off-period, I_L falls to zero after δ.T:

$$I_{L_{\max}} + \frac{V_o\,\delta\,T}{L} = 0$$

Using the two previous equations, δ is:

$$\delta = -\frac{V_i\,D}{V_o}$$

The load current I_o is equal to the average diode current (I_D). As can be seen on figure 4, the diode current is equal to the inductor current during the off-state. Therefore, the output current can be written as:

$$I_o = \bar{I_D} = \frac{I_{L_{\max}}}{2}\delta$$

Replacing $I_{L_{\max}}$and δ by their respective expressions yields:

$$I_o = -\frac{V_i\,D\,T}{2L}\frac{V_i\,D}{V_o} = -\frac{V_i^2\,D^2\,T}{2L\,V_o}$$

Therefore, the output voltage gain can be written as:

$$\frac{V_o}{V_i} = -\frac{V_i\,D^2\,T}{2L\,I_o}$$

Compared to the expression of the output voltage gain for the continuous mode, this expression is much more complicated. Furthermore, in discontinuous operation, the output voltage not only depends on the duty cycle, but also on the inductor value, the input voltage and the output current.

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Limit between continuous and discontinuous modes

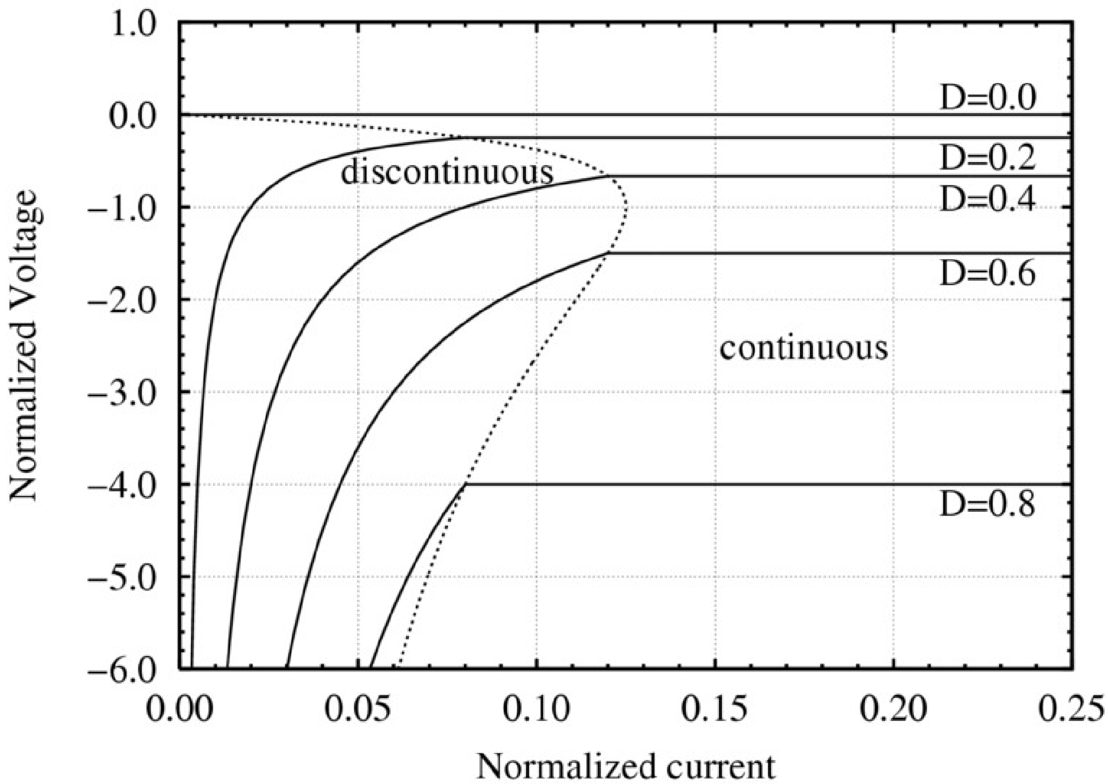

Fig 5: Evolution of the normalized output voltage with the normalized output current in a buck–boost converter.

As told at the beginning, the converter operates in discontinuous mode when low current is drawn by the load, and in continuous mode at higher load current levels. The limit between discontinuous and continuous modes is reached when the inductor current falls to zero exactly at the end of the commutation cycle. with the notations of figure 4, this corresponds to :

$$DT + \delta T = T$$
$$D + \delta = 1$$

In this case, the output current $I_{o_{\lim}}$(output current at the limit between continuous and discontinuous modes) is given by:

$$I_{o_{\lim}} = \bar{I_D} = \frac{I_{L_{\max}}}{2}(1 - D)$$

Replacing $I_{L_{\max}}$by the expression given in the *discontinuous mode* section yields:

$$I_{o_{\lim}} = \frac{V_i DT}{2L}(1 - D)$$

As $I_{o_{\text{lim}}}$ is the current at the limit between continuous and discontinuous modes of operations, it satisfies the expressions of both modes. Therefore, using the expression of the output voltage in continuous mode, the previous expression can be written as:

$$I_{o_{\text{lim}}} = \frac{V_i\,D\,T}{2L}\frac{V_i}{V_o}(-D)$$

Let's now introduce two more notations:

- the normalized voltage, defined by $|V_o| = \frac{V_o}{V_i}$. It corresponds to the gain in voltage of the converter;
- the normalized current, defined by $|I_o| = \frac{L}{T\,V_i}I_o$. The term $\frac{T\,V_i}{L}$ is equal to the maximum increase of the inductor current during a cycle; i.e., the increase of the inductor current with a duty cycle D=1. So, in steady state operation of the converter, this means that $|I_o|$ equals 0 for no output current, and 1 for the maximum current the converter can deliver.

Using these notations, we have:

- in continuous mode, $|V_o| = -\frac{D}{1-D}$;
- in discontinuous mode, $|V_o| = -\frac{D^2}{2|I_o|}$;
- the current at the limit between continuous and discontinuous mode is $I_{o_{\text{lim}}} = \frac{V_i\,T}{2L}D(1-D) = \frac{I_{o_{\text{lim}}}}{2|I_o|}D(1-D)$. Therefore the locus of the limit between continuous and discontinuous modes is given by $\frac{1}{2|I_o|}D(1-D) = 1$.

These expressions have been plotted in figure 5. The difference in behaviour between the continuous and discontinuous modes can be seen clearly.

Non-ideal circuit

Effect of parasitic resistances

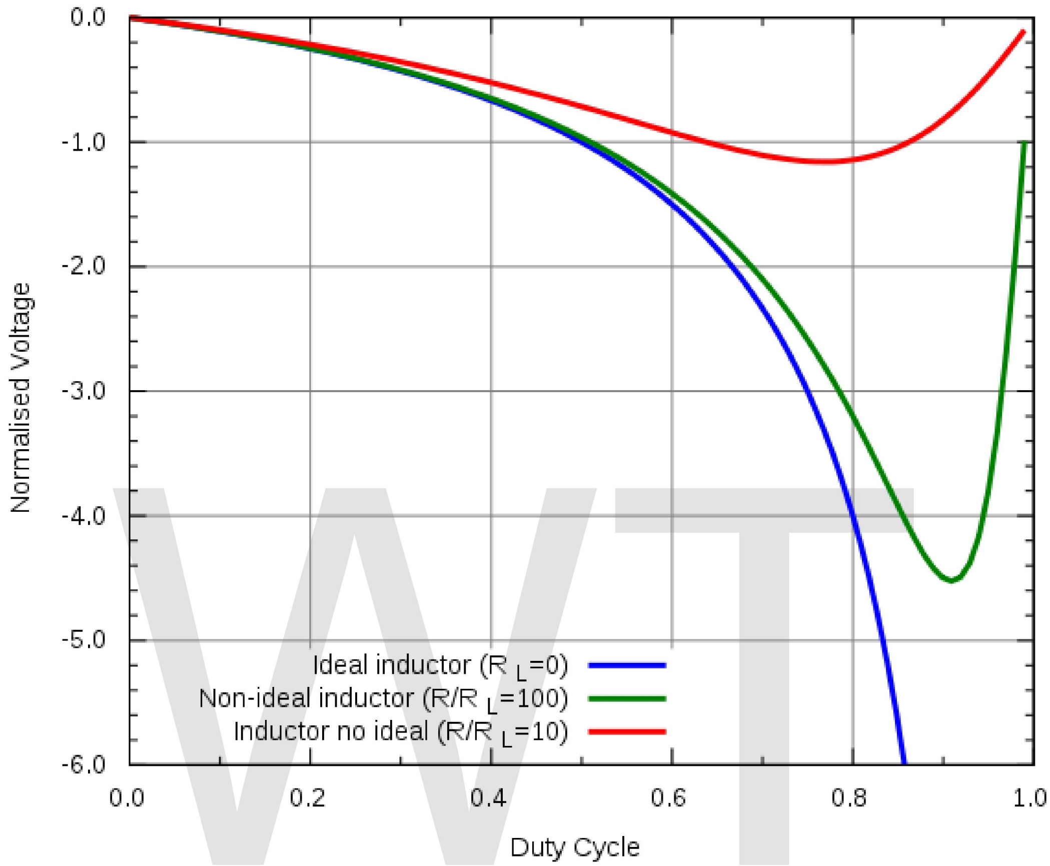

Fig 6: Evolution of the output voltage of a buck–boost converter with the duty cycle when the parasitic resistance of the inductor increases.

In the analysis above, no dissipative elements (resistors) have been considered. That means that the power is transmitted without losses from the input voltage source to the load. However, parasitic resistances exist in all circuits, due to the resistivity of the materials they are made from. Therefore, a fraction of the power managed by the converter is dissipated by these parasitic resistances.

For the sake of simplicity, we consider here that the inductor is the only non-ideal component, and that it is equivalent to an inductor and a resistor in series. This assumption is acceptable because an inductor is made of one long wound piece of wire, so it is likely to exhibit a non-negligible parasitic resistance (R_L). Furthermore, current flows through the inductor both in the on and the off states.

Using the state-space averaging method, we can write:

$$V_i = \bar{V}_L + \bar{V}_S$$

where $\bar{V}_L$ and $\bar{V}_S$ are respectively the average voltage across the inductor and the switch over the commutation cycle. If we consider that the converter operates in steady-state, the average current through the inductor is constant. The average voltage across the inductor is:

$$\bar{V}_{\mathrm{L}} = L\frac{d\bar{I}_{\mathrm{L}}}{dt} + R_{\mathrm{L}}\bar{I}_{\mathrm{L}} = R_{\mathrm{L}}\bar{I}_{\mathrm{L}}$$

When the switch is in the on-state, $V_S=0$. When it is off, the diode is forward biased (we consider the continuous mode operation), therefore $V_S=V_i-V_o$. Therefore, the average voltage across the switch is:

$$\bar{V}_S = D\,0 + (1-D)(V_i - V_o) = (1-D)(V_i - V_o)$$

The output current is the opposite of the inductor current during the off-state. the average inductor current is therefore:

$$\bar{I}_{\mathrm{L}} = \frac{-I_o}{1-D}$$

Assuming the output current and voltage have negligible ripple, the load of the converter can be considered as purely resistive. If R is the resistance of the load, the above expression becomes:

$$\bar{I}_{\mathrm{L}} = \frac{-V_o}{(1-D)R}$$

Using the previous equations, the input voltage becomes:

$$V_i = R_{\mathrm{L}}\frac{-V_o}{(1-D)R} + (1-D)(V_i - V_o)$$

This can be written as:

$$\frac{V_o}{V_i} = \frac{-D}{\frac{R_{\mathrm{L}}}{R(1-D)} + 1 - D}$$

If the inductor resistance is zero, the equation above becomes equal to the one of the *ideal* case. But as R_L increases, the voltage gain of the converter decreases compared to the ideal case. Furthermore, the influence of R_L increases with the duty cycle. This is summarized in figure 6.