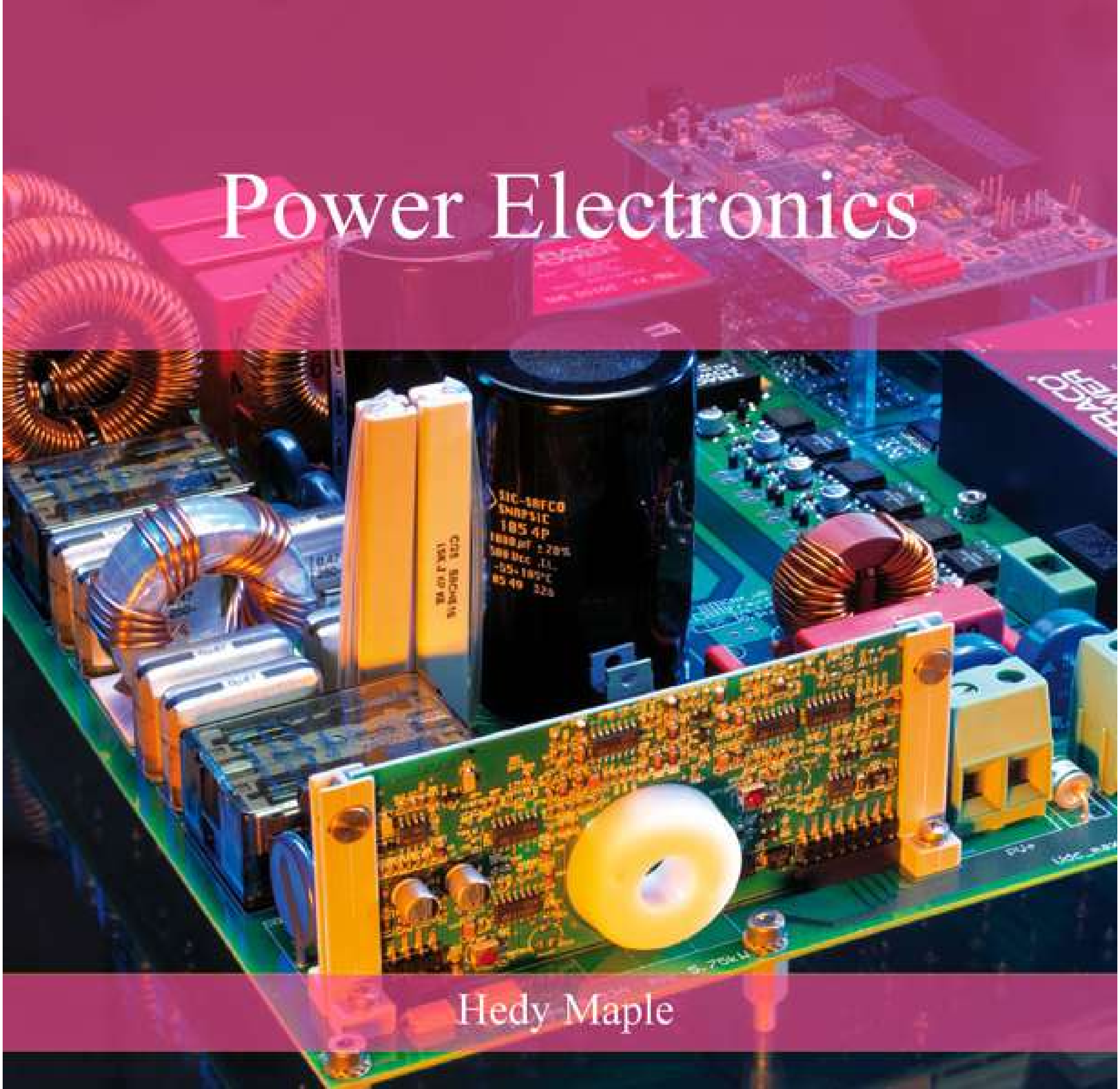
Power Electronics



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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 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
  - Step-up (Boost) - The output voltage is higher than the input voltage
  - SEPIC - The output voltage can be lower or higher than the input
- **Inverting**: the output voltage is of the opposite polarity as the input
  - Inverting (Buck-Boost)
  - 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 than other switching converters. Linear converters produce practically no RF noise. Too much RF noise causes electromagnetic interference (EMI).

AC/AC converter

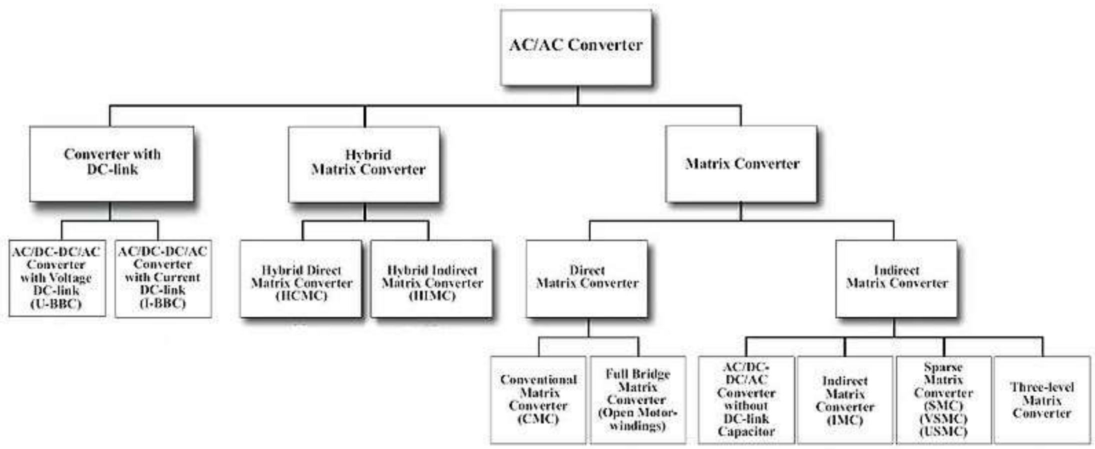


Fig 1: Classification of three-phace AC/AC converter circuits.

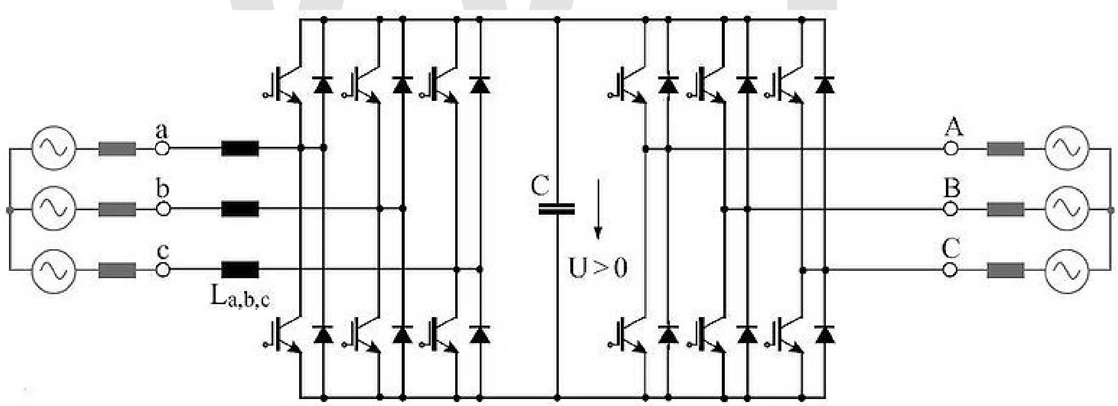


Fig 2: Topology of the three-phase AC/AC converter with voltage DC-link

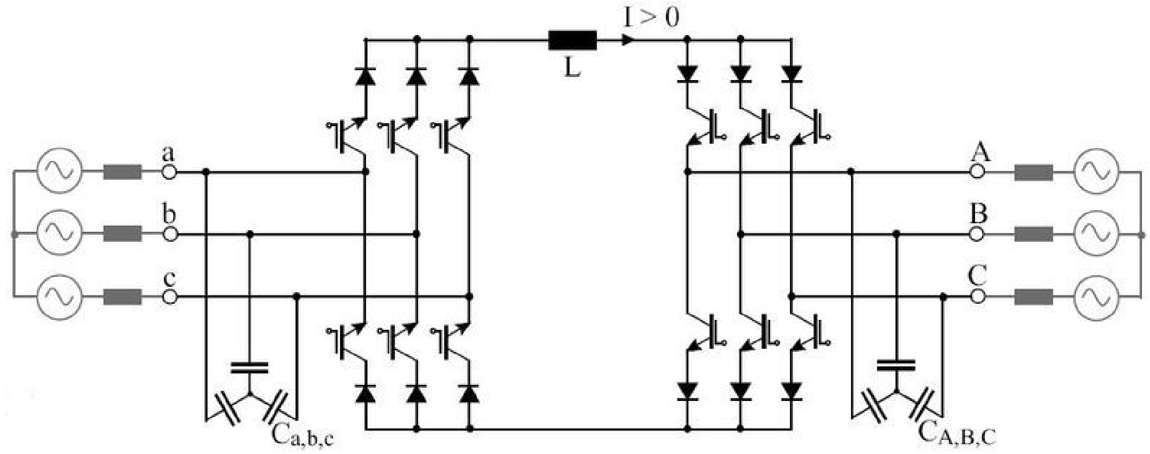


Fig 3: Topology of the three-phase AC/AC converter with current DC-link

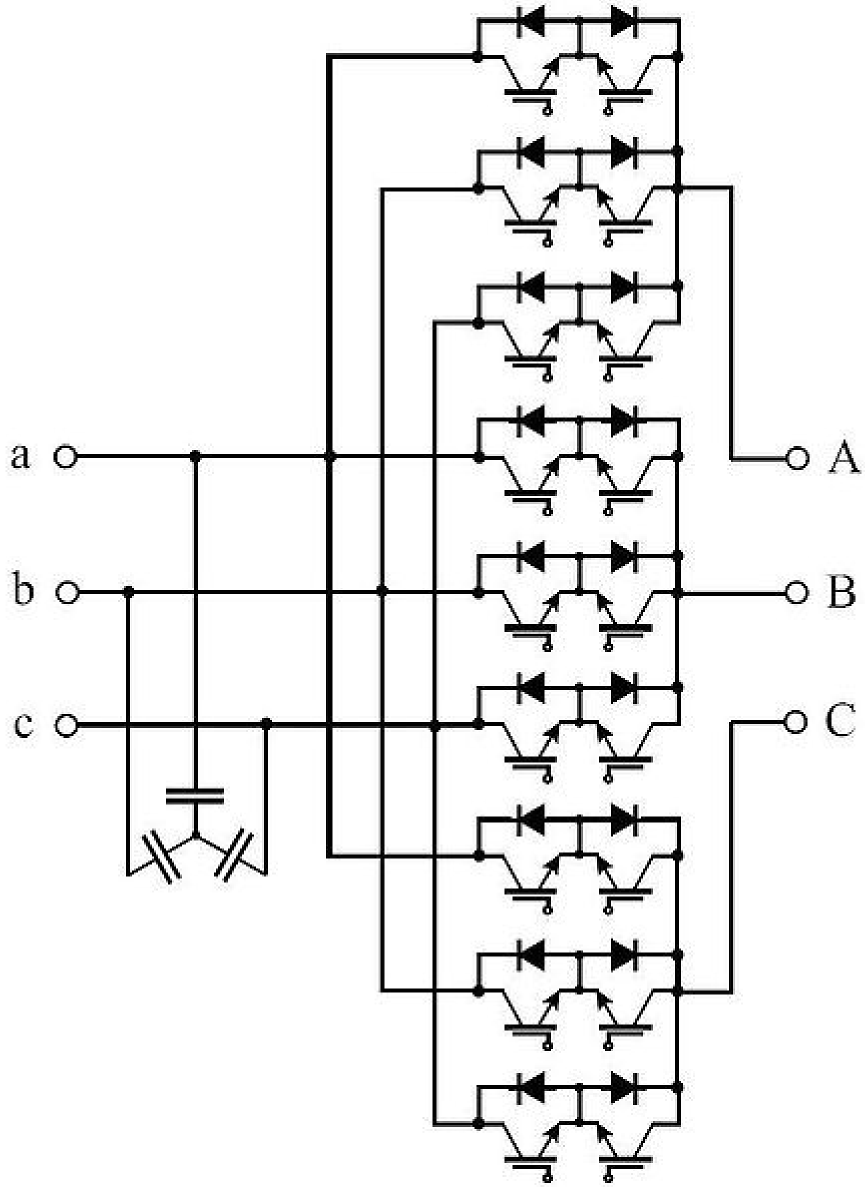


Fig 4: Topology of the Conventional Direct Matrix Converter

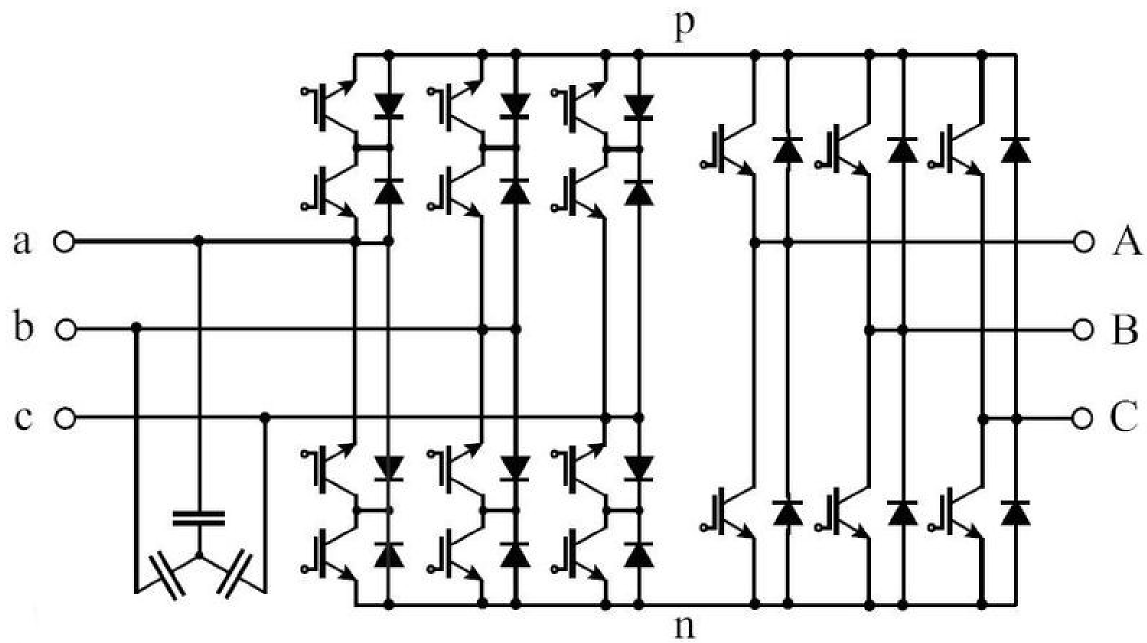


Fig 5: Topology of the indirect matrix converter

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.

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.

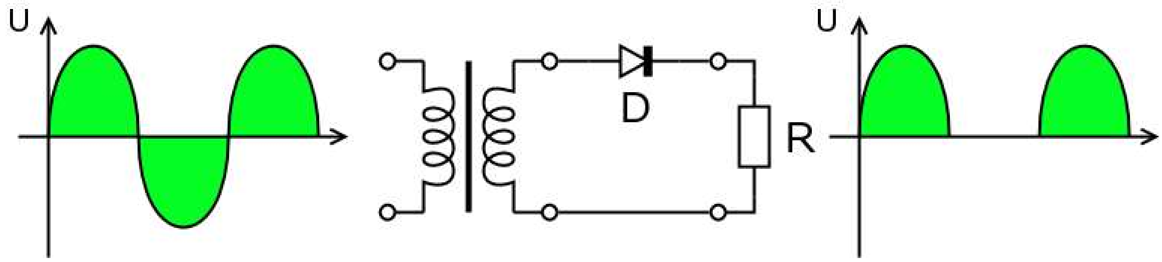
A device which performs the opposite function (converting DC to AC) is known as an inverter.

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.

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.



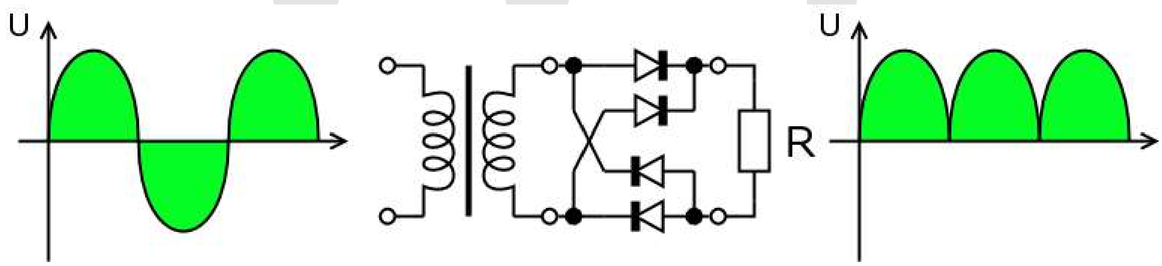
The output DC voltage of a half wave rectifier can be calculated with the following two ideal equations:

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

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

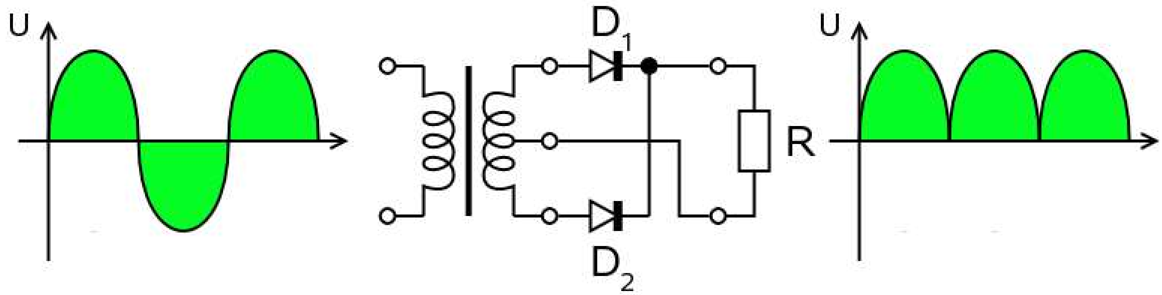
Full-wave rectification

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:

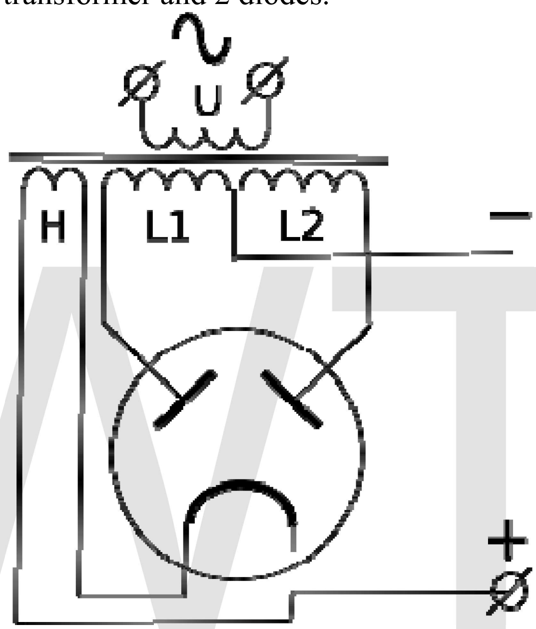


Graetz bridge rectifier: a full-wave rectifier using 4 diodes.

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.

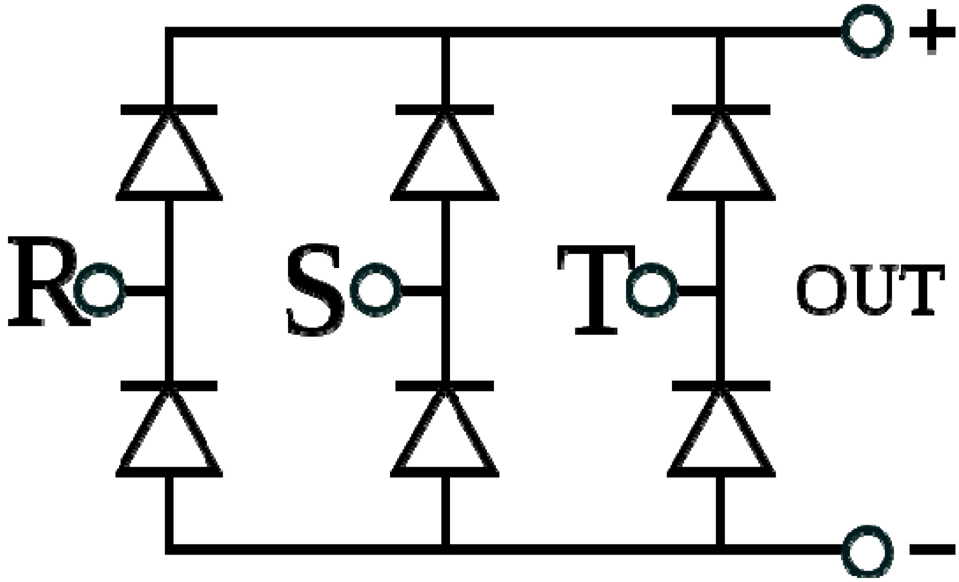


Full-wave rectifier using a transformer and 2 diodes.

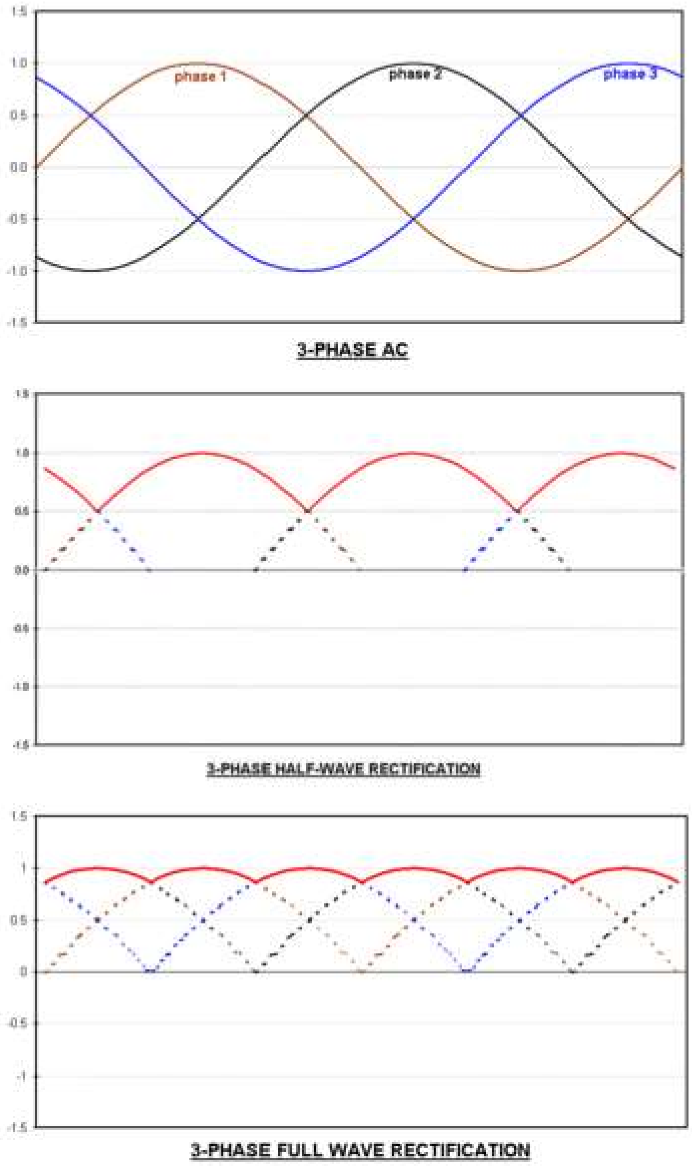


Full-wave rectifier, with vacuum tube having two anodes.

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.

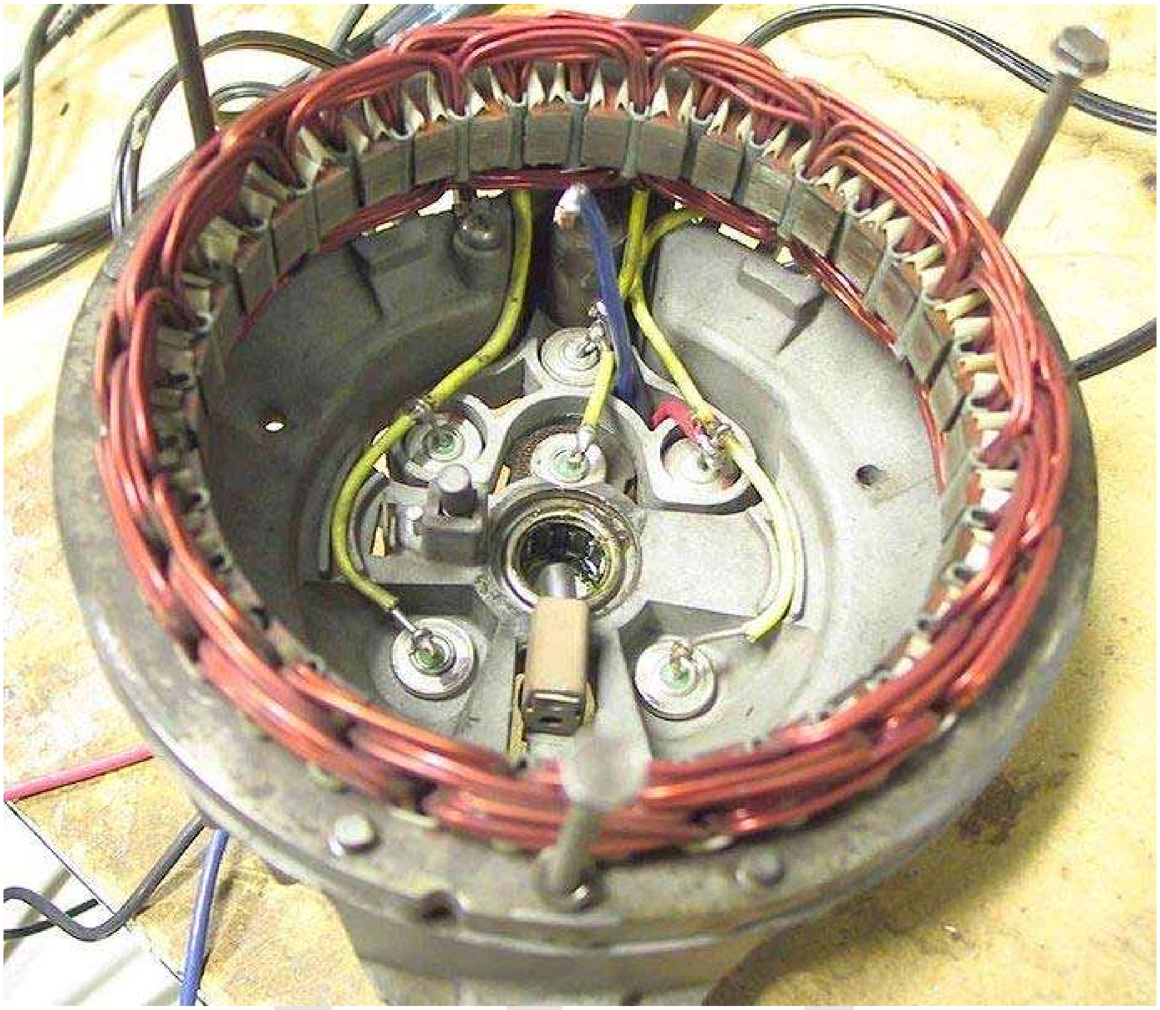


A three-phase bridge rectifier.



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

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.



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:

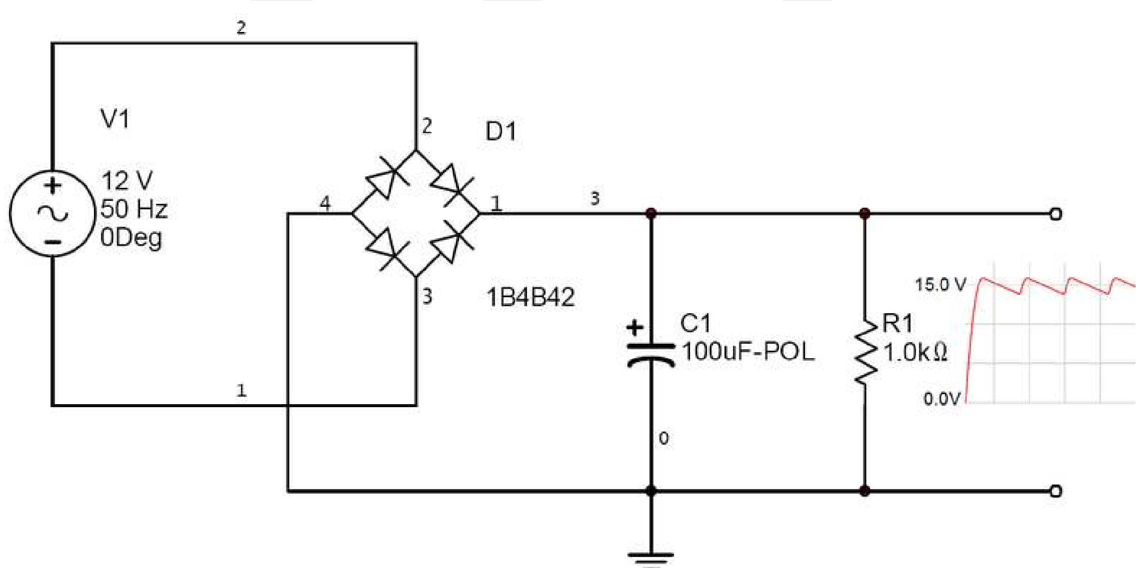
V_{dc},V_{av} - the average or DC output voltage,
V_p - the peak value of half wave,
V_{rms} - the root-mean-square value of output voltage.
π = ~ 3.14159

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.

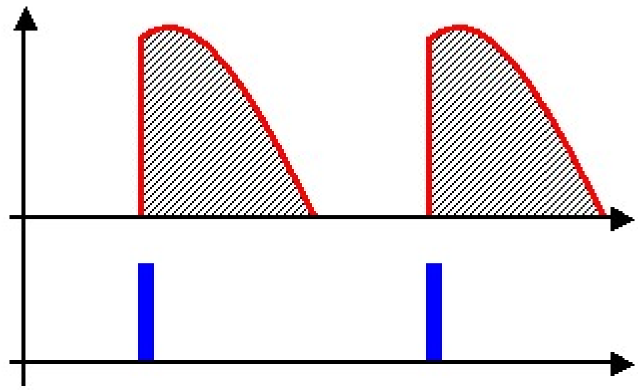
Applications

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.

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.

Chapter- 3

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.

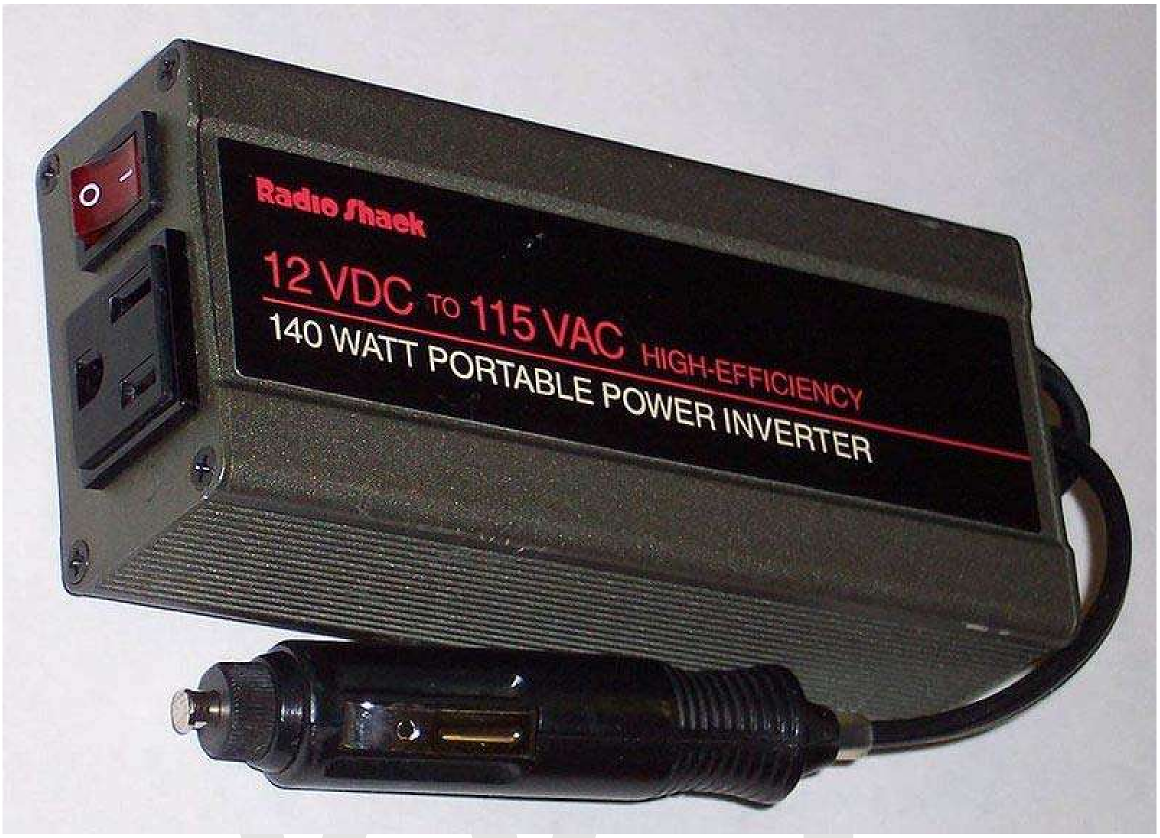
Static inverters have no moving parts and are used in a wide range of applications, from small switching power supplies in computers, to large electric utility high-voltage direct current applications that transport bulk power. Inverters are commonly used to supply AC power from DC sources such as solar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

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.

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.

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 is used to supply 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. 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.

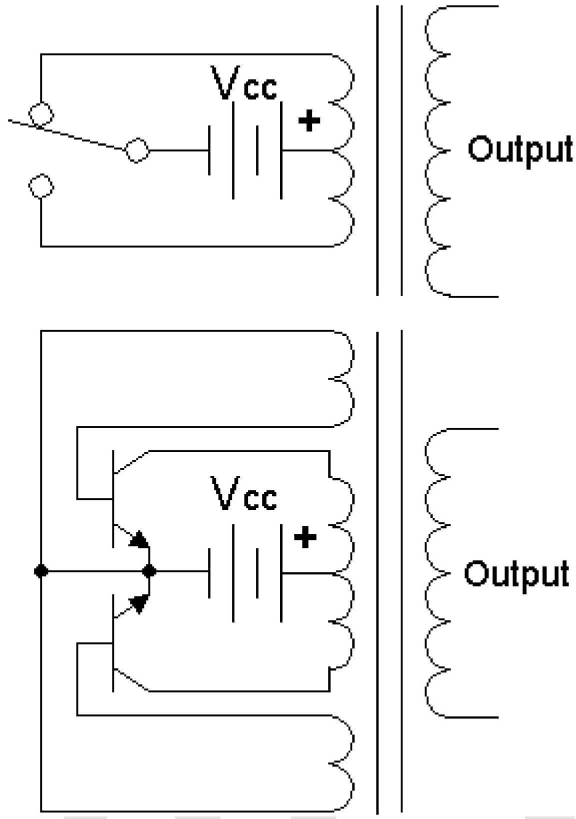
Air conditioning

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

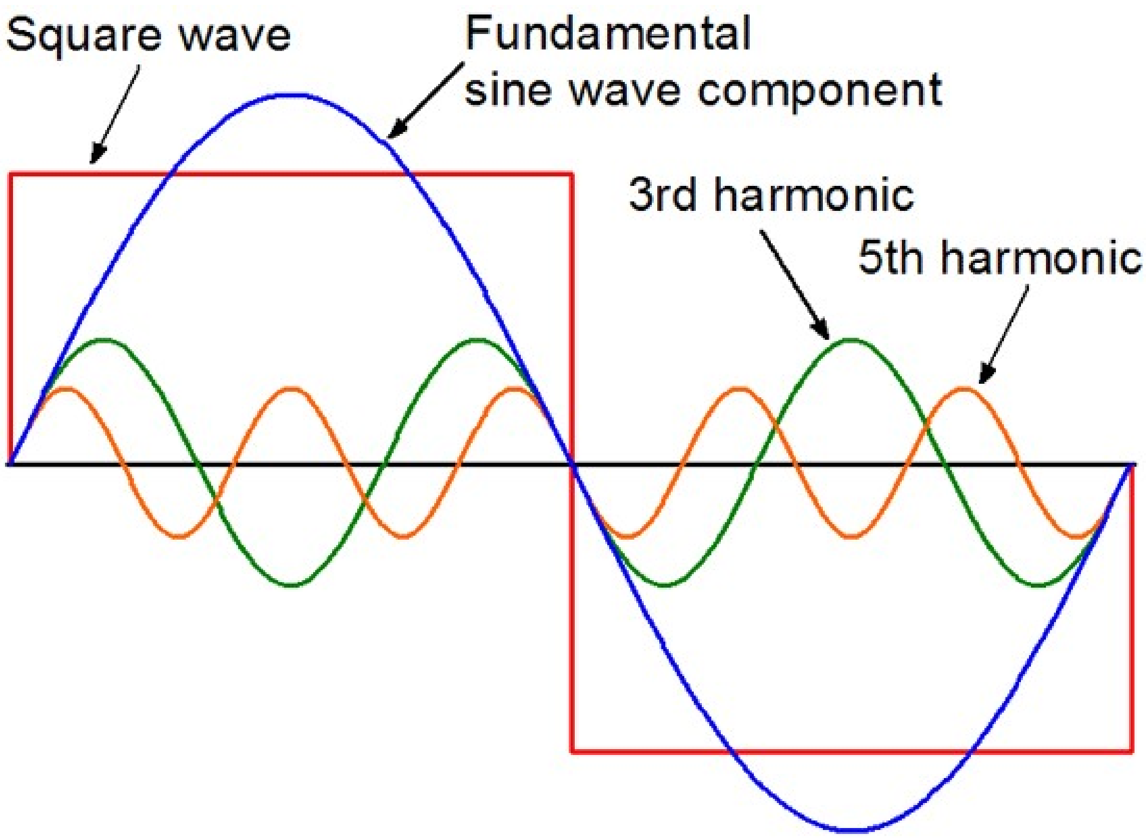
The general case

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 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

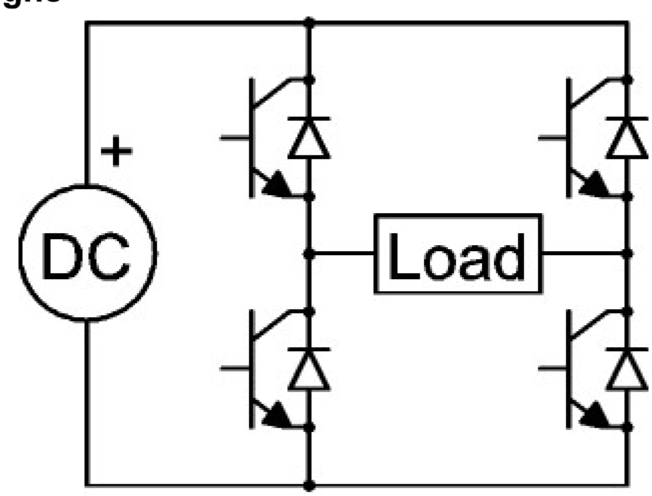
The switch in the simple inverter described above, when not coupled to an output transformer, produces a square voltage waveform due to its simple off and on nature as opposed to the sinusoidal waveform that is the usual waveform of an AC power supply. Using Fourier analysis, periodic waveforms are represented 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.

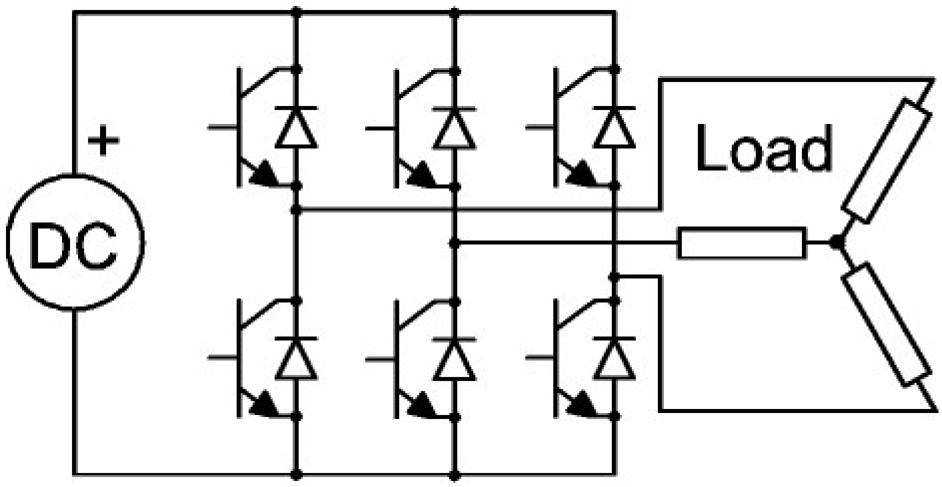
Since most loads contain inductance, feedback rectifiers or antiparallel diodes are often connected across each semiconductor switch to provide a path for the peak inductive load current when the switch is turned off. The antiparallel diodes are somewhat similar to the *freewheeling diodes* used in AC/DC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

Fourier analysis reveals that a waveform, like a square wave, that is antisymmetrical about the 180 degree point contains only odd harmonics, the 3rd, 5th, 7th etc. Waveforms that have steps of certain widths and heights eliminate or “cancel” additional 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 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 more effective at high frequencies than at low frequencies. *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.

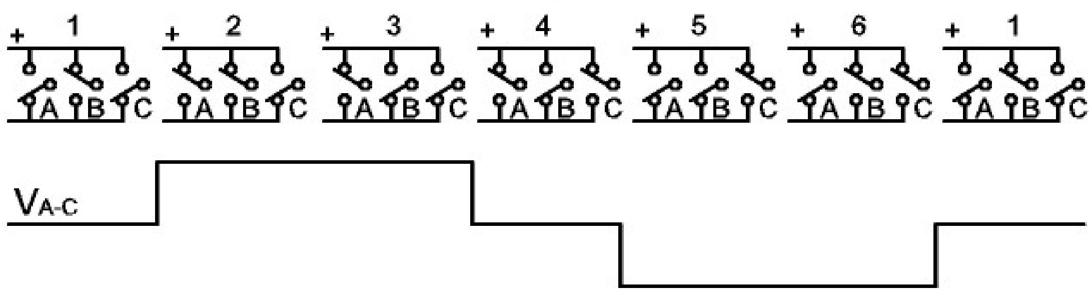
Multilevel inverters provide another approach to harmonic cancellation. Multilevel inverters provide an output waveform that exhibits multiple steps at several voltage levels. For example, it is possible to produce a more sinusoidal wave by having split-rail direct current inputs at two voltages, or 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

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

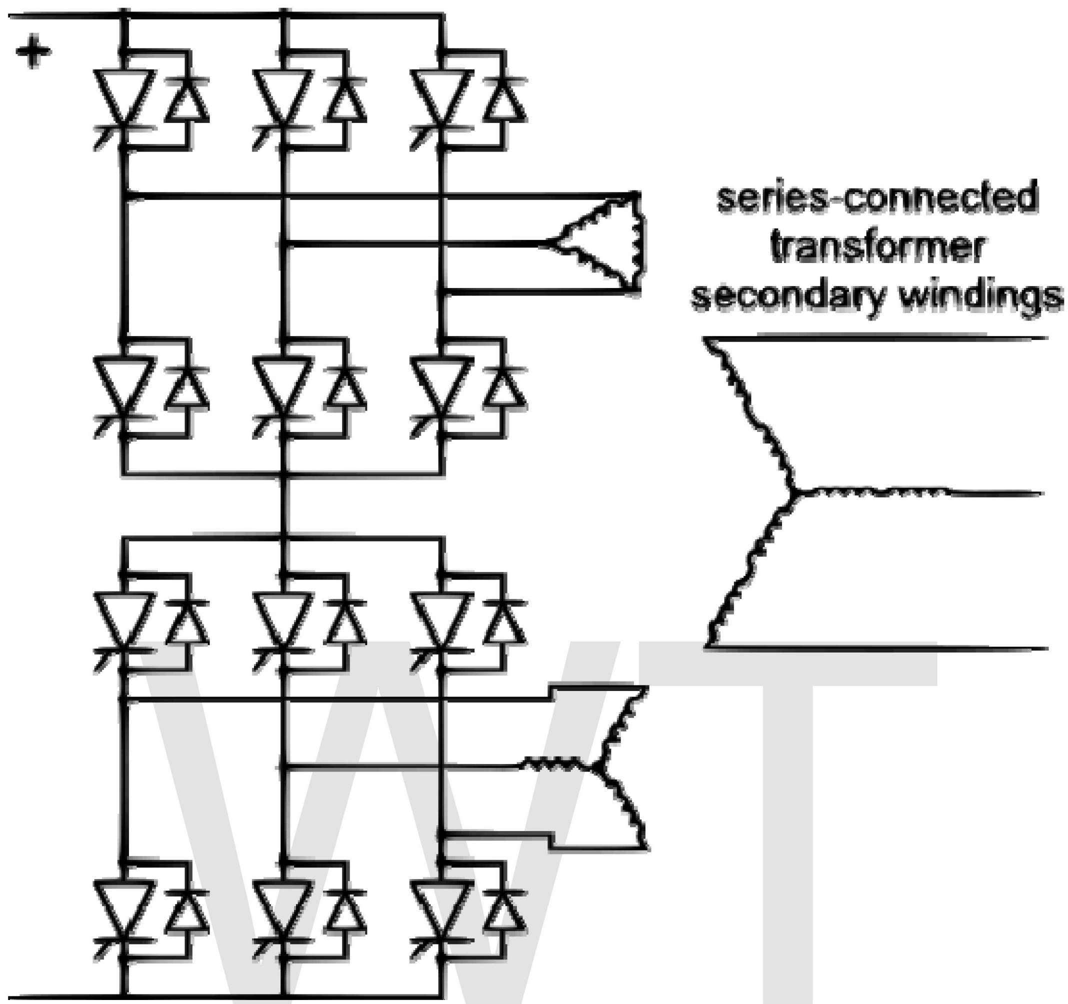
Early inverters

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

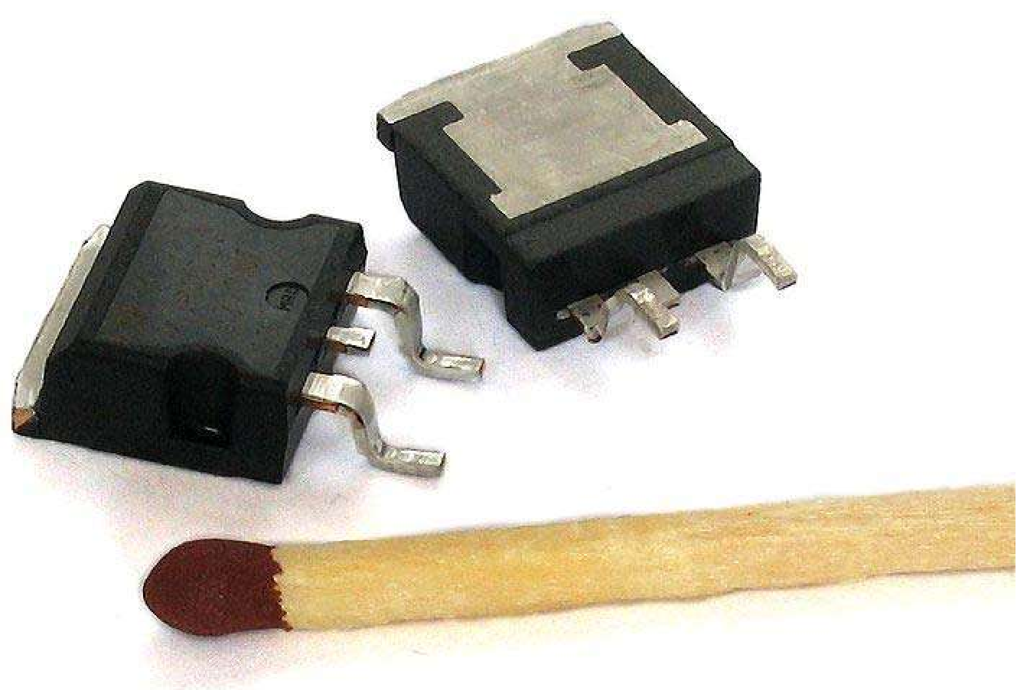
Rectifier circuits are often classified by the number of current pulses that flow to the DC side of the rectifier per cycle of AC input voltage. A single-phase half-wave rectifier is a one-pulse circuit and a single-phase full-wave rectifier is a two-pulse circuit. A three-phase half-wave rectifier is 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- 4

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

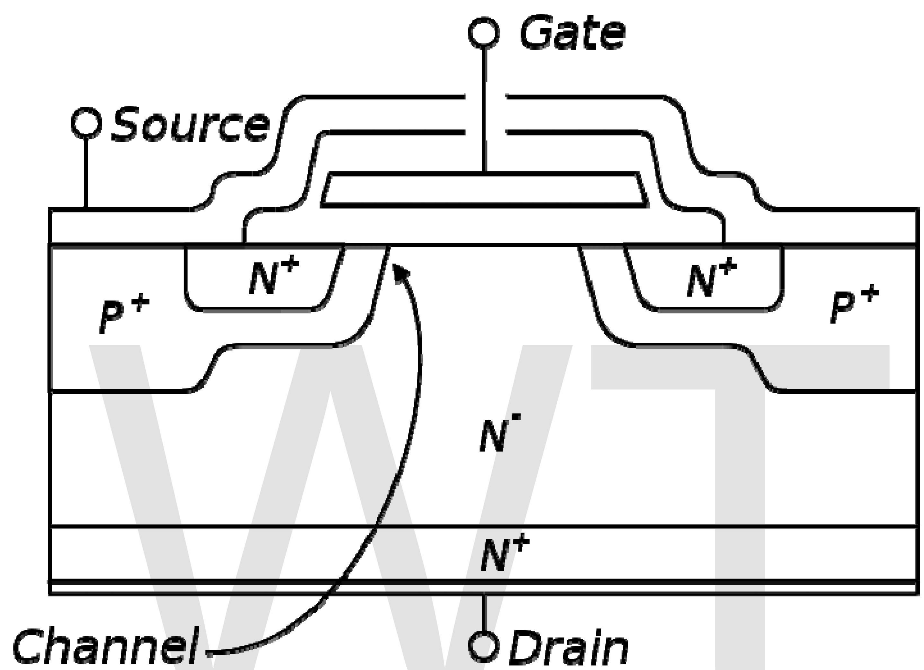


Fig. 1: Cross section of a VDMOS, showing an elementary cell. Note that a cell is very small (some micrometres to some tens of micrometres wide), and that a power MOSFET is composed of several thousand of them.

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

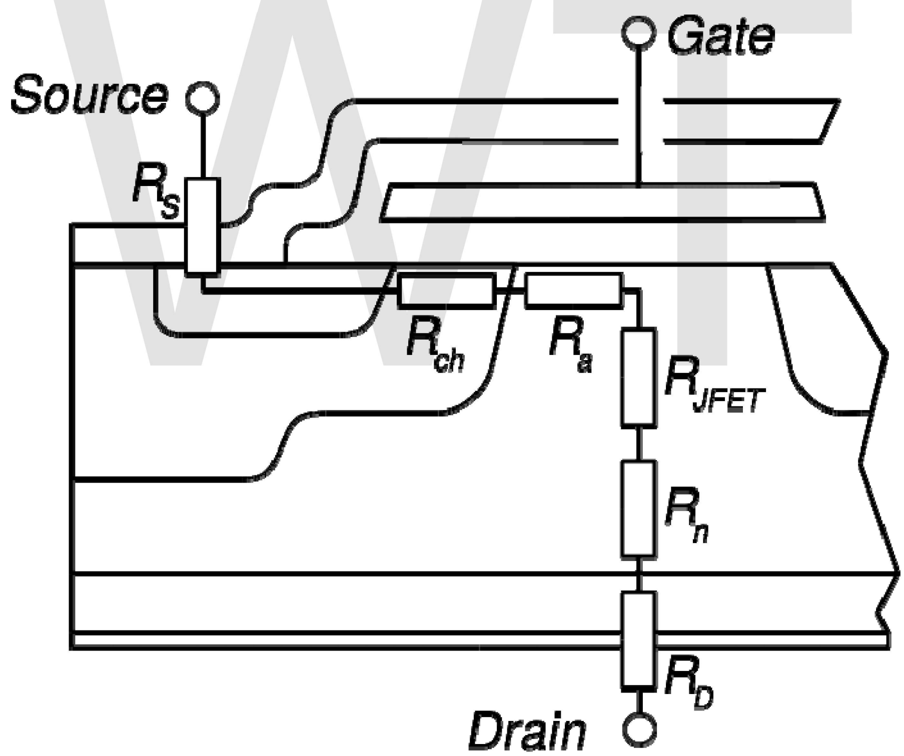


Fig.2: Contribution of the different parts of the MOSFET to the on-state resistance.

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

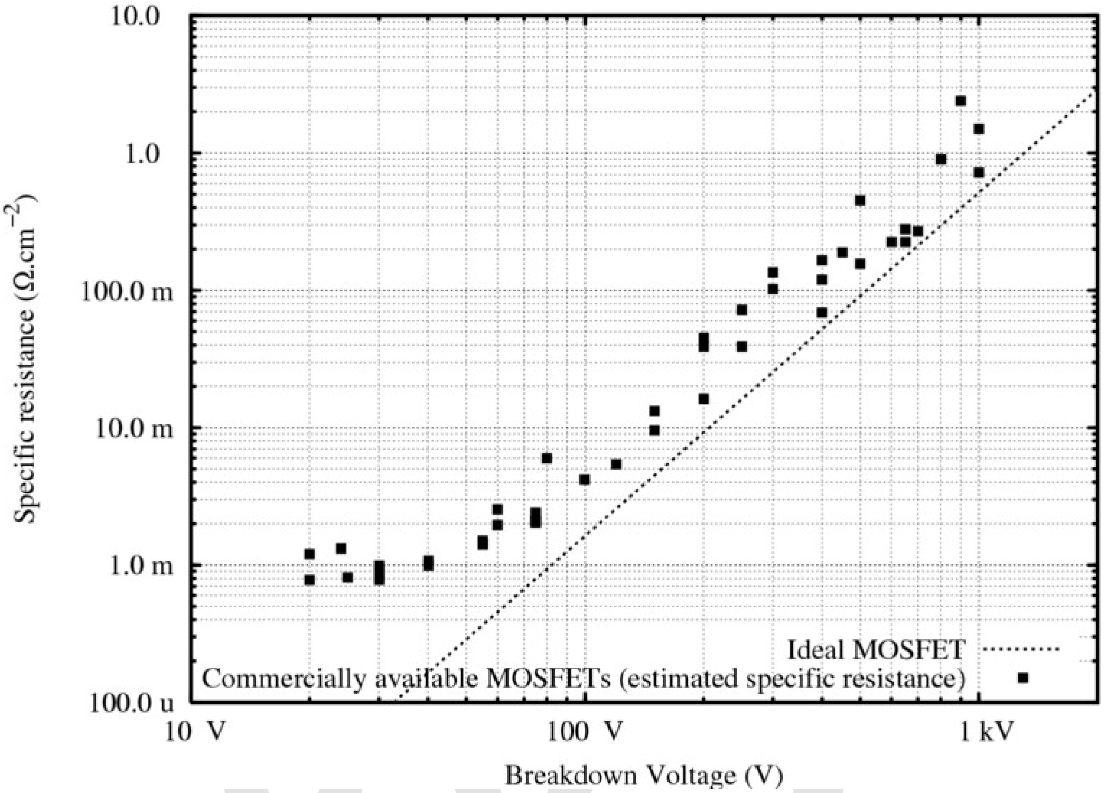


Fig. 3: The R_{DSon} of the MOSFETs increase with their Voltage rating.

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

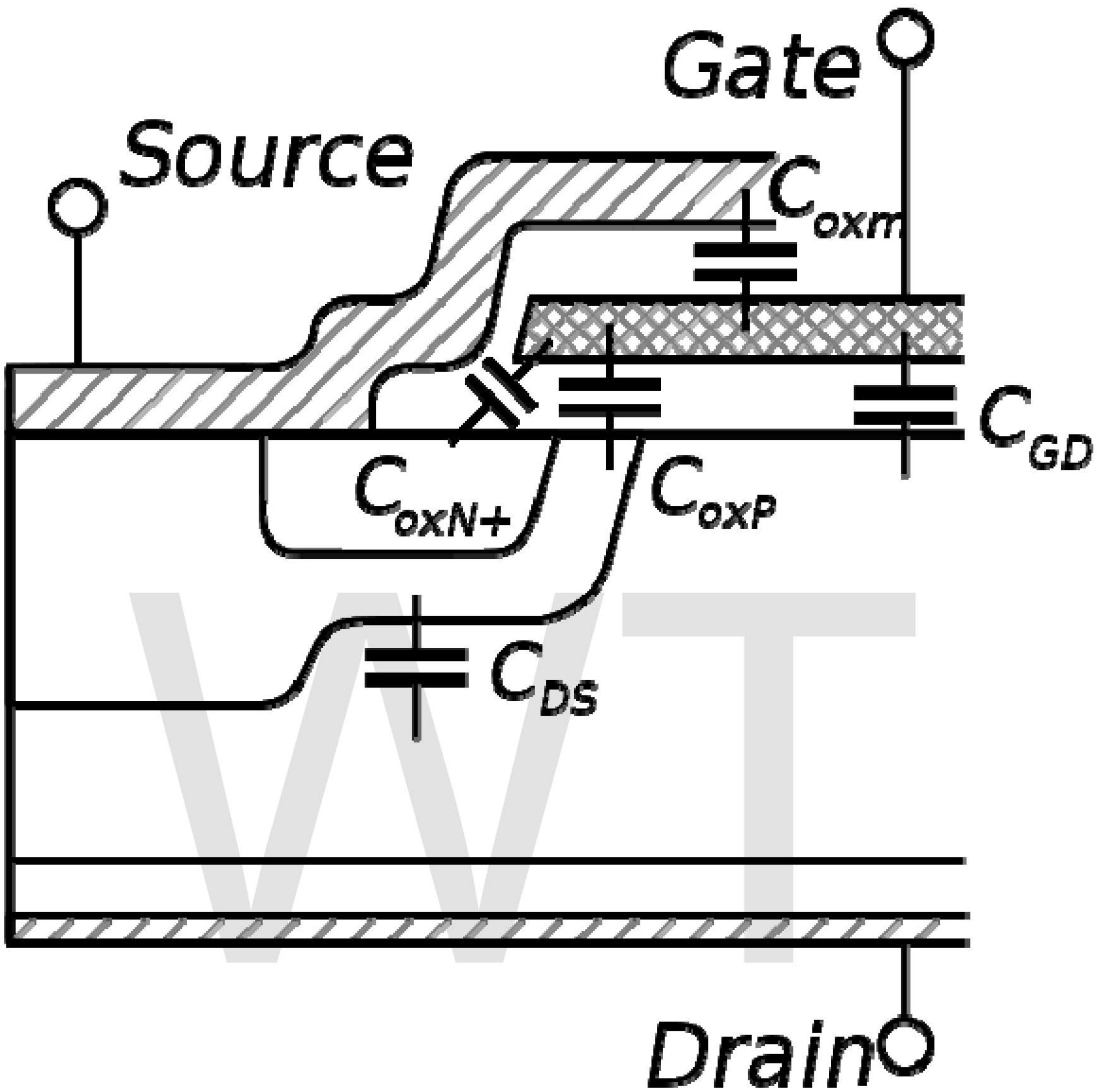


Fig. 4: Location of the intrinsic capacitances of a power MOSFET.

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:

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

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:

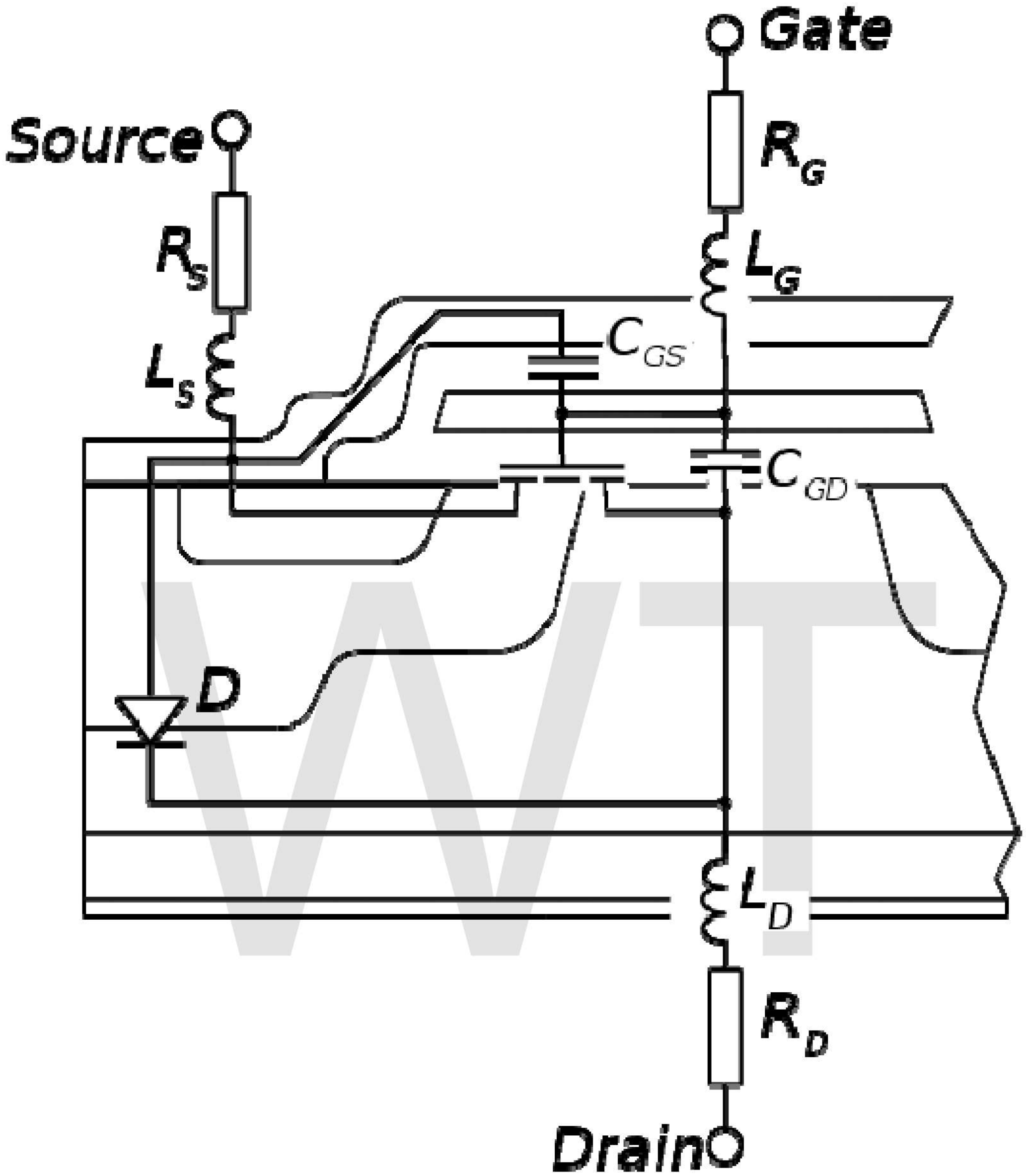
$$C_{GDj}\left(V_{GD}\right) = A_{GD}\sqrt{\frac{q\epsilon_{Si}N}{2V_{GD}}}$$

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}.

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 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.

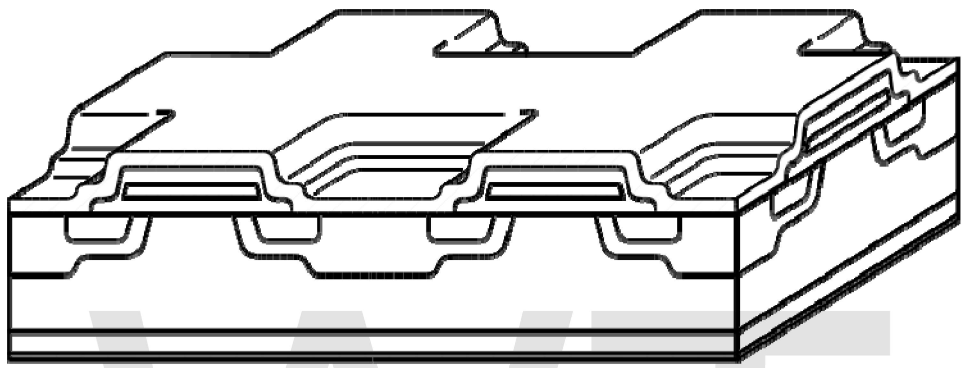
Latch-up (LU)

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.

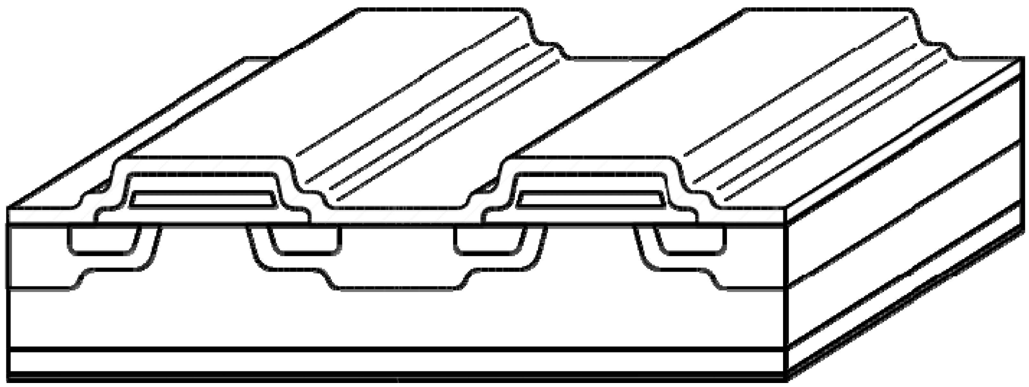
Technology

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.

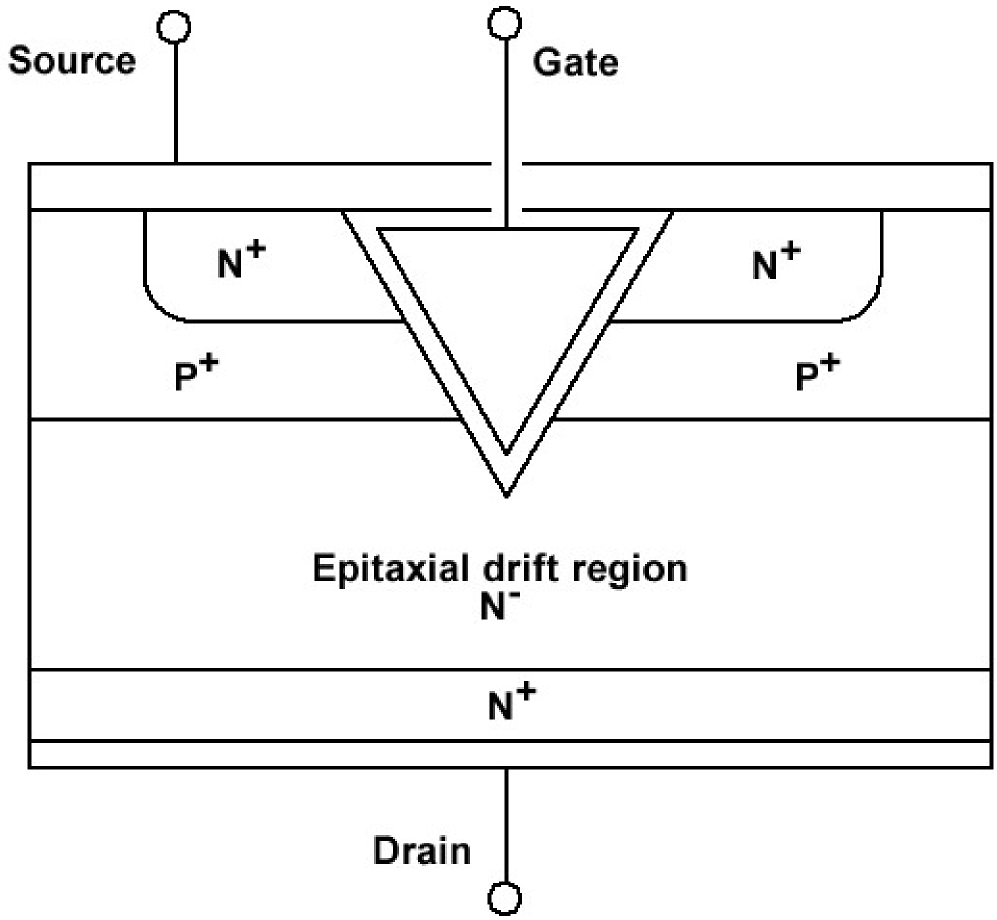
Structures

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.

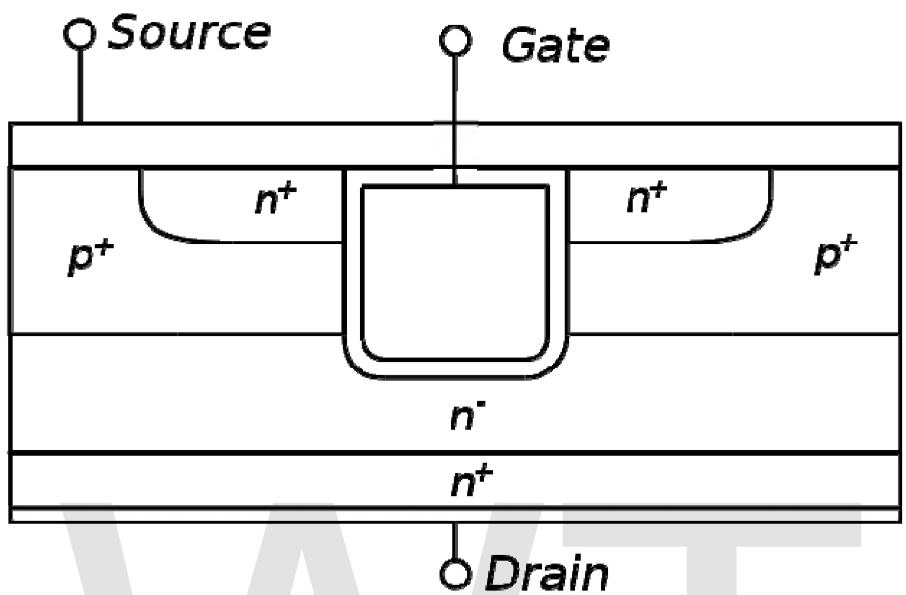
VMOS



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- 5

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.

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

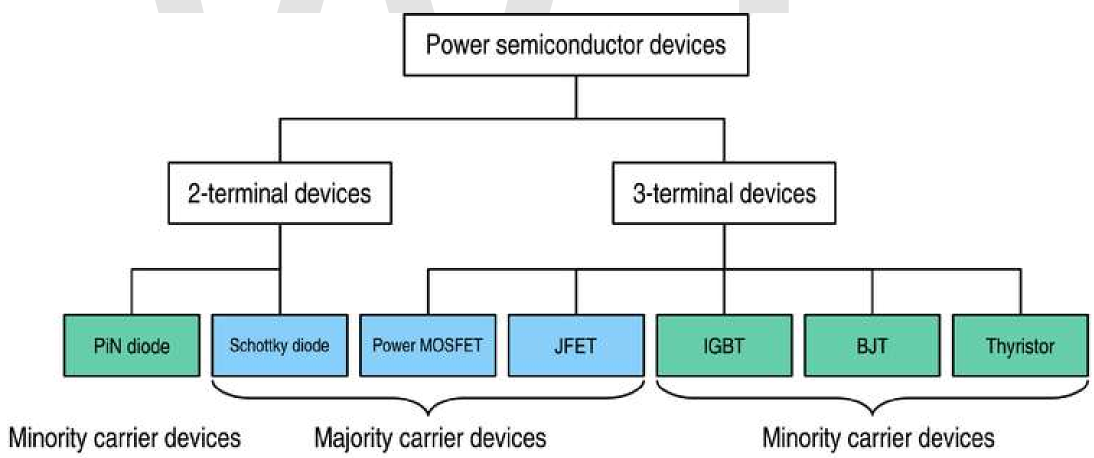


Fig. 1: The power devices family, showing the principal power switches.

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.

Switches

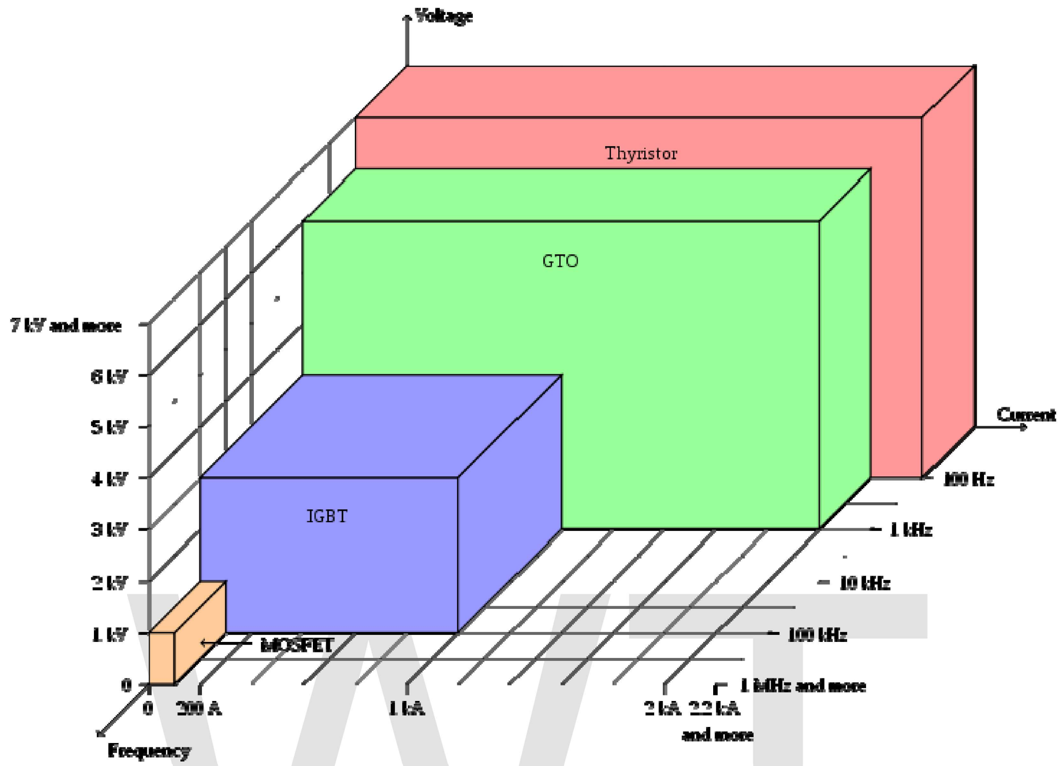


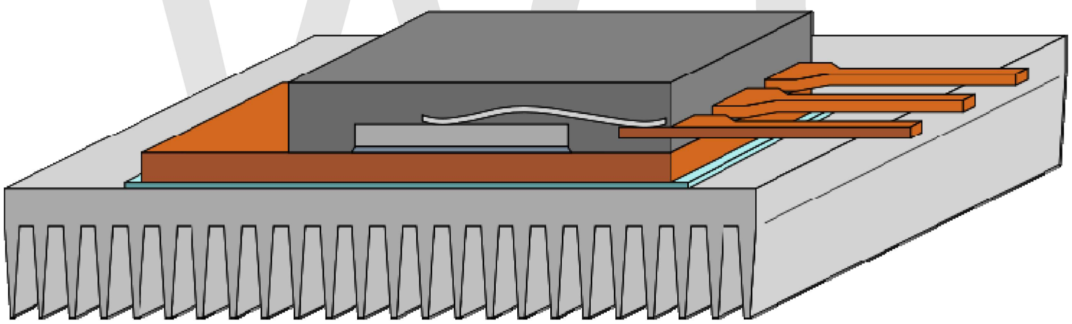
Fig.2 : Current/Voltage/switching frequency domains of the main power electronics switches.

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.

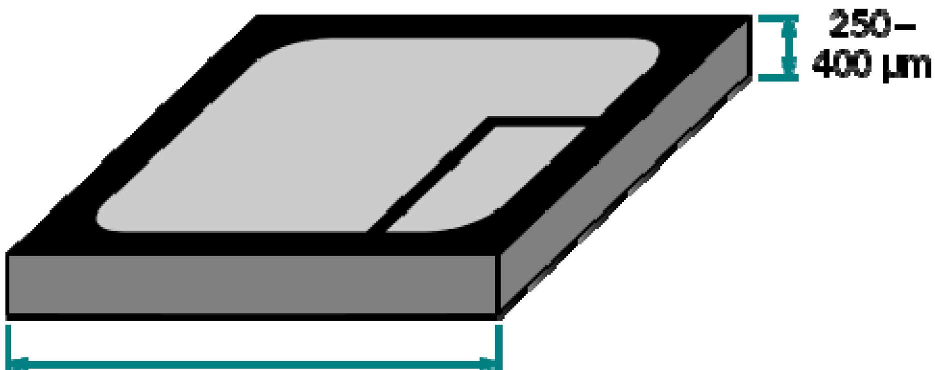
The IGBT is a recent component, so its performance improves regularly as technology evolves. It has already completely replaced the bipolar transistor in power applications, and the availability of power modules (in which several IGBT dice are connected in parallel) makes it attractive for power levels 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.

Improvement of structures

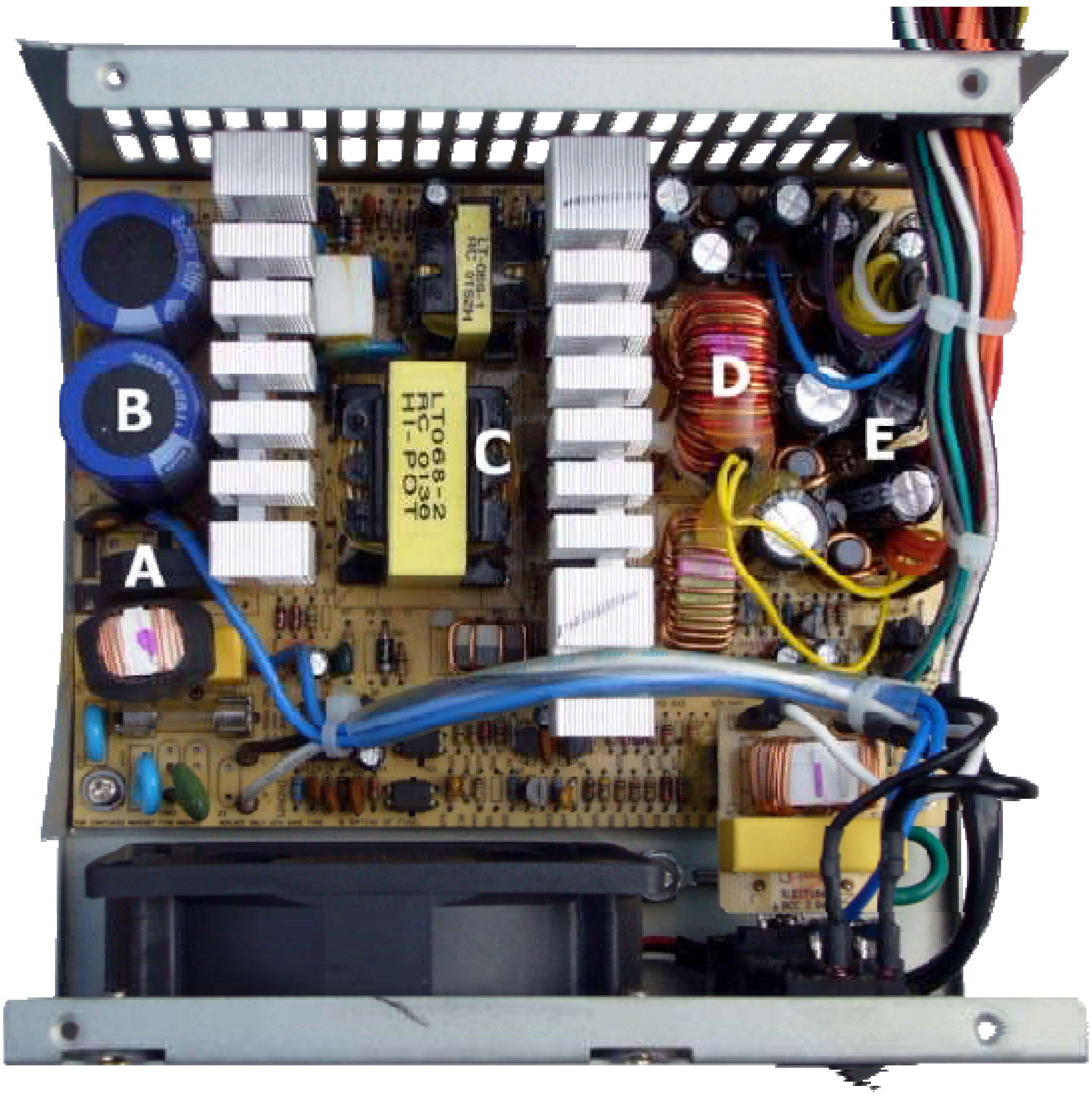
IGBTs are still under development and we can expect increased operating voltages in the future. At the high-power end of the range, MOS-Controlled Thyristor are promising devices. A major improvement over conventional MOSFET structure is achieved by employing superjunction charge-balance principle to 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.

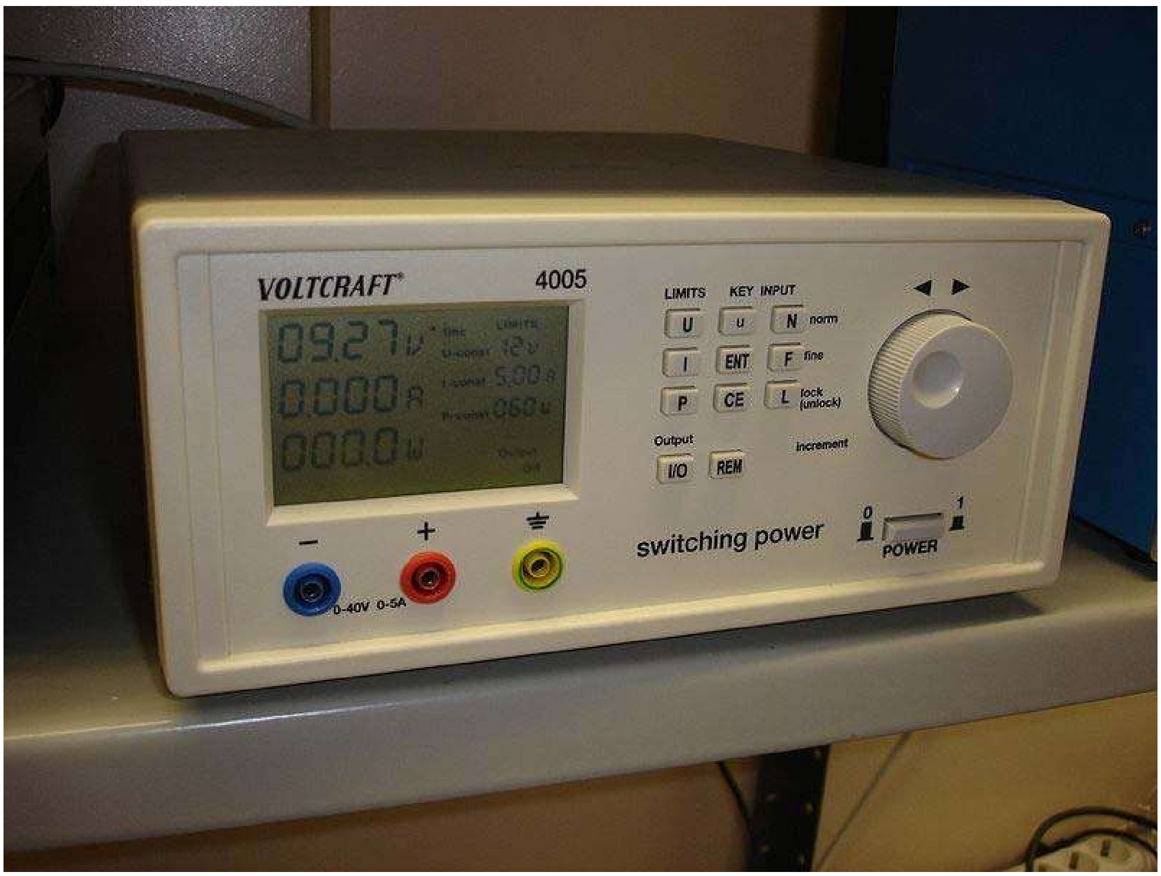
Chapter- 6

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

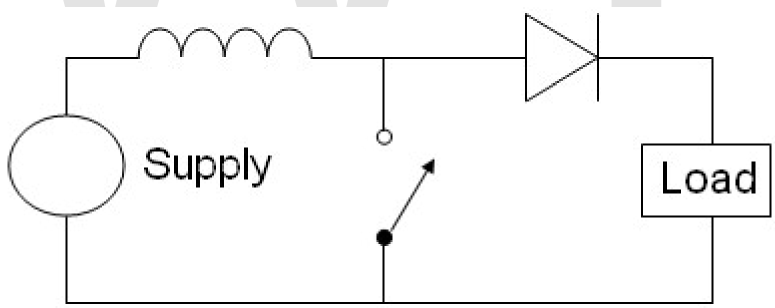
A **switched-mode power supply** (**switching-mode power supply**, **SMPS**, or simply **switcher**) is an electronic power supply that incorporates a switching regulator in order to be highly efficient in the conversion of electrical power. Like other types of power supplies, an SMPS transfers power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

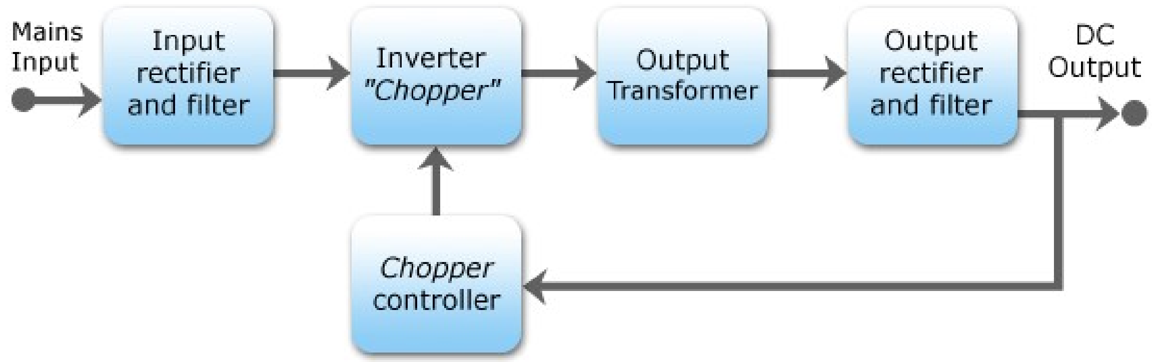
Very low cost SMPSs may couple electrical switching noise back onto the mains power line, causing interference with A/V equipment connected to the same phase. Non-power-factor-corrected SMPSs also cause harmonic distortion.

Classification

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

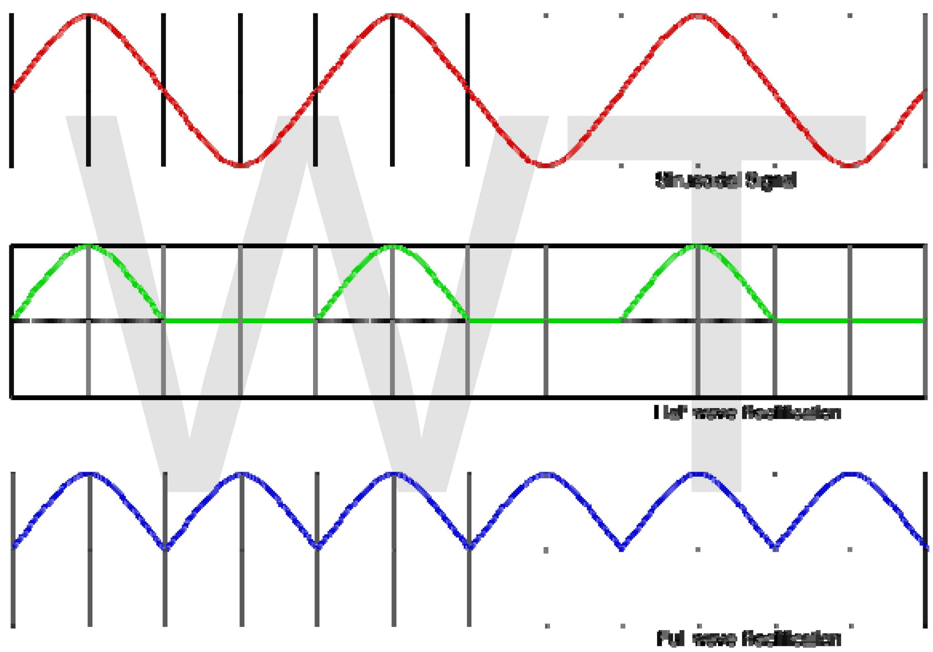
- AC in, DC out: rectifier, off-line converter input stage
- DC in, DC out: voltage converter, or current converter, or DC to DC converter
- AC in, AC out: frequency changer, cycloconverter, transformer, phase converter
- DC in, AC out: inverter

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.

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, $V_2 = D V_1$	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

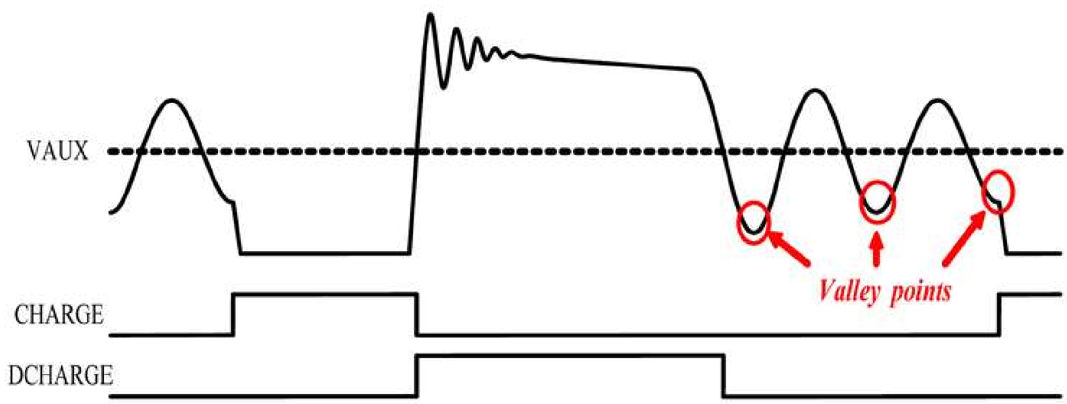
All isolated topologies include a transformer, and thus can produce an output of higher or lower voltage than the input by adjusting the turns ratio. For some topologies, multiple windings can be placed on the transformer to produce multiple output voltages. Some converters use the transformer for energy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

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.

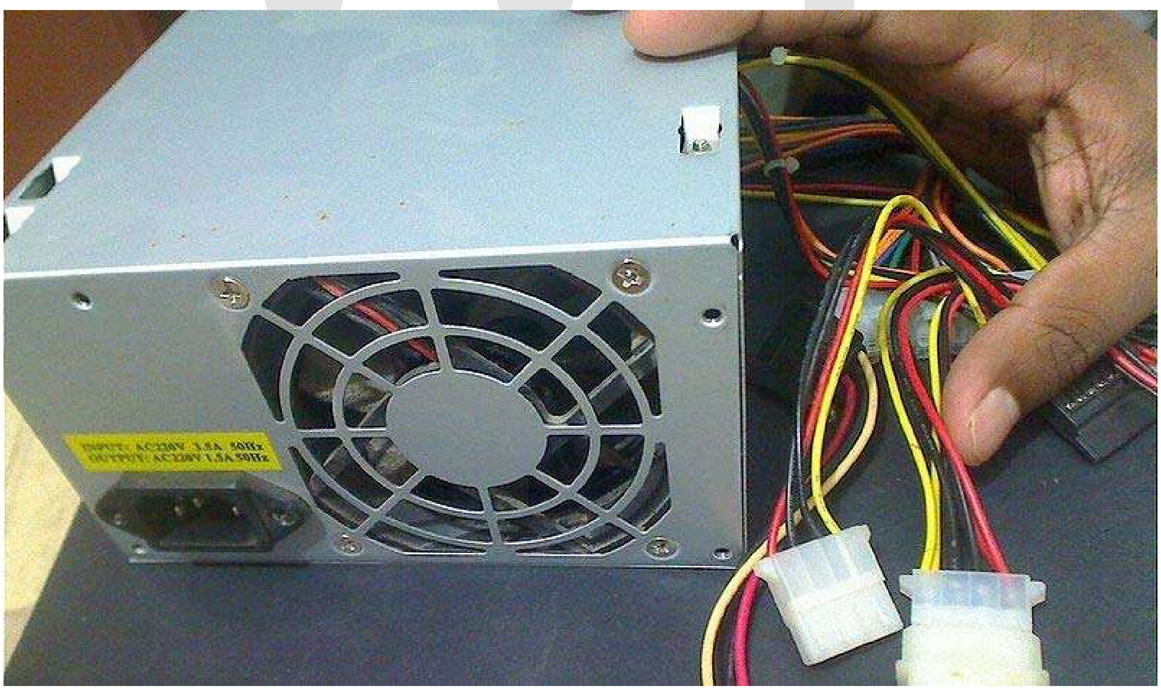
Precautions

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.

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- 7

Motor Controller

A **motor controller** is a device or group of devices that serves to govern in some predetermined manner the performance of an electric motor. A motor controller might include a manual or automatic means for starting and stopping the motor, selecting forward or reverse rotation, selecting and regulating the speed, regulating or limiting the torque, and protecting against overloads and faults.

Applications

Every electric motor has to have some sort of controller. The motor controller will have differing features and complexity depending on the task that the motor will be performing.

The simplest case is a switch to connect a motor to a power source, such as in small appliances or power tools. The switch may be manually operated or may be a relay or contactor connected to some form of sensor to automatically start and stop the motor. The switch may have several positions to select different connections of the motor. This may allow reduced-voltage starting of the motor, reversing control or selection of multiple speeds. Overload and overcurrent protection may be omitted in very small motor controllers, which rely on the supplying circuit to have overcurrent protection. Small motors may have built-in overload devices to automatically open the circuit on overload. Larger motors have a protective overload relay or temperature sensing relay included in the controller and fuses or circuit breakers for overcurrent protection. An automatic motor controller may also include limit switches or other devices to protect the driven machinery.

More complex motor controllers may be used to accurately control the speed and torque of the connected motor (or motors) and may be part of closed loop control systems for precise positioning of a driven machine. For example, a numerically controlled lathe will accurately position the cutting tool according to a preprogrammed profile and compensate for varying load conditions and perturbing forces to maintain tool position.

Types of motor controllers

Motor controllers can be manually, remotely or automatically operated. They may include only the means for starting and stopping the motor or they may include other functions.

An electric motor controller can be classified by the type of motor it is to drive such as permanent magnet, servo, series, separately excited, and alternating current.

A motor controller is connected to a power source such as a battery pack or power supply, and control circuitry in the form of analog or digital input signals.

Motor starters

A small motor can be started by simply plugging it into an electrical receptacle or by using a switch or circuit breaker. A larger motor requires a specialized switching unit called a motor starter or motor contactor. When energized, a direct on line (DOL) starter immediately connects the motor terminals directly to the power supply. A motor soft starter connects the motor to the power supply through a voltage reduction device and increases the applied voltage gradually or in steps.

Adjustable-speed drives

An adjustable-speed drive (ASD) or variable-speed drive (VSD) is an interconnected combination of equipment that provides a means of driving and adjusting the operating speed of a mechanical load. An electrical adjustable-speed drive consists of an electric motor and a speed controller or power converter plus auxiliary devices and equipment. In common usage, the term “drive” is often applied to just the controller.

Motor control centers

right A small, early 1960's-vintage motor control center for 480 volt motors.

A motor control center (MCC) is an assembly of one or more enclosed sections having a common power bus and principally containing motor control units. Motor control centers are in modern practice a factory assembly of several motor starters. A motor control center can include variable frequency drives, programmable controllers, and metering and may also be the electrical service entrance for the building. Motor control centers are usually used for low voltage three-phase alternating current motors from 230 volts to 600 volts. Medium-voltage motor control centers are made for large motors running at 2300 V to around 15000 V, using vacuum contactors for switching and with separate compartments for power switching and control.

Motor control centers have been used since 1950 by the automobile manufacturing industry which used large numbers of electric motors. Today they are used in many industrial and commercial applications. Where very dusty or corrosive processes are used, the motor control center may be installed in a separate air-conditioned room, but often an MCC will be on the factory floor adjacent to the machinery controlled.

A motor control center consists of one or more vertical metal cabinet sections with power bus and provision for plug-in mounting of individual motor controllers. Very large controllers may be bolted in place but smaller controllers can be unplugged from the cabinet for testing or maintenance. Each motor controller contains a contactor or a solid-state motor controller, overload relays to protect the motor, fuses or a circuit breaker to provide short-circuit protection, and a disconnecting switch to isolate the motor circuit. Three-phase power enters each controller through separable connectors. The motor is wired to terminals in the controller. Motor control centers provide wire ways for field control and power cables.

Each motor controller in an MCC can be specified with a range of options such as separate control transformers, pilot lamps, control switches, extra control terminal blocks, various types of bi-metal and solid-state overload protection relays, or various classes of power fuses or types of circuit breakers. A motor control center can either be supplied ready for the customer to connect all field wiring, or can be an engineered assembly with internal control and interlocking wiring to a central control terminal panel board or programmable controller.

Motor control centers (MCC) usually sit on floors, which are often required to have a fire-resistance rating. Firestops may be required for cables that penetrate fire-rated floors and walls.

Speed controls for AC induction motors

Recent developments in drive electronics have allowed efficient and convenient speed control of these motors, where this has not traditionally been the case. The newest advancements allow for torque generation down to zero speed. This allows the polyphase AC induction motor to compete in areas where DC motors have long dominated, and presents an advantage in robustness of design, cost, and reduced maintenance.

Variable frequency drives

Phase vector drives

Phase vector drives (or simply **vector drives**) are an improvement over variable frequency drives (VFDs) in that they separate the calculations of magnetizing current and torque generating current. These quantities are represented by phase vectors, and are combined to produce the driving phase vector which in turn is decomposed into the driving components of the output stage. These calculations need a fast microprocessor, typically a DSP device.

Unlike a VFD, a vector drive is a closed loop system. It takes feedback on rotor position and phase currents. Rotor position can be obtained through an encoder, but is often sensed by the reverse EMF generated on the motor leads.

In some configurations, a vector drive may be able to generate full rated motor torque at zero speed.

Direct torque control drives

Direct torque control has better torque control dynamics than the PI-current controller based vector control. Thus it suits better to servo control applications. However, it has some advantage over other control methods in other applications as well because due to the faster control it has better capabilities to damp mechanical resonances and thus extend the life of the mechanical system.

Brushed DC motor speed or torque controls

An industrial grade first quadrant PWM DC-motor controller

These controls are applicable to brushed DC motors with either a wound or permanent magnet stator. A valuable characteristic of these motors is that they are easily controlled in torque, the torque being fairly directly proportional to the driving current. Speed control is derived by simply modulating the motor torque.

SCR or thyristor drive

SCR controls for DC motors convert AC power to direct current, with adjustable voltage. Small DC drives are common in industry, running from line voltages, with motors rated at 90V for 120V line, and 180V for a 240V line. Larger drives, up to thousands of horsepower, are powered by three phase supplies and are used in such applications as rolling mills, paper machines, excavators, and ship propulsion. DC drivers are available in reversing and non-reversing models. The waveform of the current through the motor by a single-phase drive will have strong ripple components due to the switching at line frequency. This can be reduced by use of a poly phase supply or smoothing inductors in the motor circuit; otherwise the ripple currents produce motor heating, excess noise, and loss of motor torque.

PWM or chopper drives

PWM controls use pulse width modulation to regulate the current sent to the motor. Unlike SCR controls which switch at line frequency, PWM controls produce smoother current at higher switching frequencies, typically between 1 and 20 kHz. At 20 kHz, the switching frequency is inaudible to humans, thereby eliminating the hum which switching at lower frequency produces. However, some motor controllers for radio controlled models make use of the motor to produce audible sound, most commonly simple beeps.

A PWM controller typically contains a large reservoir capacitor and an H-bridge arrangement of switching elements (thyristors, Mosfets, solid state relays, or transistors).

Servo controllers

Servo controllers is a wide category of motor control. Common features are:

- precise closed loop position control
- fast acceleration rates
- precise speed control

Servo motors may be made from several motor types, the most common being

- brushed DC motor
- brushless DC motors
- AC servo motors

Servo controllers use position feedback to close the control loop. This is commonly implemented with encoders, resolvers, and Hall effect sensors to directly measure the rotor's position.

A servo may be controlled using pulse-width modulation (PWM). How long the pulse remains high (typically between 1 and 2 milliseconds) determines where the motor will try to position itself. Another control method is pulse and direction.

Other position feedback methods measure the back EMF in the undriven coils to infer the rotor position, or detect the Kick-Back voltage transient (spike) that is generated whenever the power to a coil is instantaneously switched off. These are therefore often called "sensorless" control methods.

Sensorless control methods

Ripple Counting

Ripple counting works on the 'law of induction', or more specifically Lenz's law, which says that the magnetic field of any induced current opposes the charge that induces it.

This so-called back EMF (sometimes called the counter electromotive force) can be detected by measuring the current flowing through each coil as the motor rotates .

In a fully encapsulated motor and particularly a multi pole motor this is difficult to measure. Therefore ripple counting usually relies on measuring the voltage variations over a small resistor inserted in one of the power supply wires to the motor. The result is a voltage curve representing the accumulated currents running through the coils of the motor assembly as the motor rotates.

The current ripple waveform characteristics are highly dependent of a number of factors such as the supply voltage and the actual load, speed, direction and temperature of the motor. Other factors such as the in-rush current, aging of motor parts and electromagnetic interference can also influence the ripple waveform. The amplitude and the shape of the waveform can vary significantly due to these factors. In other applications noise transients superposed onto the ripple current waveform can generate false counting pulses.

It has proven difficult to design a detection system based on ripple counting that can be used to precisely and reliably count the number of commutations of a rotating motor from start to stop. Numerous attempts to seek to improve the reliability of ripple counting have been described in the literature, examples in .

Transient Counting

Transient counting works on the basic principle of Ohm's law and the behavior of a collapsing magnetic field in which a Back-Fire or Kick-Back transient (spike) is generated whenever the power to a coil is instantaneously switched off .

At each commutation point, when the brush breaks contact with a commutation segment, the energy stored in the motor winding as a magnetic field causes an arc or voltage spike between the brush and the commutator segment. This occurs not only during normal commutation but also in situations where the brushes bounce on the rotating commutator.

A dedicated transient detector circuit (in effect a high pass filter) detects the Kick-Back spike from the collapsing magnetic field in the coil when the power to the coil is turned off. The Kick-Back transients trigger the modulation of an electronic encoder signal for each of the motor commutations. Thus an N pole motor will encode N signals per rotation. The Kick-Back spikes can be measured anywhere on the power supply wires to the motor. The encoded signal can be used as position feedback in the servo controller.

The performance of transient counting is by and large unaffected by the parameters which are influencing ripple counting. Whether the motor is powered or is coasting in generator mode driven by the inertia of a load has no influence on the counting reliability . The amplitude of the Kick-Back transients is mainly influenced by the conductivity of the surrounding air. This is because the intensity of the arc generated between a brush and a commutator depends on the air conductivity.

Stepper motor controllers

A stepper, or stepping, motor is a synchronous, brushless, high pole count, polyphase motor. Control is usually, but not exclusively, done open loop, i.e. the rotor position is assumed to follow a controlled rotating field. Because of this, precise positioning with steppers is simpler and cheaper than closed loop controls.

Modern stepper controllers drive the motor with much higher voltages than the motor nameplate rated voltage, and limit current through chopping. The usual setup is to have a positioning controller, known as an **indexer**, sending step and direction pulses to a separate higher voltage drive circuit which is responsible for commutation and current limiting.

Relevant circuits to motor control

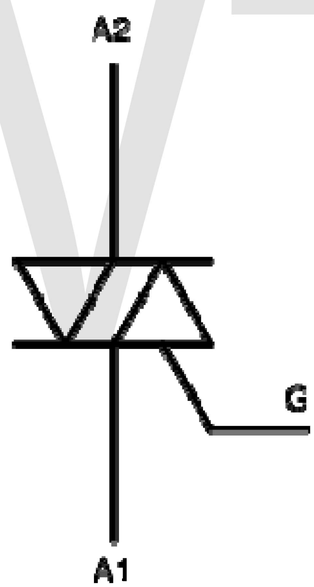
H-bridge

DC motors are typically controlled by using a transistor configuration called an "H-bridge". This consists of a minimum of four mechanical or solid-state switches, such as two NPN and two PNP transistors. One NPN and one PNP transistor are activated at a time. Both NPN or PNP transistors can be activated to cause a short across the motor terminals, which can be useful for slowing down the motor from the back EMF it creates.

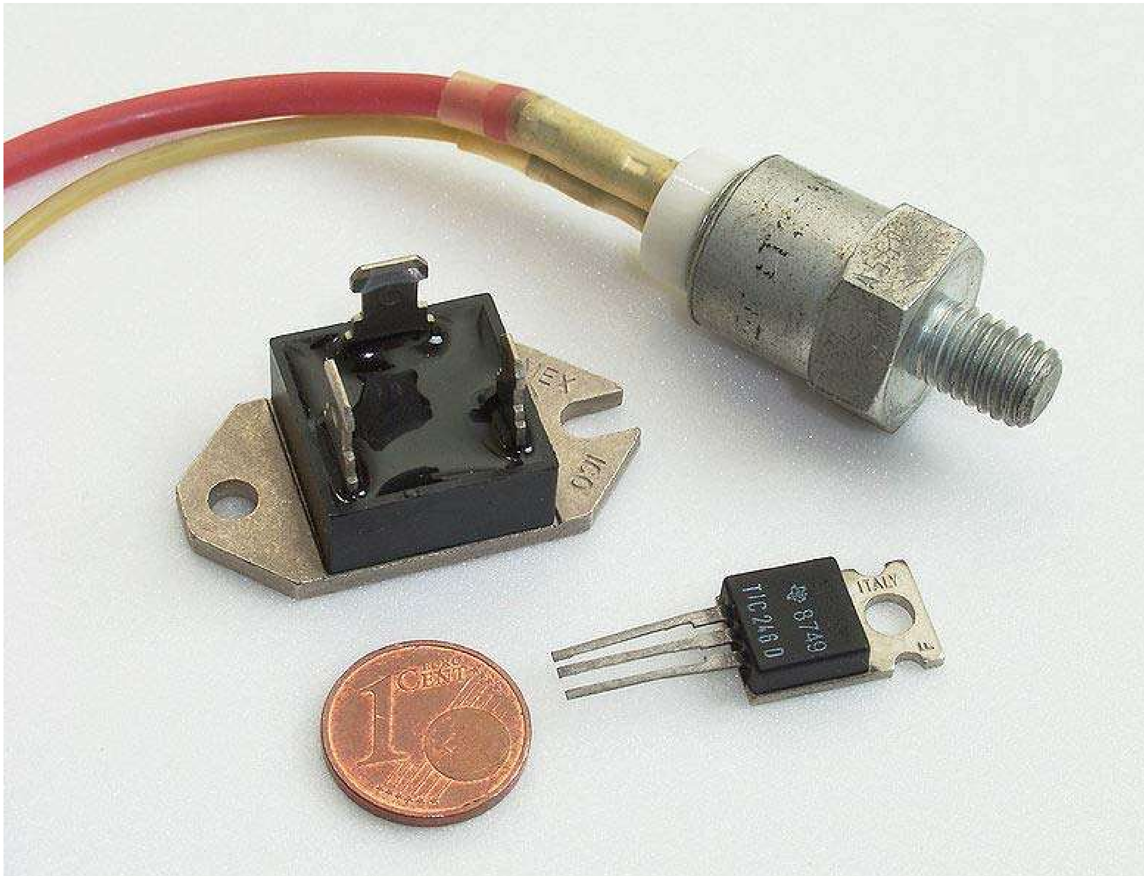
Chapter- 8

Examples & Applications of Power Electronics

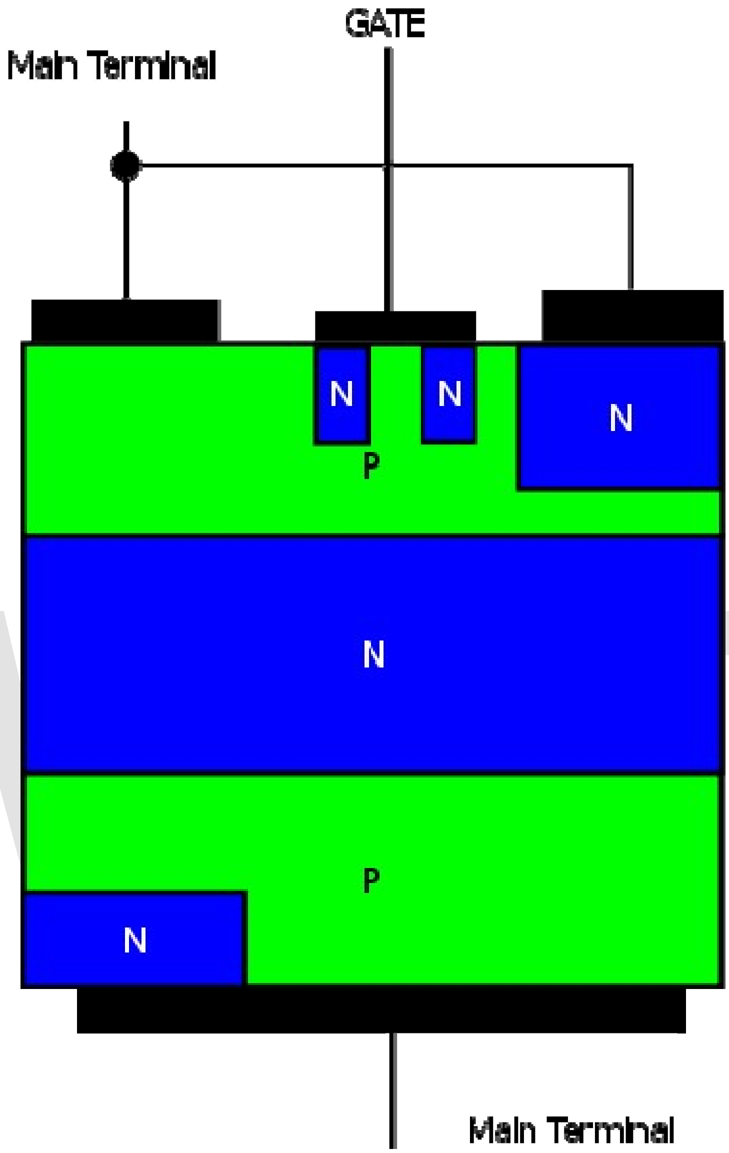
TRIAC



TRIAC schematic symbol



Some examples of TRIACs



TRIAC semiconductor construction

TRIAC, from **Triode for Alternating Current**, is a genericized tradename for an electronic component which can conduct current in either direction when it is triggered (turned on), and is formally called a **bidirectional triode thyristor** or **bilateral triode thyristor**.

A TRIAC is approximately equivalent to two complementary unilateral thyristors (one is anode triggered and another is cathode triggered SCR) joined in inverse parallel (paralleled but with the polarity reversed) and with their gates connected together. It can be triggered by either a positive or a negative voltage being applied to its *gate* electrode (with respect to A1, otherwise known as MT1). Once triggered, the device continues to conduct until the current through it drops below a certain threshold value, the holding current, such as at the end of a half-cycle of alternating current (AC) mains power. This makes the TRIAC a very convenient switch for AC circuits, allowing the control of very large power flows with milliampere-scale control currents. In addition, applying a trigger pulse at a controllable point in an AC cycle allows one to control the percentage of current that flows through the TRIAC to the load (phase control).

Application

Low power TRIACs are used in many applications such as light dimmers, speed controls for electric fans and other electric motors, and in the modern computerized control circuits of many household small and major appliances.

However, when used with inductive loads such as electric fans, care must be taken to assure that the TRIAC will turn off correctly at the end of each half-cycle of the AC power.

A snubber circuit (usually of the RC type) is often used between A1 and A2 to assist this turn-off. Snubber circuits are also used to prevent premature triggering, caused for example by voltage spikes in the mains supply. Also, a gate resistor or capacitor (or both in parallel) may be connected between gate and A1 to further prevent false triggering. That, however, increases the required trigger current and / or adds latency (capacitor charging).

For higher-powered, more-demanding loads, two SCRs in inverse parallel may be used instead of one TRIAC. Because each SCR will have an entire half-cycle of reverse polarity voltage applied to it, turn-off of the SCRs is assured, no matter what the character of the load. However, due to the separate gates, proper triggering of the SCRs is more complex than triggering a TRIAC.

In addition to commutation, a TRIAC may also not turn on reliably with non-resistive loads if the phase shift of the current prevents achieving holding current at trigger time. To overcome that, pulse trains may be used to repeatedly try to trigger the TRIAC until it finally turns on. The advantage is that the gate current does not need to be maintained throughout the entire conduction angle, which can be beneficial when there is only limited drive capability available.

Example data

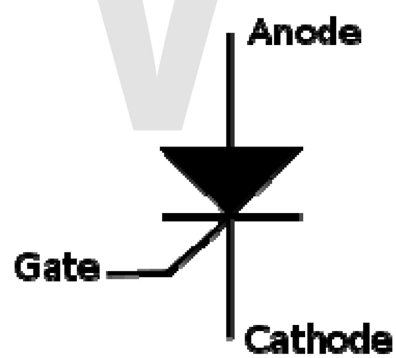
Variable name	Parameter	Typical value	Unit
V_{gt}	Gate threshold Voltage	1.5	V
I_{gt}	Gate threshold Current	10 - 50	mA
V_{drm}	Repetitive peak off-state Voltages	600 - 800	V
I_t	RMS on-state current Non-repetitive peak	4 - 40	A

Alternistor

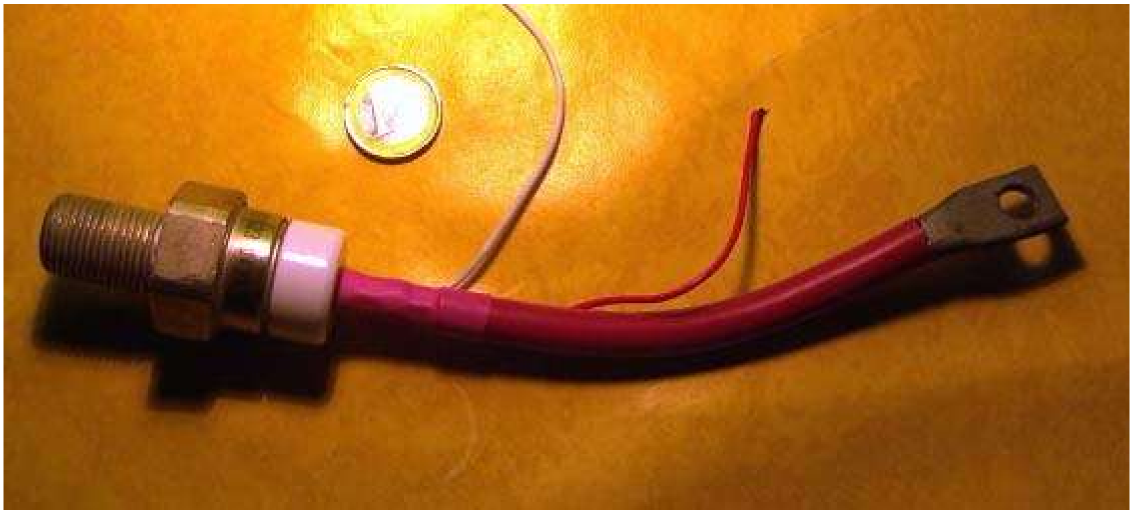
Alternistor is a trade name for a proprietary class of TRIAC with an improved turn-off (commutation) characteristic. The term "Alternistor" has been used for the first time by Thomson Semiconductors (now named ST Microelectronics).

These devices are made specifically for improved commutation when controlling a highly-inductive load, such as a motor, an application which causes problems for "normal" Triacs due to high voltage/current angles. Most Triacs' commutation with inductive loads can be improved by use of a "snubber network", but Alternistors are made specifically for this purpose and they dispose of the snubber requirement altogether. This improvement is achieved at the expense of the ability to trigger the device in the 4th quadrant (negative voltage and positive gate current). However, this is usually no problem, because this trigger mode is seldom used since even normal TRIACs are least sensitive there. ST Microelectronics has another version of improved commutation Triac, but they are not marketing them under the proprietary "Alternistor" moniker, but uses the trademark "SNUBBERLESS".

Silicon-controlled rectifier



SCR schematic symbol



A high power SCR

A **silicon-controlled rectifier** (or **semiconductor-controlled rectifier**) is a four-layer solid state device that controls current. The name "silicon controlled rectifier" or **SCR** is General Electric's trade name for a type of thyristor. The SCR was developed by a team of power engineers led by Gordon Hall and commercialized by Frank W. "Bill" Gutzwiller in 1957.

Construction of SCR

An SCR consists of four layers of alternating P and N type semiconductor materials. Silicon is used as the intrinsic semiconductor, to which the proper dopants are added. The junctions are either diffused or alloyed. The planar construction is used for low power SCRs (and all the junctions are diffused). The mesa type construction is used for high power SCRs. In this case, junction J2 is obtained by the diffusion method and then the outer two layers are alloyed to it, since the PNPN pellet is required to handle large currents. It is properly braced with tungsten or molybdenum plates to provide greater mechanical strength. One of these plates is hard soldered to a copper stud, which is threaded for attachment of heat sink. The doping of PNPN will depend on the application of SCR, since its characteristics are similar to those of the thyratron. Today, the term thyristor applies to the larger family of multilayer devices that exhibit bistable state-change behaviour, that is, switching either ON or OFF.

Modes of operation

In the normal "off" state, the device restricts current to the leakage current. When the gate-to-cathode voltage exceeds a certain threshold, the device turns "on" and conducts current. The device will remain in the "on" state even after gate current is removed so long as current through the device remains above the holding current. Once current falls below the holding current for an appropriate period of time, the device will switch "off".

If the gate is pulsed and the current through the device is below the holding current, the device will remain in the "off" state.

If the applied voltage increases rapidly enough, capacitive coupling may induce enough charge into the gate to trigger the device into the "on" state; this is referred to as "dv/dt triggering." This is usually prevented by limiting the rate of voltage rise across the device, perhaps by using a snubber. "dv/dt triggering" may not switch the SCR into full conduction rapidly and the partially-triggered SCR may dissipate more power than is usual, possibly harming the device.

SCRs can also be triggered by increasing the forward voltage beyond their rated breakdown voltage (also called as break over voltage), but again, this does not rapidly switch the entire device into conduction and so may be harmful so this mode of operation is also usually avoided. Also, the actual breakdown voltage may be substantially higher than the rated breakdown voltage, so the exact trigger point will vary from device to device. This device is generally used in switching applications.

Reverse Bias

SCR are available with or without reverse blocking capability. Reverse blocking capability adds to the forward voltage drop because of the need to have a long, low doped P1 region. Usually, the reverse blocking voltage rating and forward blocking voltage rating are the same. The typical application for reverse blocking SCR is in current source inverters.

SCR incapable of blocking reverse voltage are known as **asymmetrical SCR**, abbreviated **ASCR**. They typically have a reverse breakdown rating in the 10's of volts. ASCR are used where either a reverse conducting diode is applied in parallel (for example, in voltage source inverters) or where reverse voltage would never occur (for example, in switching power supplies or DC traction choppers).

Asymmetrical SCR can be fabricated with a reverse conducting diode in the same package. These are known as RCT, for reverse conducting thyristor.

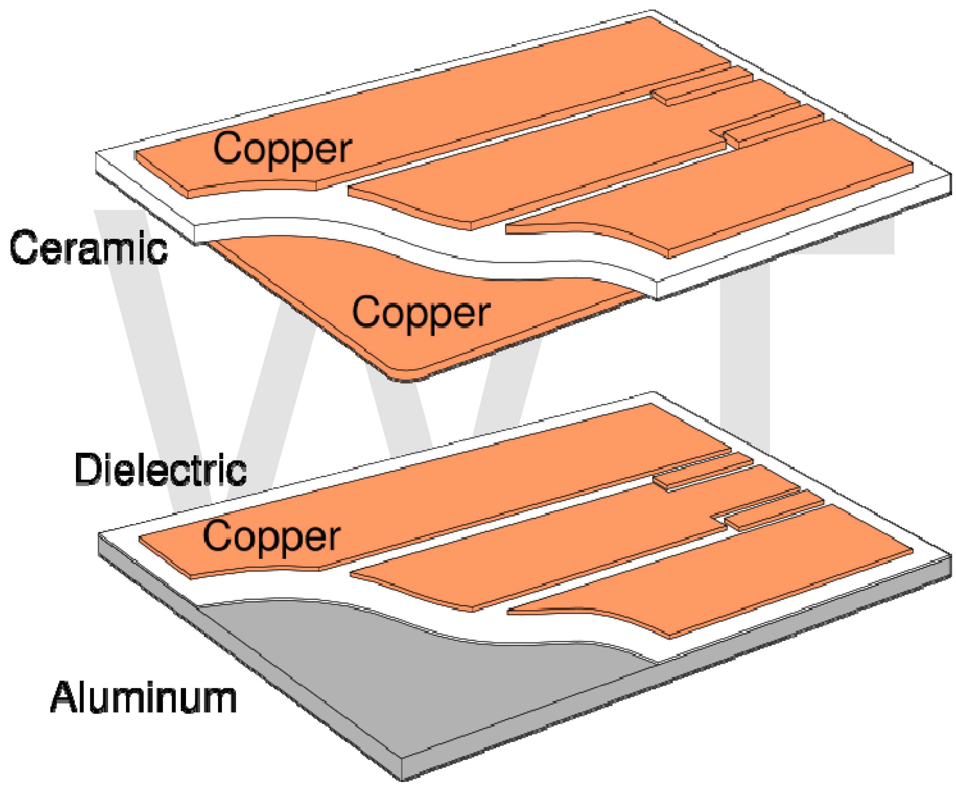
Application of SCRs

SCRs are mainly used in devices where the control of high power, possibly coupled with high voltage, is demanded. Their operation makes them suitable for use in medium to high-voltage AC power control applications, such as lamp dimming, regulators and motor control.

Power electronic substrate

The role of the **substrate in power electronics** is to provide the interconnections to form an electric circuit (like a printed circuit board), and to cool the components. Compared to materials and techniques used in lower power microelectronics, these substrates must carry higher currents and provide a higher voltage isolation (up to several thousand volts). They also must operate over a wide temperature range (up to 150 or 200°C).

Direct bonded copper substrate



Structure of a direct bonded copper substrate (top) and an insulated metal substrate (bottom).

Direct bonded copper (DBC) substrates are commonly used in power modules, because of their very good thermal conductivity. They are composed of a ceramic tile (commonly alumina) with a sheet of copper bonded to one or both sides by a high-temperature oxidation process (the copper and substrate are heated to a carefully controlled temperature in an atmosphere of nitrogen containing about 30 ppm of oxygen; under these conditions, a copper-oxygen eutectic forms which bonds successfully both to copper and the oxides used as substrates). The top copper layer can be preformed prior to firing or chemically etched using printed circuit board technology to form an electrical circuit, while the bottom copper layer is usually kept plain. The substrate is attached to a heat spreader by soldering the bottom copper layer to it.

Ceramic material used in DBC include:

- alumina (Al_2O_3), which is widely used because of its low cost. It is however not a really good thermal conductor (24-28 W/mK) and is brittle.
- aluminium nitride (AlN), which is more expensive, but has far better thermal performance (> 150 W/mK).
- beryllium oxide (BeO), which has good thermal performance, but is often avoided because of its toxicity when the powder is ingested or inhaled.

One of the main advantages of the DBC substrates is their low coefficient of thermal expansion, which is close to that of silicon (compared to pure copper). This ensures good thermal cycling performances (up to 50,000 cycles). The DBC substrates also have excellent electrical insulation and good heat spreading characteristics.

A related technique uses a seed layer, photoimaging, and then additional copper plating to allow for fine lines (as small as 50 micrometres) and through-vias to connect front and back sides. This can be combined with polymer-based circuits to create high density substrates that eliminate the need for direct connection of power devices to heat sinks.

Insulated metal substrate

Insulated metal substrate (IMS) consists of a metal baseplate (aluminium is commonly used because of its low cost and density) covered by a thin layer of dielectric (usually an epoxy-based layer) and a layer of copper (35 μm to more than 200 μm thick). The FR-4-based dielectric is usually thin (about 100 μm) because it has poor thermal conductivity compared to the ceramics used in DBC substrates.

Due to its structure, the IMS is a single-sided substrate, i.e it can only accommodate components on the copper side. In most applications, the baseplate is attached to a heatsink to provide cooling, usually using thermal grease and screws. Some IMS substrates are available with a copper baseplate for better thermal performances.

Compared to a classical printed circuit board, the IMS provides a better heat dissipation. It is one of the simplest way to provide efficient cooling to surface mount components.

Other substrates

- When the power devices are attached to a proper heatsink, there is no need for a thermally efficient substrate. Classical printed circuit board (PCB) material can be used (this method is typically used with through-hole technology components). This is also true for low-power applications (from some milliwatts to some watts), as the PCB can be thermally enhanced by using thermal vias or wide tracks to improve convection. An advantage of this method is that multilayer PCB allows design of complex circuits, whereas DBC and IMS are mostly single-sided technologies.

- Flexible substrates can be used for low-power applications. As they are built using Kapton as a dielectric, they can withstand high temperatures and high voltages. Their intrinsic flexibility makes them resistant to thermal cycling damage.

- Ceramic substrates (thick film technology) can also be used in some applications (such as automotive) where reliability is more important than good power dissipation.

PLECS

	PLECS
Developer(s)	Plexim
Initial release	2002
Operating system	Mac OS X, Windows, Linux
Platform	Simulink
Available in	English, Japanese
Type	Simulation software
License	Proprietary

PLECS (Piecewise Linear Electrical Circuit Simulation) is a Simulink toolbox for system-level simulations of electrical circuits developed by Plexim. It is especially designed for power electronics but can be used for any electrical network.

Integration with MATLAB/Simulink or Standalone

The program Simulink is ideally suited for the simulation of controls. Therefore, Simulink is also a convenient tool for the design of closed loop controlled electrical systems. PLECS enhances Simulink with the capability to simulate electrical circuits directly. The user can simply enter a circuit as a schematic of electrical components. At

Simulink block level the circuit is represented as a subsystem, so the user can build controls and other non-electrical elements around it and take full advantage of the Simulink environment and its toolboxes.

The concept of integration into Simulink has the advantage that only the part of the system in which electrical units are of interest needs to be modeled as an electrical circuit. The simulation of all non-electrical parts such as controls and mechanics should be done in Simulink.

MATLAB can be employed to compute circuit parameters and to post process and visualize the simulation results.

Standalone version

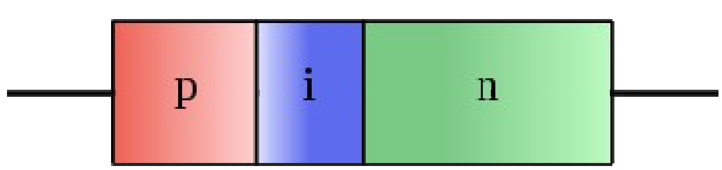
There is also a standalone version of PLECS that allows simulation of electrical circuits and control systems directly within the PLECS package.

Semiconductors modeled as ideal switches

Most circuit simulation programs model switches as highly nonlinear elements. Due to steep voltage and current transients, the simulation becomes slow when switches are toggled. In the most simple case a switch is modeled as a variable resistance that changes between a very small and a very large value. In other cases, it is represented by a sophisticated semiconductor model.

When simulating complex power electronic systems, however, the processes during switching are of little interest. Here, it is more appropriate to use ideal switches that toggle instantaneously between a closed and an open circuit. This approach, which is implemented in PLECS, has two major advantages: Firstly, it yields systems that are piecewise-linear across switching instants, (thus resolving the otherwise difficult problem of simulating the non-linear discontinuity that occurs in the equivalent-circuit at the switching instant). Secondly, to handle discontinuities at the switching instants, only two integration steps are required (one for before the instant, and one after). Both of these advantages speed up the simulation considerably.

PIN diode



Layers of a PIN diode

A **PIN diode** is a diode with a wide, lightly doped 'near' intrinsic semiconductor region between a p-type semiconductor and an n-type semiconductor region. The p-type and n-type regions are typically heavily doped because they are used for ohmic contacts.

The wide intrinsic region is in contrast to an ordinary PN diode. The wide intrinsic region makes the PIN diode an inferior rectifier (the normal function of a diode), but it makes the PIN diode suitable for attenuators, fast switches, photodetectors, and high voltage power electronics applications.

Operation

A PIN diode operates under what is known as high-level injection. In other words, the intrinsic "i" region is flooded with charge carriers from the "p" and "n" regions. Its function can be likened to filling up a water bucket with a hole on the side. Once the water reaches the hole's level it will begin to pour out. Similarly, the diode will conduct current once the flooded electrons and holes reach an equilibrium point, where the number of electrons is equal to the number of holes in the intrinsic region. When the diode is forward biased, the injected carrier concentration is typically several orders of magnitudes higher than the intrinsic level carrier concentration. Due to this high level injection, which in turn is due to the depletion process, the electric field extends deeply (almost the entire length) into the region. This electric field helps in speeding up of the transport of charge carriers from p to n region, which results in faster operation of the diode, making it a suitable device for high frequency operations.

Characteristics

A PIN diode obeys the standard diode equation for low frequency signals. At higher frequencies, the diode looks like an almost perfect (very linear, even for large signals) resistor. There is a lot of stored charge in the intrinsic region. At low frequencies, the charge can be removed and the diode turns off. At higher frequencies, there is not enough time to remove the charge, so the diode never turns off. The PIN diode has a poor reverse recovery time.

The high-frequency resistance is inversely proportional to the DC bias current through the diode. A PIN diode, suitably biased, therefore acts as a variable resistor. This high-frequency resistance may vary over a wide range (from 0.1 ohm to 10 kΩ in some cases; the useful range is smaller, though).

The wide intrinsic region also means the diode will have a low capacitance when reverse biased.

In a PIN diode, the depletion region exists almost completely within the intrinsic region. This depletion region is much larger than in a PN diode, and almost constant-size, independent of the reverse bias applied to the diode. This increases the volume where electron-hole pairs can be generated by an incident photon. Some photodetector devices, such as PIN photodiodes and phototransistors (in which the base-collector junction is a PIN diode), use a PIN junction in their construction.

The diode design has some design tradeoffs. Increasing the dimensions of the intrinsic region (and its stored charge) allows the diode to look like a resistor at lower frequencies. It adversely affects the time needed to turn off the diode and its shunt capacitance. PIN diodes will be tailored for a particular use.

Applications

PIN diodes are useful as RF switches, attenuators, and photodetectors.

RF and Microwave Switches

A PIN Diode RF Microwave Switch.

Under zero or reverse bias, a PIN diode has a low capacitance. The low capacitance will not pass much of an RF signal. Under a forward bias of 1 mA, a typical PIN diode will have an RF resistance of about 1 ohm, making it a good RF conductor. Consequently, the PIN diode makes a good RF switch.

Although RF relays can be used as switches, they switch very slowly (on the order of 10 milliseconds). A PIN diode switch can switch much more quickly (e.g., 1 microsecond).

The capacitance of an off discrete PIN diode might be 1pF. At 320MHz, the reactance of 1pF is about 500 ohms. In a 50 ohm system, the off state attenuation would be about 20dB -- which may not be enough attenuation. In applications that need higher isolation, switches are cascaded to improve the isolation. Cascading three of the above switches would give 60dB of attenuation.

PIN diode switches are used not only for signal selection, but they are also used for component selection. For example, some low phase noise oscillators use PIN diodes to range switch inductors.

RF and Microwave Variable Attenuators

A RF Microwave PIN diode Attenuator. Picture courtesy of Herley

By changing the bias current through a PIN diode, it's possible to quickly change the RF resistance.

At high frequencies, the PIN diode appears as a resistor whose resistance is an inverse function of its forward current. Consequently, PIN diode can be used in some variable attenuator designs as amplitude modulators or output leveling circuits.

PIN diodes might be used, for example, as the bridge and shunt resistors in a bridged-T attenuator.

Limiters

PIN diodes are sometimes used as input protection devices for high frequency test probes. If the input signal is within range, the PIN diode has little impact as a small capacitance.

If the signal is large, then the PIN diode starts to conduct and becomes a resistor that shunts most of the signal to ground.

Photodetector and photovoltaic cell

The PIN photodiode was invented by Jun-ichi Nishizawa and his colleagues in 1950.

PIN photodiodes are used in fibre optic network cards and switches. As a photodetector, the PIN diode is reverse biased. Under reverse bias, the diode ordinarily does not conduct (save a small dark current or I_s leakage). A photon entering the intrinsic region frees a carrier. The reverse bias field sweeps the carrier out of the region and creates a current. Some detectors can use avalanche multiplication.

The PIN photovoltaic cell works in the same mechanism. In this case, the advantage of using a PIN structure over conventional semiconductor junction is the better long wavelength response of the former. In case of long wavelength irradiation, photons penetrate deep into the cell. But only those electron-hole pairs generated in and near the depletion region contribute to current generation. The depletion region of a PIN structure extends across the intrinsic region, deep into the device. This wider depletion width enables electron-hole pair generation deep within the device. This increases the quantum efficiency of the cell.

Typically, amorphous silicon thin-film cells use PIN structures. On the other hand, CdTe cells use NIP structure, a variation of the PIN structure. In a NIP structure, an intrinsic CdTe layer is sandwiched by n-doped CdS and p-doped ZnTe. The photons are incident on the n-doped layer unlike a PIN diode.

Example Diodes

SFH203 or BPW43 are cheap general purpose PIN diodes in 5 mm clear plastic case with bandwidth over 100 MHz. They are used in RONJA telecommunication systems and other circuitry applications.

Motor soft starter

A **motor soft starter** is a device used with AC electric motors to temporarily reduce the load and torque in the powertrain of the motor during startup. This reduces the mechanical stress on the motor and shaft, as well as the electrodynamic stresses on the attached power cables and electrical distribution network, extending the lifespan of the system.

Motor soft starters can consist of mechanical or electrical devices, or a combination of both. Mechanical soft starters include clutches and several types of couplings using a fluid, magnetic forces, or steel shot to transmit torque, similar to other forms of torque limiter. Electrical soft starters can be any control system that reduces the torque by temporarily reducing the voltage or current input, or a device that temporarily alters how the motor is connected in the electric circuit.

Electrical soft starters can utilize solid state devices to control the current flow and therefore the voltage applied to the motor. They can be connected in series with the line voltage applied to the motor, or can be connected inside the delta (Δ) loop of a delta-connected motor, controlling the voltage applied to each winding. Solid state soft starters can control one or more phases of the voltage applied to the induction motor with the best results achieved by three-phase control. Typically, the voltage is controlled by reverse-parallel-connected silicon-controlled rectifiers (thyristors), but in some circumstances with three-phase control, the control elements can be a reverse-parallel-connected SCR and diode.

Another traditional and the most reliable way to soft start the motor with reduced current is with the help of series reactor. This method is called as series reactor soft starter, which refers to the IEC standard 60289. If an air core is used for designing the series reactor then a very efficient and reliable soft starter can be designed which is suitable for all type of 3 phase induction motor [synchronous / asynchronous] ranging from 25 KW 415 V to 30 MW 11 KV. Using an air core series reactor soft starter is very common practice for applications like pump, compressor, fan etc. Usually high starting torque applications do not use this technology for the starting device. A very famous type of such starters are Harmonics free (due to air core) series reactor soft starter.

Mechanical rectifier

A **mechanical rectifier** is a device for converting alternating current (AC) to direct current (DC) by means of mechanically-operated switches. The best-known type is the commutator, which is an integral part of a DC dynamo but, before solid-state devices became available, independent mechanical rectifiers were used for certain applications. Before the invention of semiconductors, rectification at high currents involved serious losses.

There were various vacuum/gas devices, such as the mercury arc rectifiers, thyratrons, ignitrons, and vacuum diodes. Solid-state technology was in its infancy, represented by copper oxide and selenium rectifiers. All of these gave excessive forward voltage-drop at high currents. One answer was mechanically opening and closing contacts, if this could be done fast and cleanly enough.

Vibrator type

This was the reverse of a vibrator inverter. An electromagnet, fed with AC, caused a spring to vibrate and the spring operated change-over contacts which converted the AC to DC. This arrangement was only suitable for low-power applications, e.g. radios and was also found in some motorcycle electrical systems, where it was combined with a voltage regulator.

Motor-driven type

This operated on the same principle as the vibrator type but the change-over contacts were operated by a synchronous motor. It was suitable for high-power applications, e.g. electrolysis cells and electrostatic precipitators.

BTH rectifier

The machine shown in the reference was designed by Read and Gimson et al., at British Thomson-Houston (BTH) Rugby, Warwickshire, England, in the early 1950s. It is a three-phase mechanical rectifier working at 220 volts and 15,000 amperes, and its application was the powering of huge banks of electrolysis cells.

The central shaft was rotated by synchronous motor, driving an eccentric with a throw of about 2mm. (0.077 inch) Push-rods from this operated the contacts. The timing was critical, and was adjusted by rotating the position of the eccentric on its shaft, and by sliding wedges between the eccentric and push-rods.

Crucial to this system were the *commutating reactors*, inductors that ensured the contacts closed when the voltage across them was small, and opened when the current was small. Without these, contact wear would have been intolerably heavy.

This machinery was undoubtedly successful; its efficiency was determined to be 97.25%. Contact life was never fully determined but considerably exceeded 2000 hours. However, the rapid development of the silicon diode made it ultimately redundant.

Magnetic amplifier

The **magnetic amplifier** (colloquially known as a "mag amp") is an electromagnetic device for amplifying electrical signals. The magnetic amplifier was invented early in the 20th century, and was used as an alternative to vacuum tube amplifiers where robustness and high current capacity were required. World War II Germany perfected this type of amplifier, and it was used for instance in the V-2 rocket. The magnetic amplifier was most prominent in power control and low-frequency signal applications from 1947 to about 1957, when the transistor began to supplant it. The magnetic amplifier has now been largely superseded by the transistor-based amplifier, except in a few safety critical, high reliability or extremely demanding applications. Combinations of transistor and mag-amp techniques are still used.

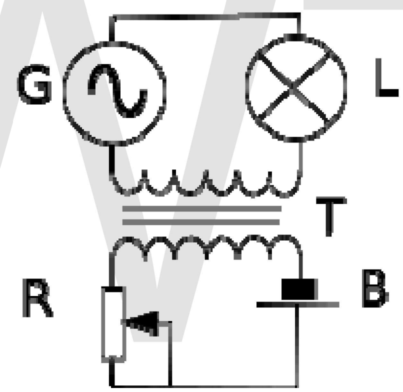
Strengths

The magnetic amplifier is a static device with no moving parts. It has no wear-out mechanism and has a good tolerance to mechanical shock and vibration. It requires no warm-up time. Multiple isolated signals may be summed by additional control windings on the magnetic cores. The windings of a magnetic amplifier have a higher tolerance to momentary overloads than comparable solid-state devices. The magnetic amplifier is also used as a transducer in applications such as current measurement and the flux gate compass

Limitations

The gain available from a single stage is limited and low compared to electronic amplifiers. Frequency response of a high gain amplifier is limited to about one-tenth the excitation frequency, although this is often mitigated by exciting magnetic amplifiers with currents at higher than utility frequency. Solid-state amplifiers can be more compact and efficient than magnetic amplifiers. The bias and feedback windings are not unilateral, and may couple energy back from the controlled circuit into the control circuit. This complicates the design of multistage amplifiers when compared with electronic devices.

Principle of operation



A saturable reactor, illustrating the principle of a magnetic amplifier

Visually a mag amp device may resemble a transformer but the operating principle is quite different from a transformer - essentially the mag amp is a saturable reactor. It makes use of magnetic saturation of the core, a non-linear property of a certain class of transformer cores. For controlled saturation characteristics the magnetic amplifier employs core materials that have been designed to have a specific B-H curve shape that is highly rectangular, in contrast to the slowly-tapering B-H curve of softly saturating core materials that are often used in normal transformers.

The typical magnetic amplifier consists of two physically separate but similar transformer magnetic cores, each of which has two windings - a control winding and an AC winding. A small DC current from a low impedance source is fed into the series-connected control windings. The AC windings may be connected either in series or in parallel, the configurations resulting in different types of mag amps. The amount of control current fed into the control winding sets the point in the AC winding waveform at which either core will saturate. In saturation, the AC winding on the saturated core will go from a high impedance state ("off") into a very low impedance state ("on") - that is, the control current controls at which voltage the mag amp switches "on".

A relatively small DC current on the control winding is able to control or switch large AC currents on the AC windings. This results in current amplification.

Applications

Magnetic amplifiers were important as modulation and control amplifiers in the early development of voice transmission by radio. A magnetic amplifier was used as voice modulator for a 2 kilowatt Alexanderson alternator, and magnetic amplifiers were used in the keying circuits of large high-frequency alternators used for radio communications. Magnetic amplifiers were also used to regulate the speed of Alexanderson alternators to maintain the accuracy of the transmitted radio frequency.

The ability to control large currents with small control power made magnetic amplifiers useful for control of lighting circuits, for stage lighting and for advertising signs. Saturable reactor amplifiers were used for control of power to industrial furnaces. Small magnetic amplifiers were used for radio tuning indicators, control of small motor and cooling fan speed, control of battery chargers.

Magnetic amplifiers were used extensively as the switching element in early switched-mode (SMPS) power supplies, as well as in lighting control. Semiconductor based solid-state switches have largely superseded them, though recently there has been some regained interest in using mag amps in compact and reliable switching power supplies. PC ATX power supplies often use mag amps for secondary side voltage regulation.

Magnetic amplifiers are still used in some arc welders.

Magnetic amplifier transformer cores designed specifically for switch mode power supplies are currently manufactured by several large electromagnetics companies, including Metglas and Mag-Inc.

Magnetic amplifiers can be used for measuring high DC-voltages without direct connection to the high voltage and are therefore still used in the HVDC-technique.

Magnetic amplifiers were used by locomotives to detect wheel slip, until replaced by Hall Effect current transducers. The cables from two traction motors passed through the core of the device. During normal operation the resultant flux was zero as both currents were the same and in opposite directions. However, the currents would differ during wheel slip, producing a resultant flux that acted as the Control winding, developing a voltage across a resistor in series with the AC winding which was sent to the wheel slip correction circuits.

History

Early development

A voltage source and a series connected variable resistor may be regarded as a direct current signal source for a low resistance load such as the control coil of a saturable reactor which amplifies the signal. Thus, in principle, a saturable reactor is already an amplifier, although before 20th century they were used for simple tasks, such as controlling lighting and electrical machinery as early as 1885.

In the early 20th Century, the General Electric Company, under the direction of engineer E. F. W. Alexanderson, developed a system of transoceanic radio communications, using continuous wave transmission over great distances. Alexanderson drew upon the work of Nikola Tesla and Reginald Fessenden as the inspiration for his system.

The result of this work was the 2 kW Alexanderson alternator, which produced radio frequencies from 50 to 100 kHz and which critics had previously denounced as impractical. Later, Guglielmo Marconi took a vested interest in the project and, in 1915, witnessed a demonstration of a new, 50 kW, 50 kHz alternator.

The experimental telegraphy and telephony demonstrations made during 1917 attracted the attention of the US Government, especially in light of partial failures in the transoceanic cable that snaked across the bottom of the Atlantic Ocean. The 50 kW alternator was commandeered by the US Navy and put into service in January 1918 and was used until 1920, when a 200 kW generator-alternator set was built and installed.

Usage in radio

Magnetic amplifiers were used early on to control large, high-power alternators by turning them on and off for telegraphy or to vary the signal for voice modulation. However, the alternator's frequency limits were rather low to where a frequency multiplier had to be utilized to generate higher radio frequencies than the alternator was capable of producing. Even so, early magnetic amplifiers incorporating powdered-iron cores were incapable of producing radio frequencies above approximately 200 kHz. Other core materials, such as ferrite cores and oil-filled transformers, would have to be developed to allow the amplifier to produce higher frequencies.

Usage in aircraft

Magnetic amplifiers were used in aircraft systems (avionics) before the advent of high reliability semiconductors. They were important in implementing early autoland systems and Concorde made use of the technology for the control of its engine air intakes before subsequent development of a replacement system using digital electronics.

Usage in computing

Magnetic amplifiers were widely studied during the 1950s as a potential switching element for mainframe computers. Mag amps could be used to sum several inputs in a single core, which was very useful in the arithmetic logic unit (ALU). Custom tubes could do the same, but transistors could not, so the mag amp was able to combine the advantages of tubes and transistors in an era when the latter were expensive and unreliable.

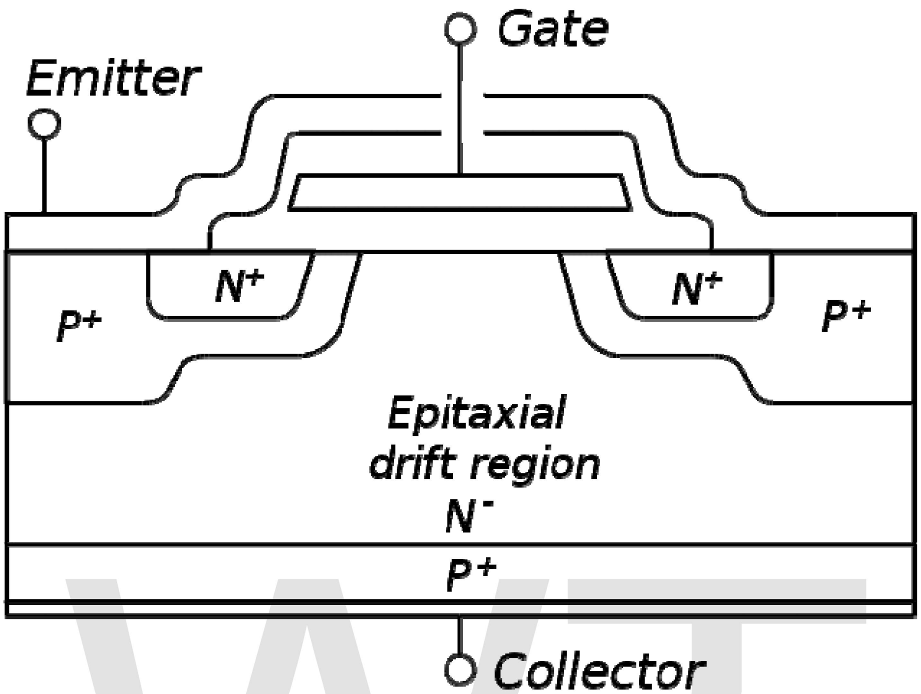
However, that era was very short, lasting from the mid 1950s to about 1960, at which point new fabrication techniques were producing great improvements in transistors and dramatically lowering their price points. Only one large-scale mag amp machine was put into production, the UNIVAC Solid State, but a number of contemporary late-1950's/early-1960s computers made some use of the technology, like the Ferranti Orion.

Misnomer uses

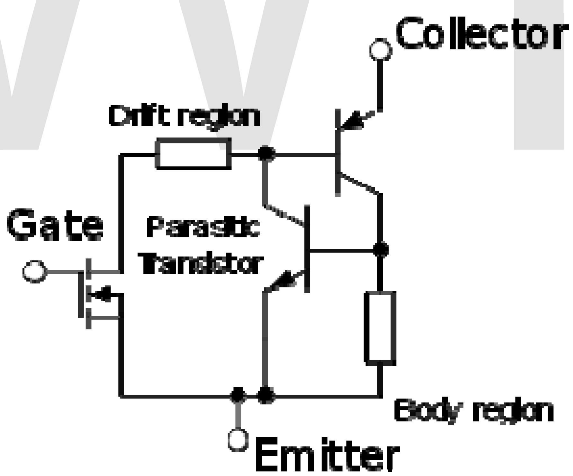
In the 1970s, Robert Carver designed and produced several high quality high-powered audio amplifiers, calling them magnetic amplifiers. In fact, they were in most respects conventional audio amplifier designs with an unusual power supply circuit. They were not magnetic amplifiers as defined here.

Insulated-gate bipolar transistor

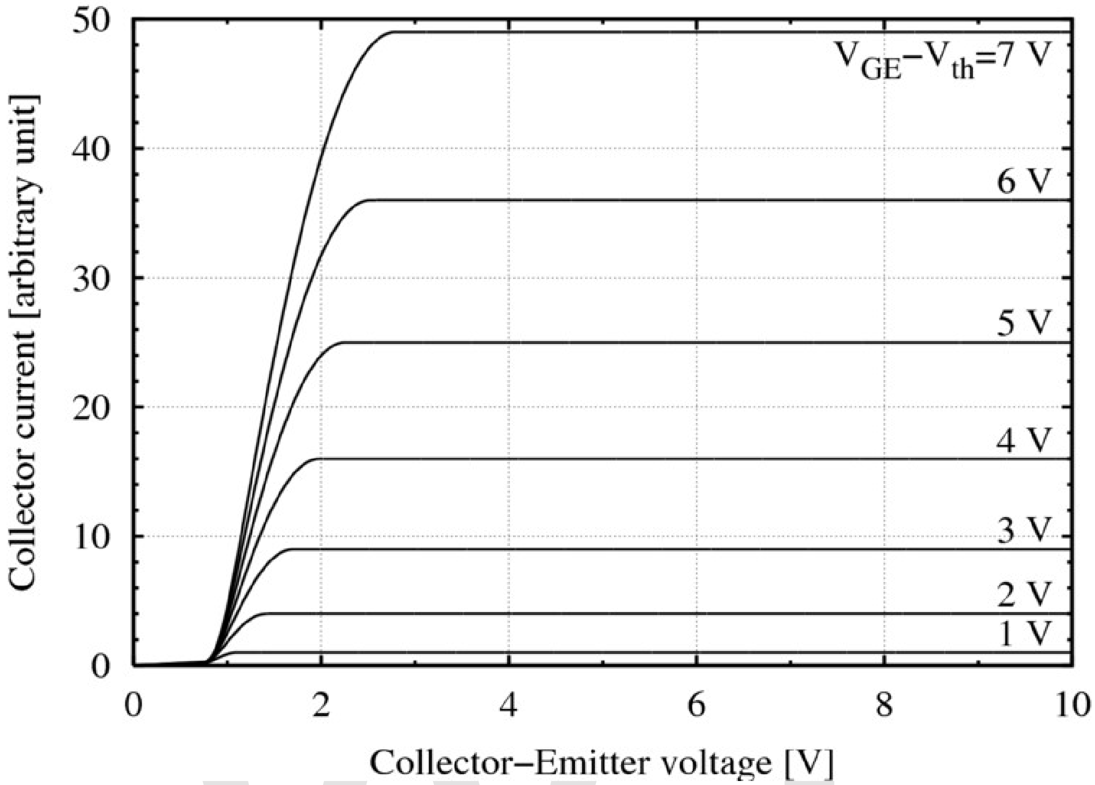
Electronic symbol for IGBT



Cross section of a typical IGBT cell. The illustration is not to scale.



Equivalent circuit for IGBT



Static characteristic of an IGBT.

The **insulated gate bipolar transistor** or **IGBT** is a three-terminal power semiconductor device, noted for high efficiency and fast switching. It switches electric power in many modern appliances: electric cars, trains, variable speed refrigerators, air-conditioners and even stereo systems with switching amplifiers. Since it is designed to rapidly turn on and off, amplifiers that use it often synthesize complex waveforms with pulse width modulation and low-pass filters.

The IGBT combines the simple gate-drive characteristics of the MOSFETs with the high-current and low–saturation-voltage capability of bipolar transistors by combining an isolated gate FET for the control input, and a bipolar power transistor as a switch, in a single device. The IGBT is used in medium- to high-power applications such as switched-mode power supply, traction motor control and induction heating. Large IGBT modules typically consist of many devices in parallel and can have very high current handling capabilities in the order of hundreds of amperes with blocking voltages of 6000 V.

The IGBT is a fairly recent invention. The first-generation devices of the 1980s and early 1990s were relatively slow in switching, and prone to failure through such modes as latchup and secondary breakdown. Second-generation devices were much improved, and the current third-generation ones are even better, with speed rivaling MOSFETs, and excellent ruggedness and tolerance of overloads.

The extremely high pulse ratings of second- and third-generation devices also make them useful for generating large power pulses in areas like particle and plasma physics, where they are starting to supersede older devices like thyratrons and triggered spark gaps.

Their high pulse ratings, and low prices on the surplus market, also make them attractive to the high-voltage hobbyist for controlling large amounts of power to drive devices such as solid-state Tesla coils and coilguns.

Availability of affordable, reliable IGBTs is a key enabler for electric vehicles and hybrid cars. Toyota's second generation hybrid Prius has a 50 kW IGBT inverter controlling two AC motor/generators connected to the DC battery pack.

History

The IGBT is a semiconductor device with four alternating layers (P-N-P-N) that are controlled by a metal-oxide-semiconductor (MOS) gate structure without regenerative action. This mode of operation was first proposed by Yamagami in his Japanese patent S47-21739, which was filed in 1968. This mode of operation was first experimentally discovered by B. Jayant Baliga in vertical device structures with a V-groove gate region and reported in the literature in 1979. The device structure was referred to as a 'V-groove MOSFET device with the drain region replaced by a p-type Anode Region' in this paper and subsequently as the insulated gate rectifier (IGR), the insulated-gate transistor (IGT), the conductivity-modulated field-effect transistor (COMFET) and "bipolar-mode MOSFET".

Plummer found the same IGBT mode of operation in the four layer device (SCR) and he first filed a patent application for the device structure in 1978. USP No.4199774 was issued in 1980 and B1 Re33209 was reissued in 1995 for the IGBT mode operation in the four layer device (SCR).

Hans W. Becke and Carl F. Wheatley invented a similar device for which they filed a patent application in 1980, and which they referred to as "power MOSFET with an anode region". This patent has been called "the seminal patent of the Insulated Gate Bipolar Transistor." The patent claimed "no thyristor action occurs under any device operating conditions." This substantially means that the device exhibits non-latch-up IGBT operation over the entire device operation range.

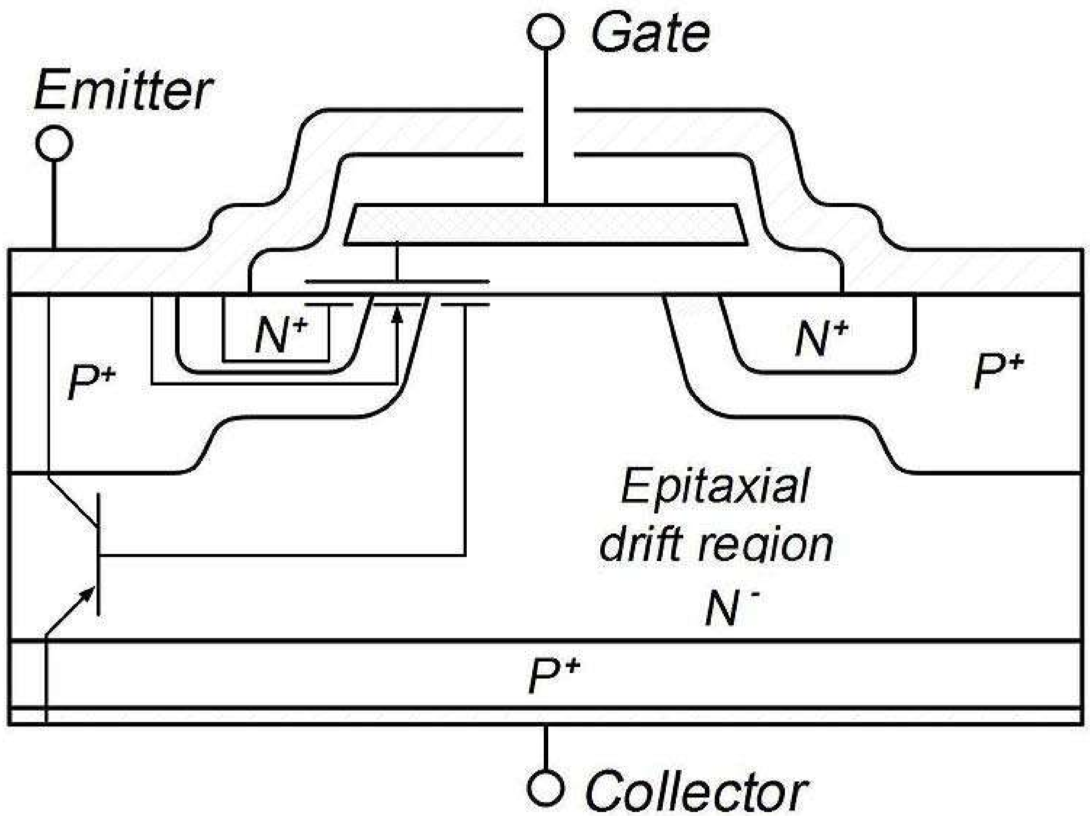
Devices capable of operating over an extended current range for use in applications were first reported by Baliga *et al.* in 1982. A similar paper was also submitted by J.P. Russel et al. to IEEE Electron Device Letter in 1982. The applications for the device were initially regarded by the power electronics community to be severely restricted by its slow switching speed and latch-up of the parasitic thyristor structure inherent within the device. However, it was demonstrated by Baliga and also by A.M. Goodman et al. in 1983 that the switching speed could be adjusted over a broad range by using electron irradiation. This was followed by demonstration of operation of the device at elevated temperatures by Baliga in 1985. Successful efforts to suppress the latch-up of the parasitic thyristor and the scaling of the voltage rating of the devices at GE allowed the introduction of commercial devices in 1983, which could be utilized for a wide variety of applications.

Complete suppression of the parasitic thyristor action and the resultant non-latch-up IGBT operation for the entire device operation range was achieved by A. Nakagawa et al. in 1984. The non-latch-up design concept was filed for US patents. To test the lack of latchup, the prototype 1200V IGBTs were directly connected without any loads across a 600V constant voltage source and were switched on for 25 microseconds. The entire 600V was dropped across the device and a large short circuit current flowed. The devices successfully withstood this severe condition. This was the first demonstration of so-called "short-circuit-withstanding-capability" in IGBTs. Non-latch-up IGBT operation was ensured, for the first time, for the entire device operation range. In this sense, the non-latch-up IGBT proposed by Hans W. Becke and Carl F. Wheatley was realized by A. Nakagawa et al. in 1984. Products of non-latch-up IGBTs were first commercialized by Toshiba in 1985.

Once the non-latch-up capability was achieved in IGBTs, it was found that IGBTs exhibited very rugged and a very large safe operating area. It was demonstrated that the product of the operating current density and the collector voltage exceeded the theoretical limit of bipolar transistors, $2x10^5 W/cm^2$, and reached $5x10^5 W/cm^2$.

Device structure

An IGBT cell is constructed similarly to a n-channel vertical construction power MOSFET except the n+ drain is replaced with a p+ collector layer, thus forming a vertical PNP bipolar junction transistor.



Cross section of a typical IGBT showing internal connection of MOSFET and Bipolar Device

This additional p+ region creates a cascade connection of a PNP bipolar junction transistor with the surface n-channel MOSFET. This connection results in a significantly lower forward voltage drop compared to a conventional MOSFET in higher blocking voltage rated devices. As the blocking voltage rating of both MOSFET and IGBT devices increases, the depth of the n- drift region must increase and the doping must decrease, resulting in roughly square relationship increase in forward conduction loss compared to blocking voltage capability of the device. By injecting minority carriers (holes) from the collector p+ region into the n- drift region during forward conduction, the resistance of the n- drift region is considerably reduced. However, this resultant reduction in on-state forward voltage comes with several penalties:

- The additional PN junction blocks reverse current flow. This means that unlike a MOSFET, IGBTs cannot conduct in the reverse direction. In bridge circuits where reverse current flow is needed an additional diode (called a freewheeling diode) is placed in parallel with the IGBT to conduct current in the opposite direction. The penalty isn't as severe as first assumed though, because at the higher voltages where IGBT usage dominates, discrete diodes are of significantly higher performance than the body diode of a MOSFET.

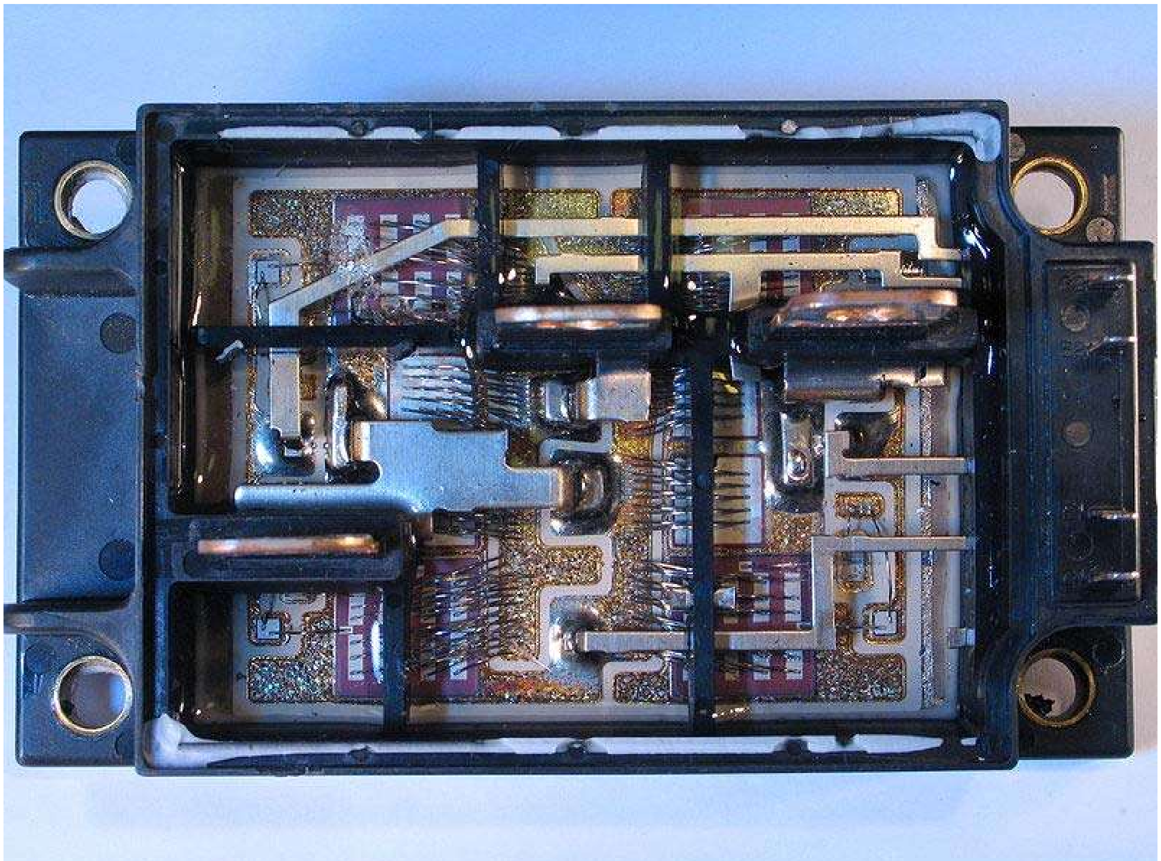
- The reverse bias rating of the N- drift region to collector P+ diode is usually only of tens of volts, so if the circuit application applies a reverse voltage to the IGBT, an additional series diode must be used.
- The minority carriers injected into the n- drift region take time to enter and exit or recombine at turn on and turn off. This results in longer switching time and hence higher switching loss compared to a power MOSFET.
- The device turns off slowly due to long recombination times, which makes it unsuitable for hard turn-off applications (such as boost or flyback power converters.
- The additional PN junction adds a diode-like voltage drop to the device. At lower blocking voltage ratings, this additional drop means that an IGBT would have a higher on-state voltage drop. As the voltage rating of the device increases, the advantage of the reduced N- drift region resistance overcomes the penalty of this diode drop and the overall on-state voltage drop is lower (the crossover is around 400 V blocking rating). Thus IGBTs are rarely used where the blocking voltage requirement is below 600 V.

IGBT models

Rather than using a device physics-based model, SPICE simulates IGBTs using Macromodels, a method that combines an ensemble of components such as FETs and BJTs in a Darlington configuration. An alternative physics-based model is the Hefner model, introduced by Allen Hefner of the NIST. It is a fairly complex model that has shown very good results. Hefner's model is described in a 1988 paper and was later extended to a thermo-electrical model and a version using SABER.

Usage

IGBT-Module (IGBTs and free wheeling diodes) with a rated current of 1,200 A and a maximum voltage of 3,300 V



Opened IGBT module with four IGBTs (half H-bridge) each rated for 400 A 600 V

Small IGBT module, rated up to 30 A, up to 900 V

Electronic speed control

An **electronic speed control** or **ESC** is an electronic circuit with the purpose to vary an electric motor's speed, its direction and possibly also to act as a dynamic brake. ESCs are often used on electrically-powered radio controlled models.

An ESC can be a stand-alone unit which plugs into the receiver's throttle control channel or incorporated into the receiver itself, as is the case in most toy-grade R/C vehicles. Some R/C manufacturers that install proprietary hobby-grade electronics in their entry-level vehicles, vessels or aircraft use onboard electronics that combine the two on a single circuit board.

Function

Regardless of the type used, an ESC interprets control information not as mechanical motion as would be the case of a servo, but rather in a way that varies the switching rate of a network of field effect transistors, or "FET's." The rapid switching of the transistors is what causes the motor itself to emit its characteristic high-pitched whine, especially noticeable at lower speeds. It also allows much smoother and more precise variation of motor speed in a far more efficient manner than the mechanical type with a resistive coil and moving arm once in common use.

Most modern ESCs incorporate a battery eliminator circuit (or BEC) to regulate voltage for the receiver, removing the need for receiver batteries. BECs are usually either linear or switched mode voltage regulators.

DC ESCs in the broader sense are PWM controllers for electric motors. The ESC generally accepts a nominal 50 Hz PWM servo input signal whose pulse width varies from 1 ms to 2 ms. When supplied with a 1 ms width pulse at 50 Hz, the ESC responds by turning off the DC motor attached to its output. A 1.5 ms pulse-width input signal results in a 50% duty cycle output signal that drives the motor at approximately half-speed. When presented with 2.0 ms input signal, the motor runs at full speed due to the 100% duty cycle (on constantly) output.

Brushless ESC

Brushless motors otherwise called outrunners or inrunners have become very popular with radio controlled airplane hobbyists because of their efficiency, power, longevity and light weight in comparison to traditional brushed motors. However, brushless DC motor controllers are much more complicated than brushed motor controllers. They have to convert the DC from the battery into phased AC (usually three phase) in order to produce the changing magnetic field.

The correct phase varies with the motor rotation, which is to be taken into account by the ESC: Usually, back EMF from the motor is used to detect this rotation, but variations exist that use magnetic (Hall Effect) or optical detectors. Computer-programmable speed controls generally have user-specified options which allows setting low voltage cut-off limits, timing, acceleration, braking and direction of rotation. Reversing the motor's direction may also be accomplished by switching any two of the three leads from the ESC to the motor.

Classification

ESCs are normally rated according to maximum current, for example, 25 amperes or 25 A. Generally the higher the rating, the larger and heavier the ESC tends to be which is a factor when calculating mass and balance in airplanes. Many modern ESCs support nickel metal hydride and lithium ion polymer batteries with a range of input and cut-off voltages. The type of battery and number of cells connected is an important consideration when choosing a Battery eliminator circuit (BEC), whether built into the controller or as a stand-alone unit. A higher number of cells connected will result in a reduced power rating and therefore a lower number of servos supported by an integrated BEC.

Applications

Cars

ESCs designed for sport use in cars generally have reversing capability; newer sport controls can have the reversing ability overridden so that it can be used in a race. Controls designed specifically for racing and even some sport controls have the added advantage of dynamic braking capability. Simply put, the ESC forces the motor to act as a generator by placing an electrical load across the armature. This in turn makes the armature harder to turn, thus slowing or stopping the model. Some controllers add the benefit of regenerative braking. This puts the voltage being generated by the motor back to work recharging the vehicle's drive batteries. On full-sized vehicles, regenerative braking is used in electric and hybrid golf cars and hybrid automobiles while dynamic braking is used in diesel-electric locomotives to help slow trains on long downgrades.

Electric Bicycles

A motor used in an electric bicycle application requires high initial torque and therefore uses Hall sensor commutation for speed measurement. Electric bicycle controllers generally use brake application sensors, pedal rotation sensors and provide potentiometer-adjustable motor speed, closed-loop speed control for precise speed regulation, protection logic for over-voltage, over-current and thermal protection. Sometimes pedal torque sensors are used to enable motor assist proportional to applied torque and sometimes support is provided for regenerative braking but infrequent braking and the low mass of bicycles limits recovered energy. An implementation is described in an application note for a 200 W, 24 V Brushless DC (BLDC) motor.

Helicopters

ESCs designed for radio-control helicopters do not require a braking feature (indeed, turning it on would likely result in the main rotor assembly being severely damaged by the rotor blades) nor do they require reverse direction. Many high-end helicopter ESCs do provide a "Governor mode" which fixes the motor RPM to a set speed, greatly aiding CCPM-based flight.

Airplanes

ESCs designed for radio-control airplanes usually contain a few safety features. If the power coming from the battery is insufficient to continue running the electric motor the ESC will reduce or cut off power to the motor while allowing continued use of ailerons, rudder and elevator function. This allows the pilot to retain control of the plane to glide or fly on low power to safety.

Boats

ESCs designed for boats are by necessity waterproof. Also, many are water-cooled. Like cars, boats need braking and reverse capability.

Commutation cell

The **commutation cell** is the basic structure in power electronics. It is composed of an electronic switch (today a high-power semiconductor, not a mechanical switch) and a diode. It was traditionally referred to as a chopper, but since switching power supplies became a major form of power conversion, this new term has become more popular.

The purpose of the commutation cell is to "chop" DC power into square wave alternating current. This is done so that an inductor and a capacitor can be used in an LC circuit to change the voltage. This is in theory a lossless process, and in practice efficiencies above 80-90% are routinely achieved. The output is then usually run through a filter to produce clean DC power. By controlling the on and off times (the duty cycle) of the switch in the commutation cell, the output voltage can be regulated.

This basic principle is the core of most modern power supplies, from tiny DC-DC converters in portable devices to huge switching stations for high voltage DC power transmission.

Connection of two power elements

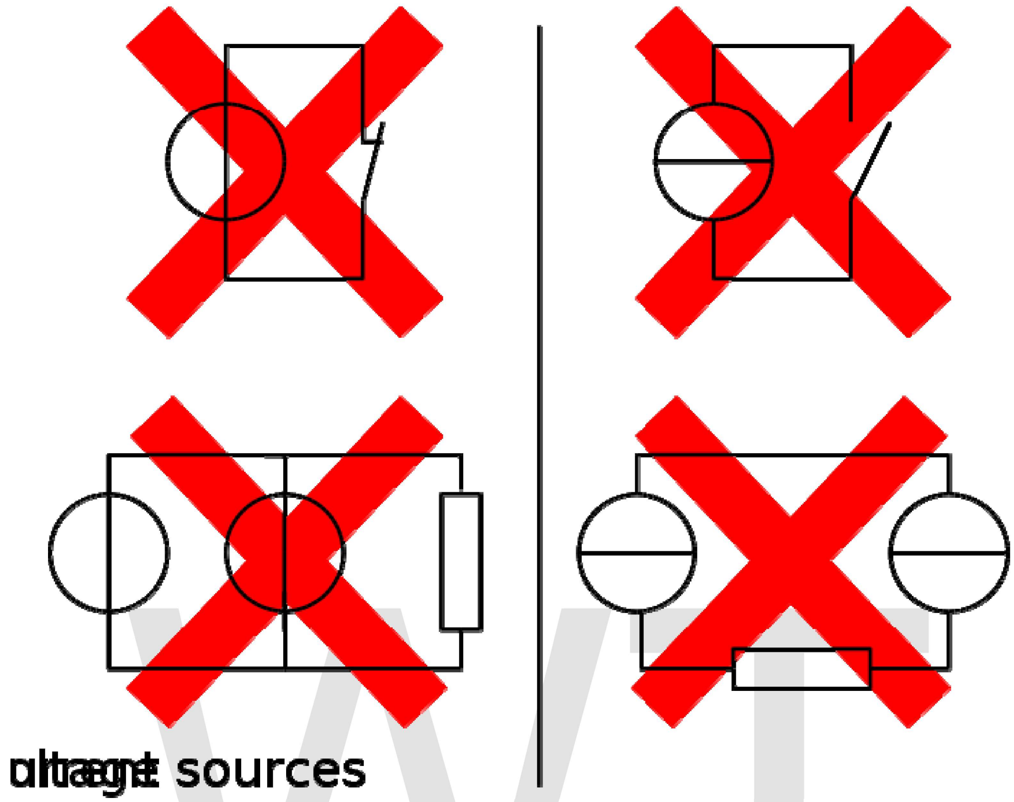


Fig. 1: The different configurations that are impossible: short circuit of a voltage source, current source in an open circuit, two voltage sources in parallel, two current sources in series. Any of these circuits will result in failure of generation of large amounts of heat!

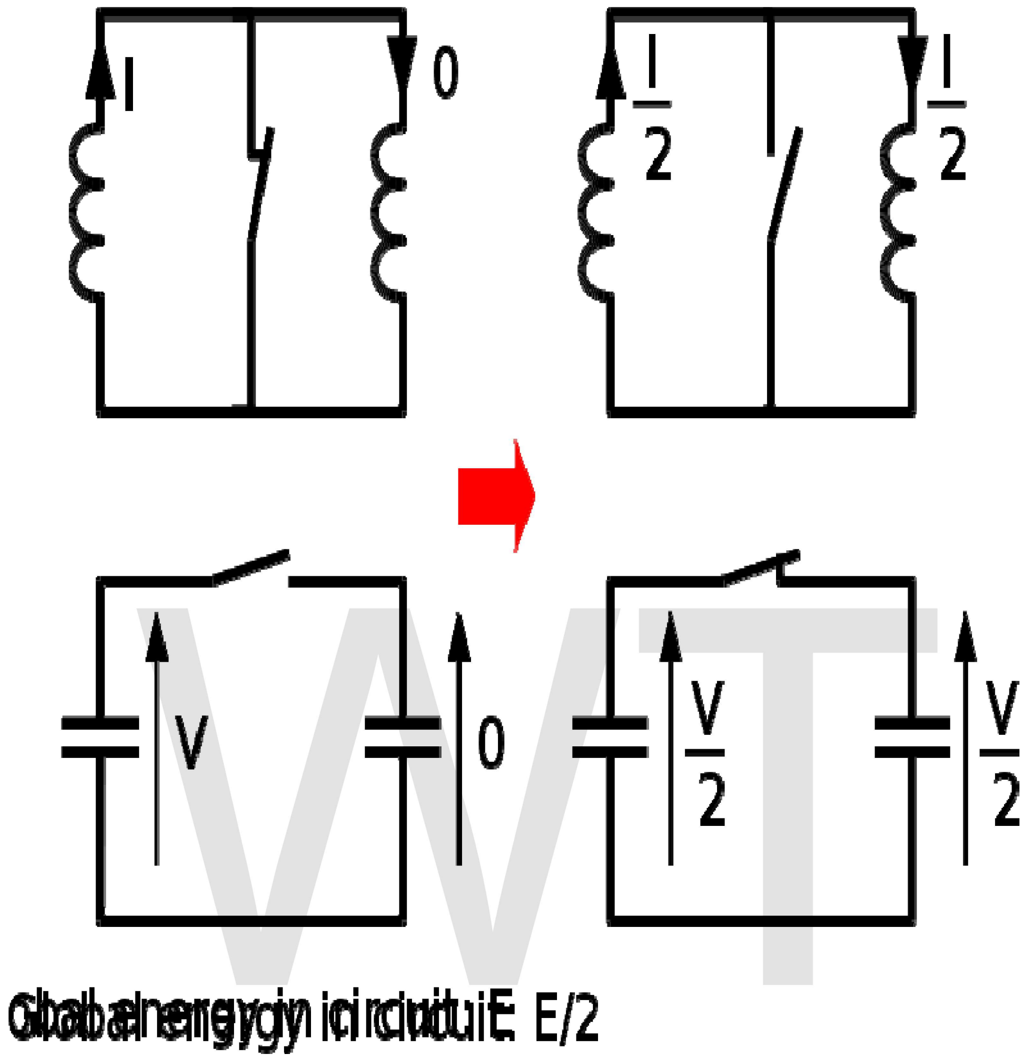


Fig. 2: As with the voltage and current sources, direct energy transfer from a capacitor to another or from an inductor to another should be avoided, as it results in important losses.

A Commutation cell connects two power elements, often referred to as sources, although they can either produce or absorb power.

Some requirements to connect power sources exist. The impossible configurations are listed in figure 1. They are basically:

- a voltage source cannot be shorted, as the short circuit would impose a zero voltage which would contradict the voltage generated by the source;
- in an identical way, a current source cannot be placed in an open circuit;
- two (or more) voltage sources cannot be connected in parallel, as each of them would try to impose the voltage on the circuit;

- two (or more) current sources cannot be connected in series, as each of them would try to impose the current in the loop.

This applies to classical sources (battery, generator), but also to capacitors and inductors: At a small time scale, a capacitor is identical to a voltage source, and an inductor to a current source. Connecting two capacitors with different voltage level in parallel therefore corresponds to connecting two voltage sources, one of the forbidden connections of figure 1.

The figure 2 illustrates the poor efficiency of such connection. One capacitor is charged to a voltage V, and is connected to a capacitor with the same capacity, but discharged.

Before the connection, the energy in the circuit is $E = \frac{1}{2}C \cdot V^2$, and the quantity of charges Q is equal to $C \cdot U$.

After the connection has been made, the quantity of charges is constant, and the total capacitance is 2*C*. Therefore the voltage across the capacitances is $\frac{Q}{2C} = \frac{V}{2}$. The energy in the circuit is then $\frac{1}{2}C\left(\frac{V}{2}\right)^2 = \frac{E}{2}$. Therefore half of the energy has been dissipated during the connection.

The same applies with the connections in series of two inductances. The magnetic flux ($\Phi = L \cdot I$) remains constant before and after the commutation. As the total inductance after the commutation is 2L, the current becomes $\frac{I}{2}$(see figure 2). The energy before the commutation is $\frac{1}{2}L \cdot I^2$. After, it is $\frac{1}{2}L \cdot \left(\frac{I}{2}\right)^2$. Here again, half of the energy is dissipated during the commutation.

As a result, it can be seen that a commutation cell can only connect a voltage source to a current source (and vice versa). However, using inductors and capacitors, it is possible to transform the behaviour of a source: for example two voltage sources can be connected through a converter if it uses an inductor to transfer energy.

The structure of a commutation cell

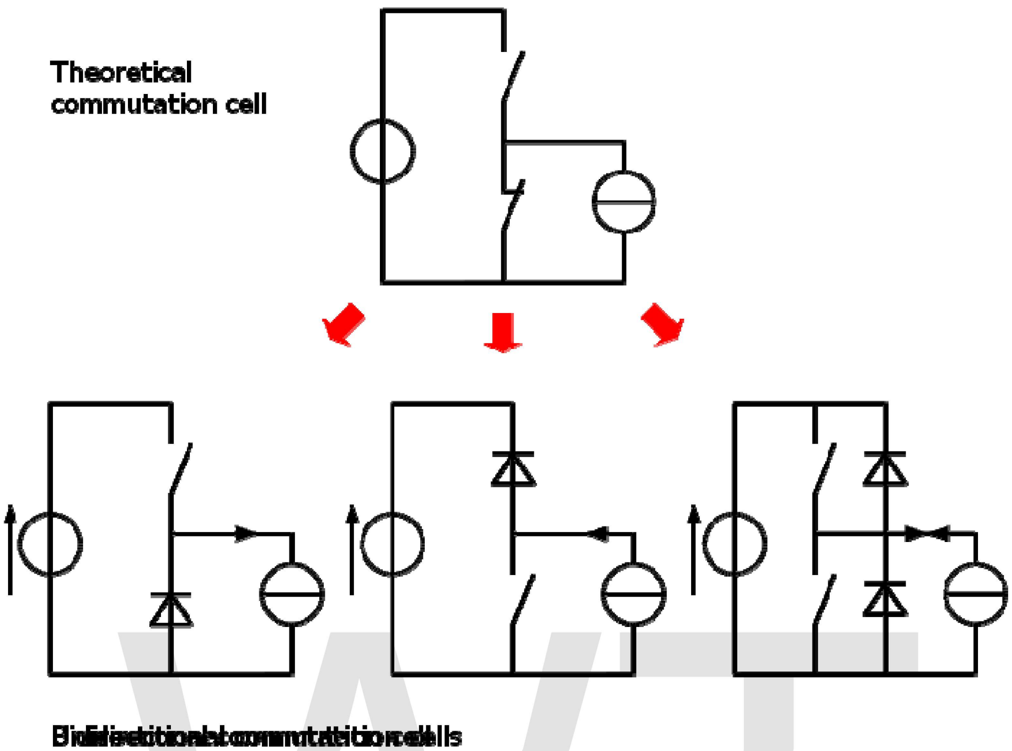


Fig. 3: A commutation cell connects two sources of different nature (current and voltage sources). It theoretically uses two switches, but as they both must be commanded with a perfect synchronization, one of the switches is replaced by a diode in practical applications. This makes the commutation cell unidirectional. A bidirectional commutation cell can be obtained by paralleling two unidirectional ones.

As told above, a commutation cell must be placed between a voltage source and a current source. Depending on the state of the cell, both sources are either connected together, or isolated. When isolated, the current source must be shorted, as it is impossible to left it in an open circuit. The basic schematic of a commutation cell is therefore given in figure 3 (top). It uses two switches with opposite states: In the configuration depicted in figure 3, both sources are isolated, and the current source is shorted. When the top switch is on (and the bottom switch is off), both sources are connected together.

In reality, it is impossible to have a perfect synchronization between the switches. At one point during the commutation, they would be either both on (thus shorting the voltage source) or off (thus leaving the current source in an open circuit). This is why one of the switches has to be replaced by a diode. A diode is a natural commutation device, i.e its state is controlled by the circuit itself. It will turn on or off at the exact moment it has to. The consequence of using a diode in a commutation cell is that it makes it unidirectional (see figure 3). A bidirectional cell can be built, but it is basically equivalent to two unidirectional cells connected in parallel.

The commutation cell in converters

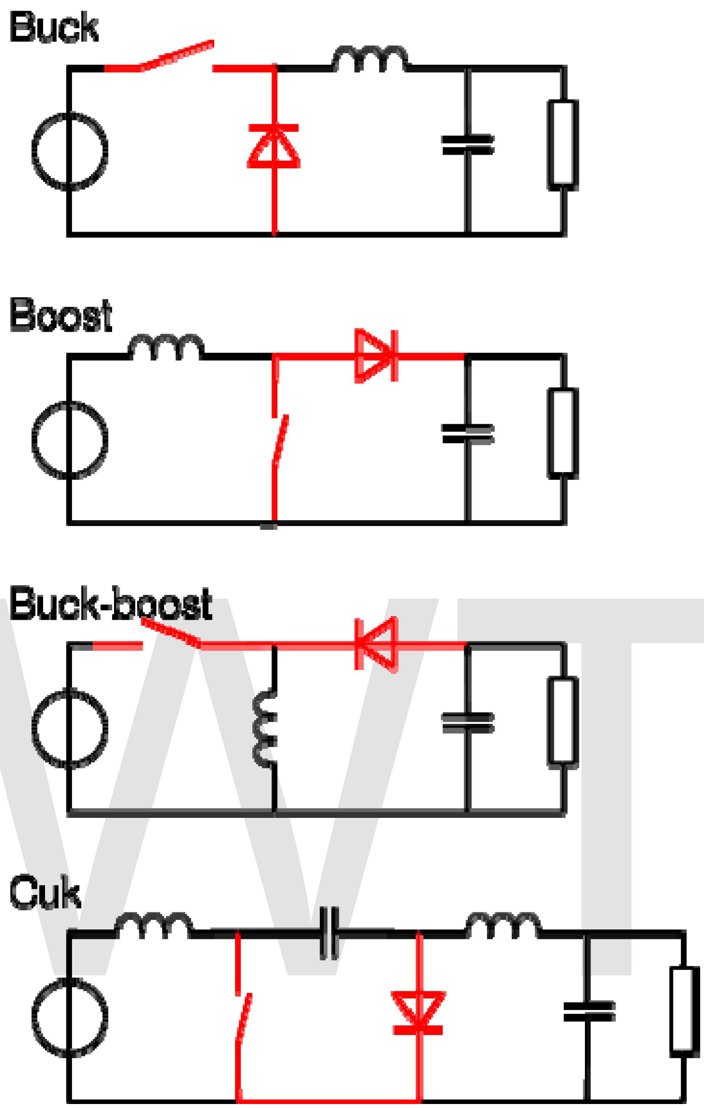


Fig. 4: The commutation cell is present in every switching power supply

The commutation cell can be found in any power electronic converter. Some examples are given in figure 4. As can be seen, a "current source" (actually a loop that contains an inductance) is always connected between the middle point and one of the external connections of the commutation cell, while a voltage source (or a capacitor, or a connection in series of voltage source and capacitor) is always connected to the two external connections.