Electric Power Systems Components

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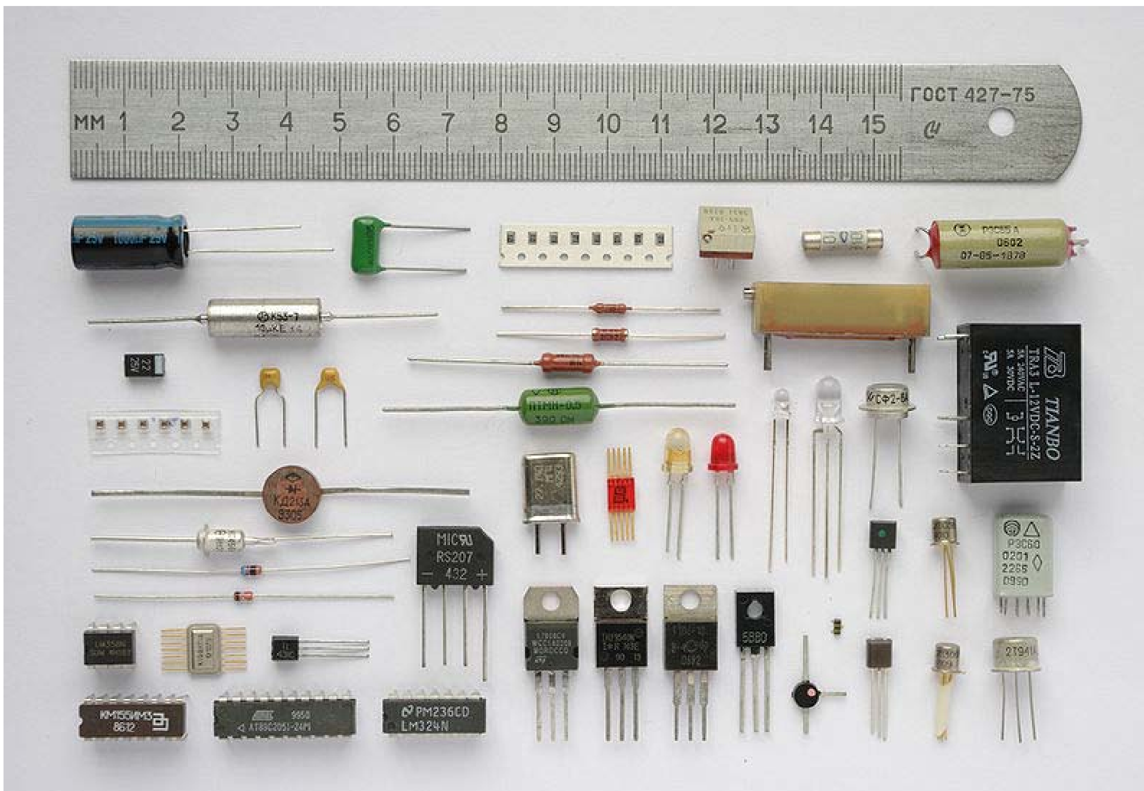
Electronic Component



Various components

An **electronic component** is a basic electronic element and may be available in a discrete form having two or more electrical terminals (or *leads*). These are intended to be connected together, usually by soldering to a printed circuit board, in order to create an electronic circuit with a particular function (for example an amplifier, radio receiver, or oscillator). Basic electronic components may be packaged discretely, as arrays or networks of like components, or integrated inside of packages such as semiconductor integrated circuits or thick film devices. The following list of electronic components focuses on the discrete version of these components, treating such packages as components in their own right.

Classification

A component may be classified as passive or active. The strict physics definition treats passive components as ones that cannot supply energy themselves, whereas a battery would be seen as an active component since it truly acts as a source of energy.

However electronic engineers performing circuit analysis use a more restrictive definition of passivity. When we are only concerned with the energy due to signals it is convenient to ignore the so-called DC circuit and pretend that the power supplying components such as transistors or integrated circuits is absent (as if each such component had its own battery built in) although it may in reality be supplied by the DC circuit which we are ignoring. Then the analysis only concerns the so-called AC circuit, an abstraction which ignores the DC voltages and currents (and the power associated with them) present in the real-life circuit. This fiction, for instance, allows us to view an oscillator as "producing energy" even though in reality the oscillator consumes even more energy from a power supply, obtained through the *DC circuit* which we have chosen to ignore. Under that restriction we define the terms as used in circuit analysis as follows:

- **Passive components** are ones which cannot introduce net energy into the circuit they are connected to. They also cannot rely on a source of power except for what is available from the (AC) circuit they are connected to. As a consequence they are unable to amplify (increase the power of a signal), although they may well increase a voltage or current such as is done by a transformer or resonant circuit. Among passive components are familiar two-terminal components such as resistors, capacitors, inductors, and most sorts of diodes.
- **Active components** rely on a source of energy (usually from the DC circuit, which we have chosen to ignore) and are usually able to inject power into a circuit although this is not part of the definition. This includes amplifying components such as transistors, triode vacuum tubes (valves), and tunnel diodes.

Passive components can be further divided into lossless and lossy components:

- **Lossless** components do not have a net power flow into or out of the component. This would include ideal capacitors, inductors, transformers, and the (theoretical) gyrator.
- **Lossy** or **dissipative** components do not have that property and generally absorb power from the external circuit over time. The prototypical example is the resistor. In practice all non-ideal passive components are at least a little lossy, but these are typically modeled in circuit analysis as consisting of an ideal lossless component with an attached resistor to account for the loss.

Most passive components with more than two terminals can be described in terms of two-port parameters satisfying the principle of reciprocity, although there are some rare exceptions. In contrast, active components (which have more than two terminals) generally lack that property.

Note that these distinctions only apply to components listed below which would be modeled as elements within circuit analysis. Practical items which act as transducers or have other connections to the outside world such as switches, cannot be subject to this form of classification since they defy the view of the electronic circuit as a closed system.

Components

Terminals and connectors

Devices to make electrical connection

- Terminal
- Connector
    - Socket
    - Screw terminal, Terminal Blocks
    - Header

Cable assemblies

Cables with connectors or terminals at their ends

- Power cord
- Patch cord
- Test lead

Switches

Components that can pass current ("closed") or break the flow of current ("open")

- Switch - Manually operated switch.
    - Electrical description: SPST, SPDT, DPST, DPDT, NPNT (general)
    - Technology: slide switches, toggle switches, rocker switches, rotary switches, pushbutton switches
- Keypad - Array of pushbutton switches
- DIP switch - Small array of switches for internal configuration settings
- Footswitch - Foot-operated switch
- Knife switch - Switch with unenclosed conductors
- Micro switch - Mechanically activated switch with snap action
- Limit switch - Mechanically activated switch to sense limit of motion
- Mercury switch - Switch sensing tilt
- Centrifugal switch - Switch sensing centrifugal force due to rate of rotation
- Relay - Electrically operated switch
- Reed switch - Magnetically activated switch

- Thermostat - Thermally activated switch
- Humidistat - Humidity activated switch
- Circuit Breaker - Switch opened in response to excessive current: a resettable fuse

Resistors

Pass current in proportion to voltage (ohms law).

- Resistor - fixed value
    - Power resistor - larger to safely dissipate heat generated
    - SIP or DIP resistor network - array of resistors in one package
- Variable resistor
    - Rheostat - Two terminal variable resistor (often for high power)
    - Potentiometer - Three terminal variable resistor (variable voltage divider)
    - Trim pot - Small potentiometer, usually for internal adjustments
- Heater - heating element
- Resistance wire, Nichrome wire - wire of high-resistance material, often used as heating element
- Thermistor - temperature-varied resistor
- Humistor - humidity-varied resistor
- Varistor, Voltage Dependent Resistor, MOV - Passes current when excessive voltage present

Protection devices

Passive components that protect circuits from excessive currents or voltages

- Fuse - Over-current protection, one time use
- Circuit Breaker - Resettable fuse in the form of a mechanical switch
- PolySwitch or Resettable fuse - Circuit breaker action using solid state device
- Ground-fault protection or Residual-current device - Circuit breaker sensitive to mains currents passing to ground
- Metal Oxide Varistor, Surge Absorber (MOV), TVS - Over-voltage protection.
- Inrush current limiter - Protection against initial Inrush current
- Gas Discharge Tube - Protection against high voltage surges
- Spark gap - Electrodes with a gap to arc over at a high voltage
- Lightning arrester - Spark gap used to protect against lightning strikes

Capacitors

Components that store and release electrical charge. Used for filtering power supply lines, for tuning resonant circuits, and for blocking DC voltages while passing AC signals, among numerous other uses.

- Capacitor - fixed capacitance
    - Capacitor network (array)

- Variable capacitor - Adjustable capacitance
    - Tuning capacitor - Variable capacitor for tuning a radio, oscillator, or tuned circuit
    - Trimmer capacitor - Small variable capacitor usually for internal adjustments
- Varicap diode - AC capacitance varies according to the DC voltage applied.

Magnetic (inductive) devices

Electrical components that use magnetism

- Inductor, coil, choke
- Variable inductor
- Saturable Inductor
- Transformer
- Magnetic amplifier (toroid)
- Ferrite impedances, beads
- Motor / Generator
- Solenoid
- Speaker / Microphone

Networks

Components that use more than one type of passive component

- RC network - forms an RC circuit, used in Snubbers
- LC Network - forms an LC circuit, used in tuneable transformers and RFI filters

Piezoelectric devices, crystals, resonators

Passive components that use piezoelectric effect

- Components that use the effect to generate or filter high frequencies
    - Crystal - Is a ceramic crystal used to generate precise frequencies
    - Ceramic resonator - Is a ceramic crystal used to generate semi-precise frequencies
    - Ceramic filter - Is a ceramic crystal used to filter a band of frequencies such as in radio receivers
    - Surface Acoustic Wave (SAW) filters
- Components that use the effect as mechanical Transducers.
    - Ultrasonic motor - Electric motor that uses the piezoelectric effect

Power sources

Sources of electrical power

- Battery - acid- or alkali-based power supply
- Fuel cell - an electrochemical generator
- Power supply - usually a mains hook-up
- Photo voltaic device - generates electricity from light
- Thermo electric generator - generates electricity from temperature gradients
- Electrical generator - an electromechanical power source

Transducers, sensors, detectors

1. Transducers generate physical effects when driven by an electrical signal, or vice-versa.
2. Sensors (detectors) are transducers that react to environmental conditions by changing their electrical properties or generating an electrical signal.
3. The Transducers listed here are single electronic components (as opposed to complete assemblies), and are passive.

- Audio
  - Loudspeaker - Magnetic or piezoelectric device to generate full audio
  - Buzzer - Magnetic or piezoelectric sounder to generate tones
- Position, motion
  - Linear variable differential transformer (LVDT) - Magnetic - detects linear position
  - Rotary encoder, Shaft Encoder - Optical, magnetic, resistive or switches - detects absolute or relative angle or rotational speed
  - Inclinometer - Capacitive - detects angle with respect to gravity
  - Motion sensor, Vibration sensor
  - Flow meter - detects flow in liquid or gas
- Force, torque
  - Strain gauge - Piezoelectric or resistive - detects squeezing, stretching, twisting
  - Accelerometer - Piezoelectric - detects acceleration, gravity
- Thermal
  - Thermocouple, thermopile - Wires that generate a voltage proportional to delta temperature
  - Thermistor - Resistor whose resistance changes with temperature, up PTC or down NTC
  - Resistance Temperature Detector (RTD) - Wire whose resistance changes with temperature
  - Bolometer
  - Thermal cutoff - Switch that is opened or closed when a set temperature is exceeded
- Magnetic field

    - Magnetometer, Gauss meter
- Humidity
    - Hygrometer
- Electromagnetic, light
    - Photo resistor - Light dependent resistor (LDR)

Semiconductors

Diodes

Conduct electricity easily in one direction, among more specific behaviors.

- Standard Diode, Rectifier, Bridge Rectifier
- Schottky Diode, Hot Carrier Diode - super fast diode with lower forward voltage drop
- Zener Diode - Passes current in reverse direction to provide a constant voltage reference
- Transient Voltage Suppression Diode (TVS), Unipolar or Bipolar - used to absorb high-voltage spikes
- Varactor, Tuning diode, Varicap, Variable Capacitance Diode - A diode whose AC capacitance varies according to the DC voltage applied.
- Light Emitting Diode (LED) - A diode which emits light
- LASER Diode - A semiconductor laser
- Photodiode - Passes current in proportion to incident light
    - Avalanche Photodiode Photodiode with internal gain
    - Solar Cell, photovoltaic cell, PV array or panel, produces power from light
- Diode for Alternating Current (DIAC, Trigger Diode, SIDAC) - Often used to trigger an SCR
- Constant current Diode
- Peltier cooler - A semiconductor heat pump

Transistors

Active components used for amplification.

- Bipolar transistors
    - Bipolar Junction Transistor (BJT, or simply "transistor") - NPN or PNP
        - Photo transistor - Amplified photodetector
    - Darlington transistor - NPN or PNP
        - Photo Darlington - Amplified photodetector
    - Sziklai pair (Compound transistor, complementary Darlington)
- Field effect transistor (FET)
    - Junction Field Effect Transistor (JFET) - N-CHANNEL or P-CHANNEL
    - Metal Oxide Semiconductor FET (MOSFET) - N-CHANNEL or P-CHANNEL
    - MEtal Semiconductor FET (MESFET)

- High Electron Mobility Transistor (HEMT)
- Thyristors
    - Silicon Controlled Rectifier (SCR) - Passes current only after triggered by a sufficient control voltage on its gate
    - TRIode for Alternating Current (TRIAC) - Bidirectional SCR
    - UniJunction Transistor (UJT)
    - Programmable UniJunction Transistor (PUT)
    - Static Induction Transistor/Thyristor (SIT, SITh)
- Composite transistors
    - Insulated Gate Bipolar Transistor (IGBT)

Integrated circuits

- Digital
- Analog
    - Hall effect sensor - Senses a magnetic field
    - Current sensor - Senses a current through it

Optoelectronic devices

- Optoelectronics
    - Opto-Isolator, Opto-Coupler, Photo-Coupler - Photodiode, BJT, JFET, SCR, TRIAC, Zero-crossing TRIAC, Open collector IC, CMOS IC, Solid State Relay (SSR)
    - Opto Switch, Opto Interrupter, Optical Switch, Optical Interrupter, Photo switch, Photo Interrupter
    - LED Display - Seven-segment display, Sixteen-segment display, Dot matrix display

Display technologies

Current:

- Filament lamp (indicator lamp)
- Vacuum fluorescent display (VFD) (preformed characters, 7 segment, starburst)
- Cathode ray tube (CRT) (dot matrix scan (e.g. computer monitor), radial scan (e.g. radar), arbitrary scan (e.g. oscilloscope)) (monochrome & colour)
- LCD (preformed characters, dot matrix) (passive, TFT) (monochrome, colour)
- Neon (individual, 7 segment display)
- LED (individual, 7 segment display, starburst display, dot matrix)
- Flap indicator (numeric, preprinted messages)
- Plasma display (dot matrix)

Obsolete:

- Filament lamp 7 segment display (aka 'minitron')

- Nixie Tube
- Dekatron (aka glow transfer tube)
- Magic eye tube indicator
- Penetron (a 2 colour see-through CRT)

Vacuum tubes (Valves)

Based on current conduction through a vacuum

- Diode or Rectifier tube

Amplifying tubes

- Triode
- Tetrode
- Pentode
- Hexode
- Pentagrid
- Octode
- Microwave tubes
  - Klystron
  - Magnetron
  - Traveling-wave tube

Optical detectors or emitters

- Phototube or Photodiode - tube equivalent of semiconductor photodiode
- Photomultiplier tube - Phototube with internal gain
- Cathode ray tube (CRT) or Television picture tube
- Vacuum fluorescent display (VFD) - Modern non-raster sort of small CRT display
- Magic eye tube - Small CRT display used as a tuning meter (obsolete)
- X-ray tube - Produces x-rays

Discharge devices

- Gas discharge tube

Obsolete:

- Mercury arc rectifier
- Voltage regulator tube
- Nixie tube
- Thyratron
- Ignitron

Antennas

Antennas transmit or receive radio waves

- Elemental dipole
- Yagi
- Phased array
- Loop antenna
- Parabolic dish
- Log-periodic dipole array
- Biconical
- Feedhorn

Assemblies, modules

Multiple electronic components assembled in a device that is in itself used as a component

- Oscillator
- Display devices
    - Liquid crystal display (LCD)
    - Digital voltmeters
- Filter

Prototyping aids

- Wire-wrap
- Breadboard

Mechanical accessories

- Enclosure
- Heat sink
- Heat sink paste & pads
- Fan

Other

- Printed circuit boards
- Lamp
- Waveguide
- Memristor

Obsolete:

- Carbon amplifier

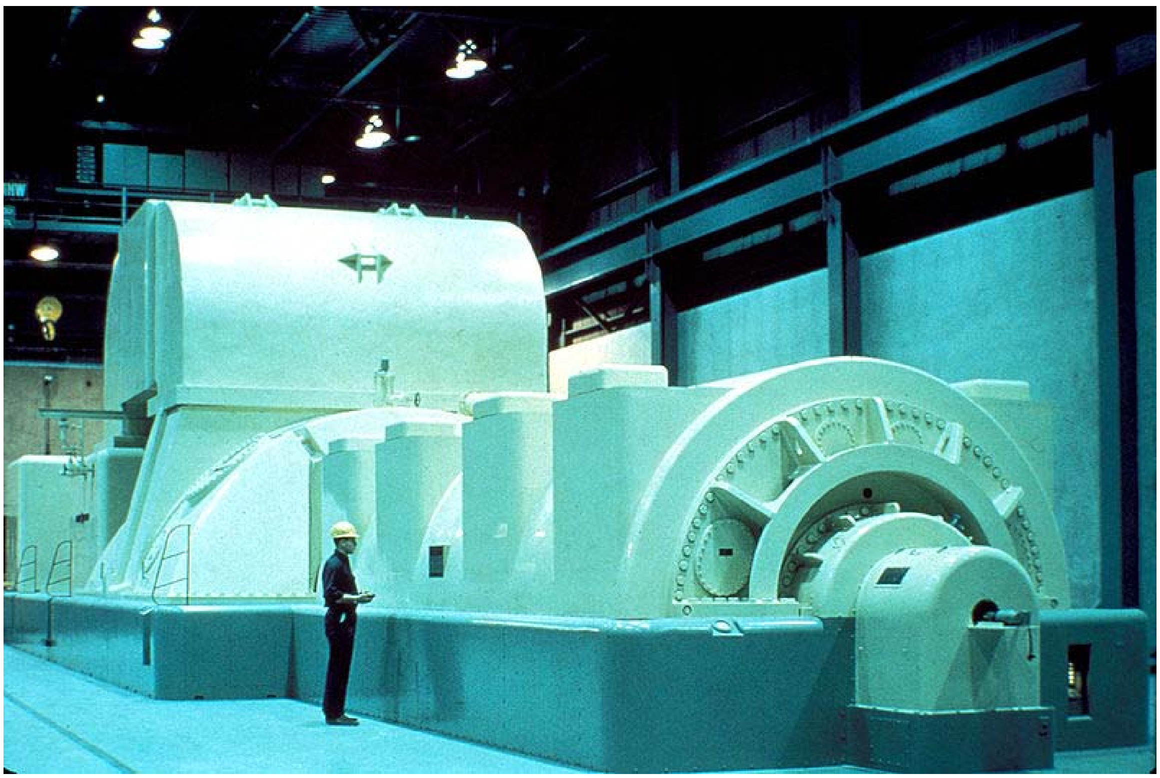
- Carbon arc (negative resistance device)
- Dynamo (historic rf generator)

Standard symbols

On a circuit diagram, electronic devices are represented by conventional symbols. Reference designators are applied to the symbols to identify the component.

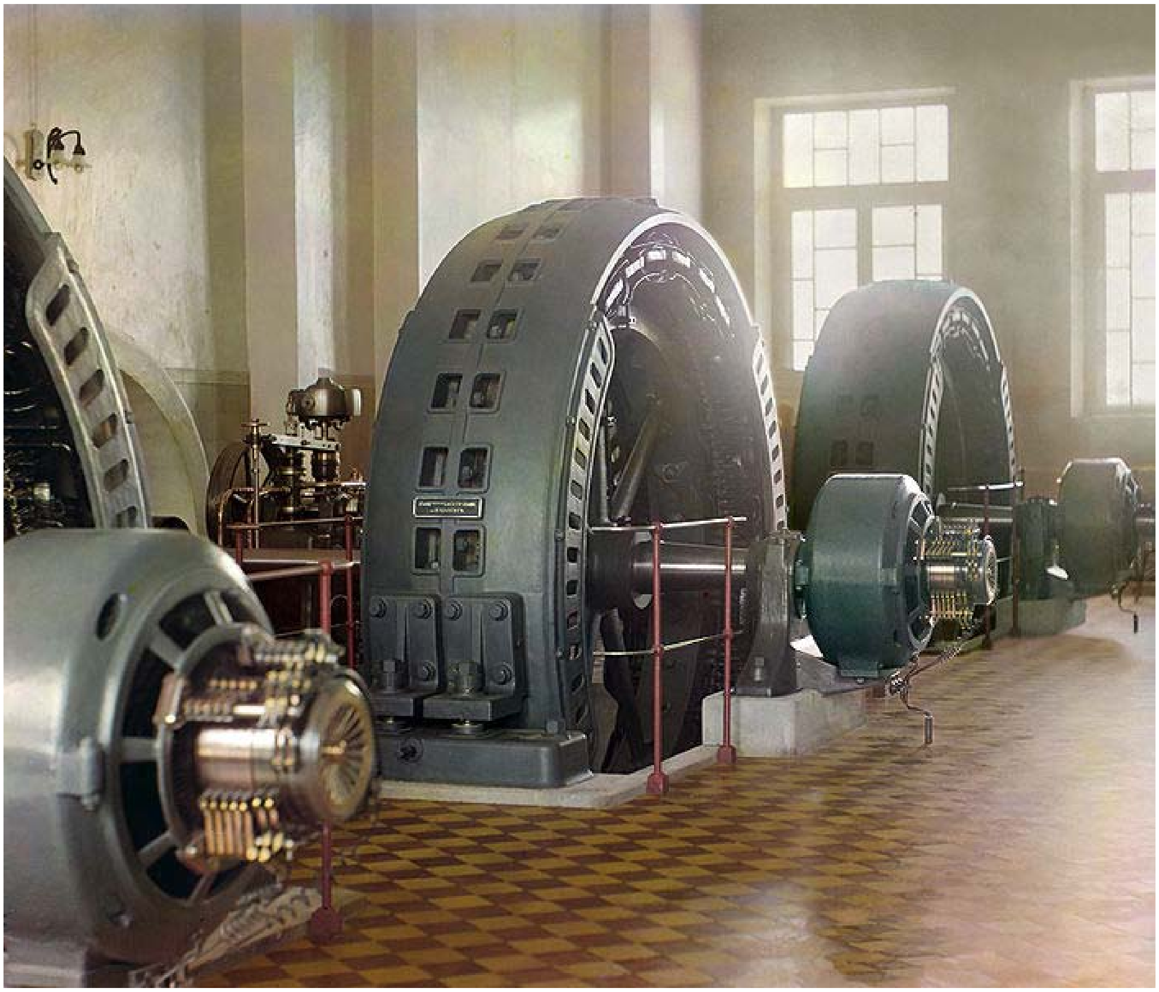
Chapter 2

Electrical Generator



U.S. NRC image of a modern steam turbine generator

In electricity generation, an **electric generator** is a device that converts mechanical energy to electrical energy. The reverse conversion of electrical energy into mechanical energy is done by a motor; motors and generators have many similarities. A generator forces electrons in the windings to flow through the external electrical circuit. It is somewhat analogous to a water pump, which creates a flow of water but does not create the water inside. The source of mechanical energy may be a reciprocating or turbine steam engine, water falling through a turbine or waterwheel, an internal combustion engine, a wind turbine, a hand crank, compressed air or any other source of mechanical energy.



Early 20th century alternator made in Budapest, Hungary, in the power generating hall of a hydroelectric station

Early Ganz Generator in Zwevegem, West Flanders, Belgium

Historical developments

Before the connection between magnetism and electricity was discovered, electrostatic generators were invented that used electrostatic principles. These generated very high voltages and low currents. They operated by using moving electrically charged belts, plates and disks to carry charge to a high potential electrode. The charge was generated using either of two mechanisms:

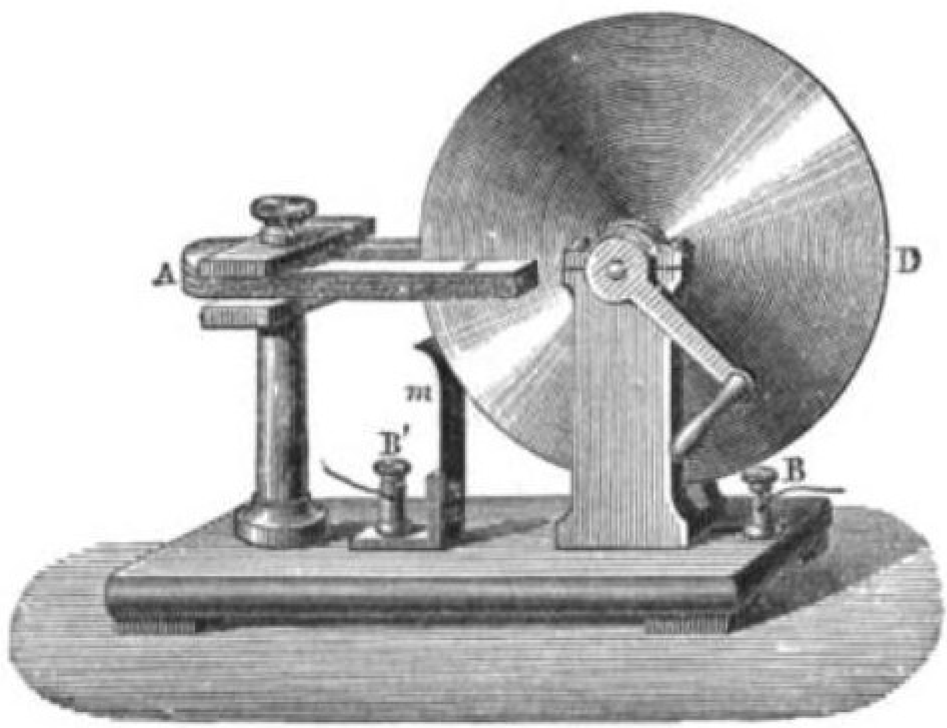
- Electrostatic induction
- The triboelectric effect, where the contact between two insulators leaves them charged.

Because of their inefficiency and the difficulty of insulating machines producing very high voltages, electrostatic generators had low power ratings and were never used for generation of commercially significant quantities of electric power. The Wimshurst machine and Van de Graaff generator are examples of these machines that have survived.

Jedlik's dynamo

In 1827, Hungarian Anyos Jedlik started experimenting with electromagnetic rotating devices which he called electromagnetic self-rotors. In the prototype of the single-pole electric starter (finished between 1852 and 1854) both the stationary and the revolving parts were electromagnetic. He formulated the concept of the dynamo at least 6 years before Siemens and Wheatstone but didn't patent it as he thought he wasn't the first to realize this. In essence the concept is that instead of permanent magnets, two electromagnets opposite to each other induce the magnetic field around the rotor. It was also the discovery of the principle of self-excitation.

Faraday's disk



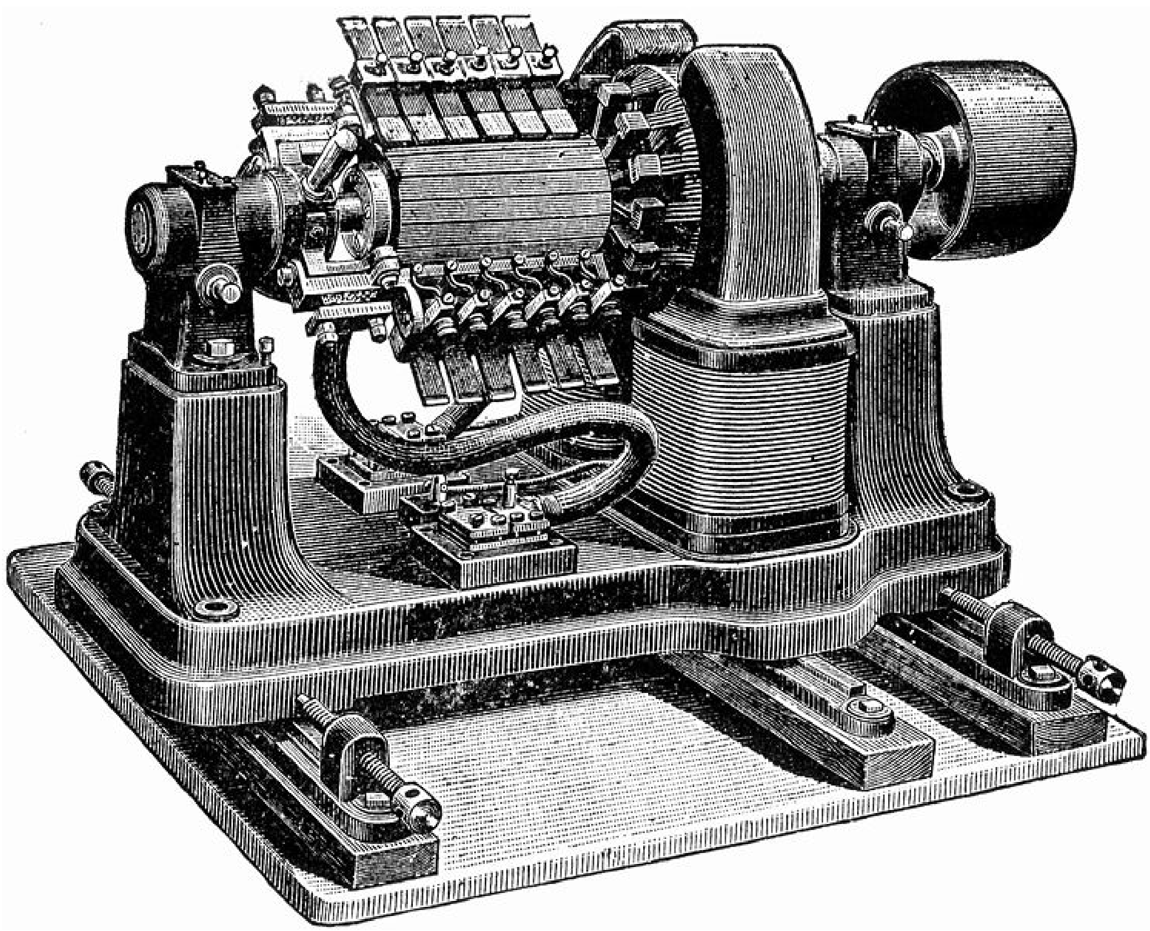
Faraday disk, the first electric generator. The horseshoe-shaped magnet *(A)* created a magnetic field through the disk *(D)*. When the disk was turned this induced an electric current radially outward from the center toward the rim. The current flowed out through the sliding spring contact *m*, through the external circuit, and back into the center of the disk through the axle.

In the years of 1831–1832, Michael Faraday discovered the operating principle of electromagnetic generators. The principle, later called Faraday's law, is that an electromotive force is generated in an electrical conductor that encircles a varying magnetic flux. He also built the first electromagnetic generator, called the Faraday disk, a type of homopolar generator, using a copper disc rotating between the poles of a horseshoe magnet. It produced a small DC voltage.

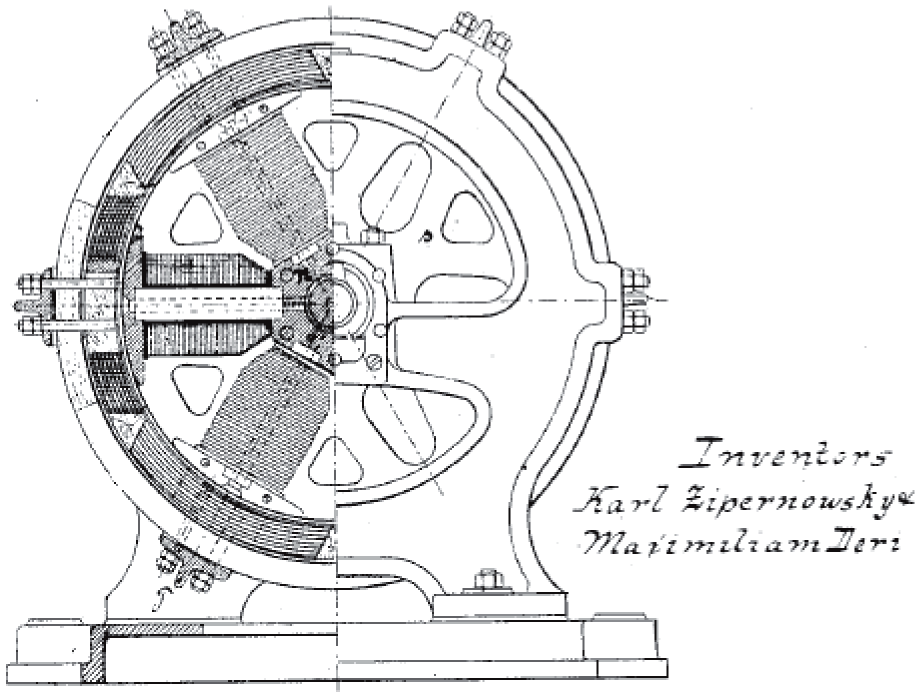
This design was inefficient due to self-cancelling counterflows of current in regions not under the influence of the magnetic field. While current was induced directly underneath the magnet, the current would circulate backwards in regions outside the influence of the magnetic field. This counterflow limits the power output to the pickup wires and induces waste heating of the copper disc. Later homopolar generators would solve this problem by using an array of magnets arranged around the disc perimeter to maintain a steady field effect in one current-flow direction.

Another disadvantage was that the output voltage was very low, due to the single current path through the magnetic flux. Experimenters found that using multiple turns of wire in a coil could produce higher more useful voltages. Since the output voltage is proportional to the number of turns, generators could be easily designed to produce any desired voltage by varying the number of turns. Wire windings became a basic feature of all subsequent generator designs.

Dynamo



Dynamos are no longer used for power generation due to the size and complexity of the commutator needed for high power applications. This large belt-driven high-current dynamo produced 310 amperes at 7 volts, or 2,170 watts, when spinning at 1400 RPM.



Dynamo Electric Machine [End View, Partly Section] (U.S. Patent 284,110)

The **dynamo** was the first electrical generator capable of delivering power for industry. The dynamo uses electromagnetic principles to convert mechanical rotation into a pulsing direct current (DC) through the use of a commutator. The first dynamo was built by Hippolyte Pixii in 1832.

Through a series of accidental discoveries, the dynamo became the source of many later inventions, including the DC electric motor, the AC alternator, the AC synchronous motor, and the rotary converter.

A dynamo machine consists of a stationary structure, which provides a constant magnetic field, and a set of rotating windings which turn within that field. On small machines the constant magnetic field may be provided by one or more permanent magnets; larger machines have the constant magnetic field provided by one or more electromagnets, which are usually called field coils.

Large power generation dynamos are now rarely seen due to the now nearly universal use of alternating current for power distribution and solid state electronic AC to DC power conversion. But before the principles of AC were discovered, very large direct-current dynamos were the only means of power generation and distribution. Now power generation dynamos are mostly a curiosity.

Other rotating electromagnetic generators

Without a commutator, a dynamo becomes an alternator, which is a synchronous singly-fed generator. When used to feed an electric power grid, an alternator must always operate at a constant speed that is precisely synchronized to the electrical frequency of the power grid. A DC generator can operate at any speed within mechanical limits but always outputs a direct current waveform.

Other types of generators, such as the asynchronous or induction singly-fed generator, the doubly-fed generator, or the brushless wound-rotor doubly-fed generator, do not incorporate permanent magnets or field windings (i.e., electromagnets) that establish a constant magnetic field, and as a result, are seeing success in variable speed constant frequency applications, such as wind turbines or other renewable energy technologies.

The full output performance of any generator can be optimized with electronic control but only the doubly-fed generators or the brushless wound-rotor doubly-fed generator incorporate electronic control with power ratings that are substantially less than the power output of the generator under control, which by itself offer cost, reliability and efficiency benefits.

MHD generator

A magnetohydrodynamic generator directly extracts electric power from moving hot gases through a magnetic field, without the use of rotating electromagnetic machinery. MHD generators were originally developed because the output of a plasma MHD generator is a flame, well able to heat the boilers of a steam power plant. The first practical design was the AVCO Mk. 25, developed in 1965. The U.S. government funded substantial development, culminating in a 25 MW demonstration plant in 1987. In the Soviet Union from 1972 until the late 1980s, the MHD plant U 25 was in regular commercial operation on the Moscow power system with a rating of 25 MW, the largest MHD plant rating in the world at that time. MHD generators operated as a topping cycle are currently (2007) less efficient than combined-cycle gas turbines.

Terminology

Rotor from generator at Hoover Dam, United States

The two main parts of a generator or motor can be described in either mechanical or electrical terms:

Mechanical:

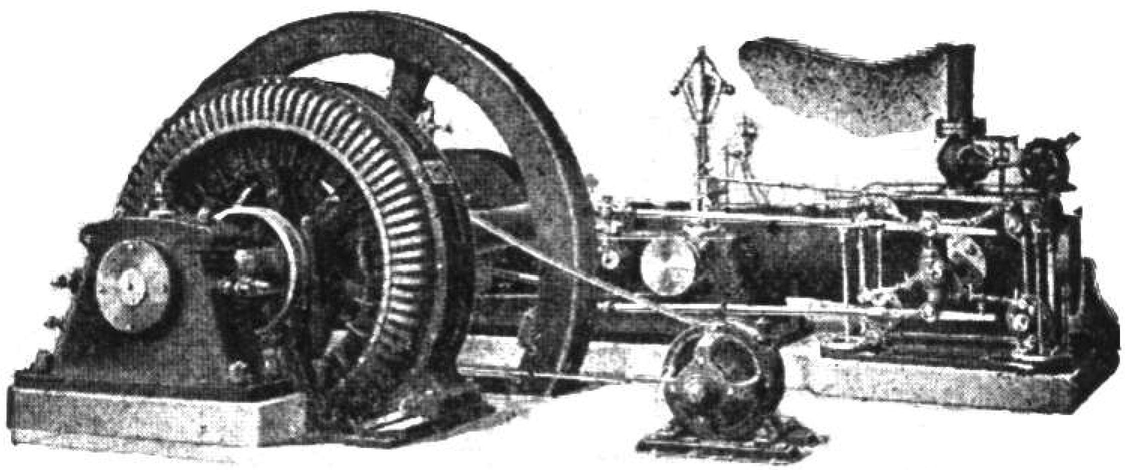
- Rotor: The rotating part of an electrical machine
- Stator: The stationary part of an electrical machine

Electrical:

- Armature: The power-producing component of an electrical machine. In a generator, alternator, or dynamo the armature windings generate the electric current. The armature can be on either the rotor or the stator.
- Field: The magnetic field component of an electrical machine. The magnetic field of the dynamo or alternator can be provided by either electromagnets or permanent magnets mounted on either the rotor or the stator.

Because power transferred into the field circuit is much less than in the armature circuit, AC generators nearly always have the field winding on the rotor and the stator as the armature winding. Only a small amount of field current must be transferred to the moving rotor, using slip rings. Direct current machines (dynamos) require a commutator on the rotating shaft to convert the alternating current produced by the armature to direct current, so the armature winding is on the rotor of the machine.

Excitation



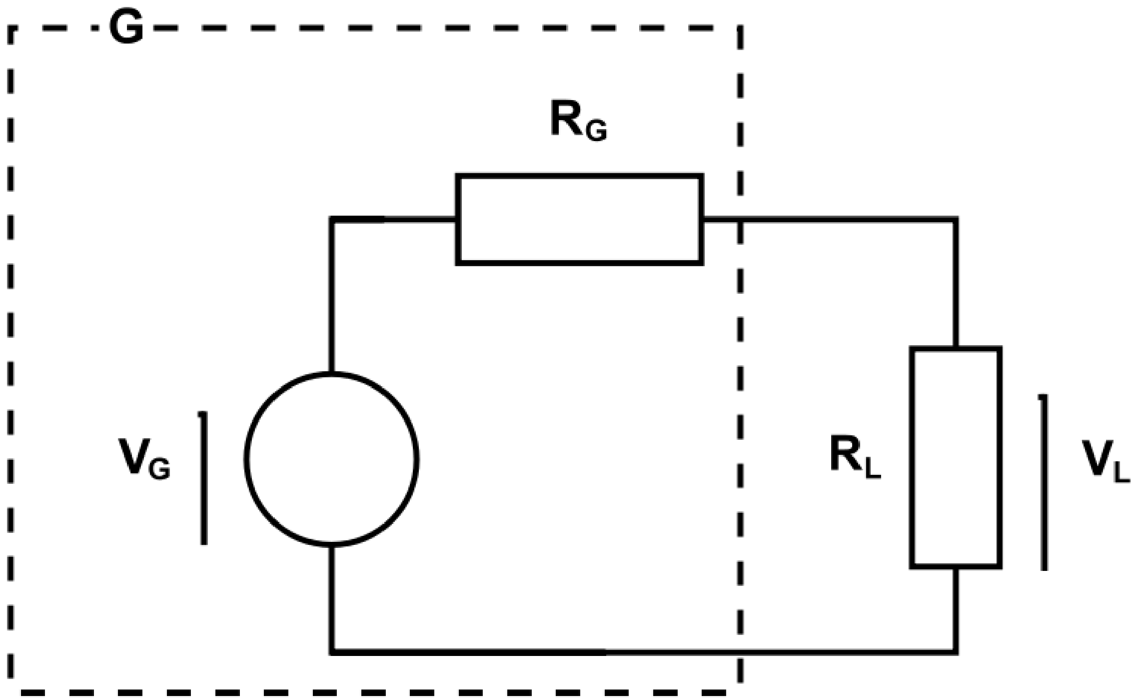
A small early 1900s 75 KVA direct-driven power station AC alternator, with a separate belt-driven exciter generator.

An electric generator or electric motor that uses field coils rather than permanent magnets requires a current to be present in the field coils for the device to be able to work. If the field coils are not powered, the rotor in a generator can spin without producing any usable electrical energy, while the rotor of a motor may not spin at all.

Smaller generators are sometimes *self-excited*, which means the field coils are powered by the current produced by the generator itself. The field coils are connected in series or parallel with the armature winding. When the generator first starts to turn, the small amount of remanent magnetism present in the iron core provides a magnetic field to get it started, generating a small current in the armature. This flows through the field coils, creating a larger magnetic field which generates a larger armature current. This "bootstrap" process continues until the magnetic field in the core levels off due to saturation and the generator reaches a steady state power output.

Very large power station generators often utilize a separate smaller generator to excite the field coils of the larger. In the event of a severe widespread power outage where islanding of power stations has occurred, the stations may need to perform a black start to excite the fields of their largest generators, in order to restore customer power service.

DC Equivalent circuit



Equivalent circuit of generator and load.
G = generator
V_G=generator open-circuit voltage
R_G=generator internal resistance
V_L=generator on-load voltage
R_L=load resistance

The equivalent circuit of a generator and load is shown in the diagram to the right. The generator's V_G and R_G parameters can be determined by measuring the winding resistance (corrected to operating temperature), and measuring the open-circuit and loaded voltage for a defined current load.

Vehicle-mounted generators

Early motor vehicles until about the 1960s tended to use DC generators with electromechanical regulators. These have now been replaced by alternators with built-in rectifier circuits, which are less costly and lighter for equivalent output. Automotive alternators power the electrical systems on the vehicle and recharge the battery after starting. Rated output will typically be in the range 50-100 A at 12 V, depending on the designed electrical load within the vehicle. Some cars now have electrically-powered steering assistance and air conditioning, which places a high load on the electrical system. Large commercial vehicles are more likely to use 24 V to give sufficient power at the starter motor to turn over a large diesel engine. Vehicle alternators do not use permanent magnets and are typically only 50-60% efficient over a wide speed range. Motorcycle alternators often use permanent magnet stators made with rare earth magnets, since they can be made smaller and lighter than other types.

Some of the smallest generators commonly found power bicycle lights. These tend to be 0.5 ampere, permanent-magnet alternators supplying 3-6 W at 6 V or 12 V. Being powered by the rider, efficiency is at a premium, so these may incorporate rare-earth magnets and are designed and manufactured with great precision. Nevertheless, the maximum efficiency is only around 80% for the best of these generators—60% is more typical—due in part to the rolling friction at the tyre–generator interface from poor alignment, the small size of the generator, bearing losses and cheap design. The use of permanent magnets means that efficiency falls even further at high speeds because the magnetic field strength cannot be controlled in any way. Hub generators remedy many of these flaws since they are internal to the bicycle hub and do not require an interface between the generator and tyre. Until recently, these generators have been expensive and hard to find. Major bicycle component manufacturers like Shimano and SRAM have only just entered this market. However, significant gains can be expected in future as cycling becomes more mainstream transportation and LED technology allows brighter lighting at the reduced current these generators are capable of providing.

Sailing yachts may use a water or wind powered generator to trickle-charge the batteries. A small propeller, wind turbine or impeller is connected to a low-power alternator and rectifier to supply currents of up to 12 A at typical cruising speeds.

Engine-generator

An *engine-generator* is the combination of an electrical generator and an engine (prime mover) mounted together to form a single piece of self-contained equipment. The engines used are usually piston engines, but gas turbines can also be used. Many different versions are available - ranging from very small portable petrol powered sets to large turbine installations.

Human powered electrical generators

A generator can also be driven by human muscle power (for instance, in field radio station equipment).

Human powered direct current generators are commercially available, and have been the project of some DIY enthusiasts. Typically operated by means of pedal power, a converted bicycle trainer, or a foot pump, such generators can be practically used to charge batteries, and in some cases are designed with an integral inverter. The average adult could generate about 125-200 watts on a pedal powered generator, but at a power of 200 W, a typical healthy human will reach complete exhaustion and fail to produce any more power after approximately 1.3 hours. Portable radio receivers with a crank are made to reduce battery purchase requirements.

Linear electric generator

In the simplest form of linear electric generator, a sliding magnet moves back and forth through a solenoid - a spool of copper wire. An alternating current is induced in the loops of wire by Faraday's law of induction each time the magnet slides through. This type of generator is used in the Faraday flashlight. Larger linear electricity generators are used in wave power schemes.

Tachogenerator

Tachogenerators are frequently used to power tachometers to measure the speeds of electric motors, engines, and the equipment they power. Generators generate voltage roughly proportional to shaft speed. With precise construction and design, generators can be built to produce very precise voltages for certain ranges of shaft speeds

Chapter 3

Arc-Fault Circuit Interrupter

An **Arc Fault Circuit Interrupter** (**AFCI**) is a circuit breaker designed to prevent fires by detecting a non-working (i.e., non-intended/non-useful) electrical arc and disconnecting the power before the arc starts a fire. An AFCI should, but may not always, distinguish between a working arc that may occur in the brushes of a vacuum cleaner, on operation of a light switch, on insertion / removal of a plug into an electrical receptacle, or during the operation of other household devices and a non-working arc that can occur — for example a lamp cord that has a broken conductor in the cord from overuse. Arc faults in a home are one of the leading causes for household fires.

Annually, over 40,000 fires are attributed to home electrical wiring. These fires result in over 350 deaths and over 1,400 injuries each year.

Conventional circuit breakers only respond to overloads and short circuits; so they do not protect against arcing conditions that produce erratic current. An AFCI is selective so that normal arcs do not cause it to trip. The AFCI circuitry continuously monitors the current through the AFCI. AFCIs use unique current sensing circuitry to discriminate between normal and unwanted arcing conditions. Once an unwanted arcing condition is detected, the control circuitry in the AFCI trips the internal contacts, thus de-energizing the circuit and reducing the potential for a fire to occur. An AFCI should not trip during normal arcing conditions, which can occur when a switch is opened or a plug is pulled from a receptacle.

AFCIs resemble a GFCI/RCD (Ground-Fault Circuit Interrupt/Residual-Current Device) in that they both have a test button although it is important to distinguish between the two. GFCIs and RCDs are designed to protect against electrical shock while AFCIs are primarily designed to protect against arcing and/or fire.

Electrical code requirements

Starting with the 1999 version of the National Electrical Code (NFPA 70) in the United States (US), and the 2002 version of the Canadian Electrical Code in Canada (CSA Standard C22.1), the national codes require AFCIs in all circuits that feed outlets in bedrooms of dwelling units. This requirement is typically accomplished by using a kind of circuit-breaker (defined by UL 1699) in the breaker panel that provides combined arc-fault and overcurrent protection. Not all US. jurisdictions have adopted the AFCI requirements of the NEC as written.

The AFCI is intended to prevent fire from arcs. AFCI circuit breakers are designed to meet one of two standards as specified by UL 1699: "branch" type or "combination" type (note: the Canadian Electrical Code uses different terminology but similar technical requirements). A branch type AFCI trips on 75 amperes of arcing current from the line wire to either the neutral or ground wire. A combination type adds series arcing detection to branch type performance. Combination type AFCIs trip on 5 amperes of series arcing.

The advanced electronics inside an AFCI breaker detect sudden bursts of electric current in milliseconds; long before a standard circuit breaker or fuse would trip. A "combination AFCI breaker" will provide protection against Parallel arcing (line to neutral), Series arcing (a loose, broken, or otherwise high resistance segment in a single line), Ground arcing (from line, or neutral, to ground), Overload protection (for resistance loads such as heaters; inductive loads such as motors may require additional overload protection) and from Short circuit protection.

In 2002 the NEC removed the word "receptacle" leaving "outlets"; in effect adding lights within dwelling bedrooms to the requirement [debated interpretation]. The 2005 code made it more clear that all outlets must be protected despite discussion in the code-making panel about excluding bedroom smoke detectors from the requirement. "Outlets" is defined in "Article 100 Definitions" of the NEC as "A point on the wiring system where current is taken to supply utilization equipment" and this includes receptacles, light fixtures and smoke alarms, amongst other things.

As of January 2008 only "combination type" AFCIs will meet the NEC requirement. The 2008 NEC requires the installation of combination-type AFCIs in all 15 and 20 ampere residential circuits with the exception of laundries, kitchens, bathrooms, garages and unfinished basements.

Limitations

AFCIs are designed to protect against fires caused by electrical arcing faults. However they provide no specific protection against "glowing" connections, excess current, high line voltages or low line voltages.

Glowing connections occur when relatively high electric current exists in a relatively large resistance object. Heat comes from power dissipation. Voltage (in volts, symbol=E) equals the current (in amperes, A) multiplied by the resistance (in ohms, symbol Ω). Further, power (in watts, W) equals the current (in amperes, symbol=I) multiplied by the voltage (in volts, symbol=E). (This is Watt's law, usually written as P=I*E.) For example a 60 watt lamp operating on a 120 V circuit draws 1/2 ampere of current. An 1,800 watt space heater on a 120 V circuit draws up to 15 amperes. If a bad wiring junction in a circuit has a resistance of 1 ohm, then a 60 W lamp will cause it to dissipate 0.25 watt of power (0.5 A * 0.5 A * 1 Ω). In contrast an 1,800 W heater could theoretically cause the bad wiring junction to dissipate 169 watts (13 A * 13 A * 1 Ω). Note that the current is less than 15 A because of the combined resistance of the heater plus the bad wiring junction. This energy, when dissipated in a small junction area, can generate temperatures above 1000 degrees Celsius and can ignite most flammable materials.

Bad wiring junctions can occur in utilization equipment, cords or in-situ wiring and especially in a defective switch, socket, plug, wiring connection and even at the circuit breaker or fuse panels. Terminal screws loosened by vibration, improper tightening or other causes offer increased resistance to the current, with consequent heating and potential thermal creep, see "Coefficient of expansion" in aluminium wire, which will cause the termination to loosen further and exacerbate the heating effect. In North America, high resistance junctions are sometimes observed at the terminations of aluminum wire circuits, where oxidation has caused increased resistance, resulting in thermal creep. No technology located in a circuit breaker or fuse panel could detect a high-resistance wiring fault as no measurable characteristic exists that differentiates a glow fault from normal branch circuit operation. Power Fault Circuit Interrupters (PFCI) located in receptacles are designed to prevent fires caused by glowing connections in premise wiring or panels. From the receptacle a PFCI can detect the voltage drop when high current exists in a high resistance junction. In a properly designed and maintained circuit substantial voltage drops should never occur. Proper wire terminations inside utilization equipment, such as appliances, and cords prevent high-resistance connections that could lead to fires.

Excess current can heat entire lengths of wire. Thermal circuit breakers are designed to protect against excess current through the permanent circuit wiring. However excess current through the smaller wires in equipment can exist at levels below the trip thresholds of a circuit breaker. Overload fault circuit interrupters (OFCI) are designed to protect against excess current drawn by utilization equipment. OFCIs must be located within receptacles. Both thermal circuit breakers and OFCIs are required to prevent fire ignition from excess current.

High line-voltage creates excess power and heat in utilization devices such as heaters, light bulbs, appliances, motors and other electronics. In extreme cases, this heat can ignite fires. One common source of high line voltage occurs from a 'neutral' path opening within a multi-wire branch circuit. A three-conductor cable supplying two 120V circuits using two ungrounded conductors ('hot legs') at 240V to each other, and one grounded conductor ('neutral') at 120V to each 'hot', may deliver 240V to connected 120V-rated loads if the ungrounded conductor is opened because of a failed connection or worker error. When the grounded conductor breaks or opens, the utilization equipment voltage can almost double to over 200 V with large leg-to-leg load imbalances. This extreme situation can result in almost four times the normal power and heat under load. During such overheating, some utilization equipment can reach self-ignition temperature in less than 10 minutes. Power fault circuit interrupters (PFCIs) are designed to prevent fires caused by excess voltage across loads. Voltage-trip circuit breakers detect excess line voltages but are unable to detect sub-circuit open neutral conditions.

Low line voltage can cause electro-mechanical relays to repeatedly turn off (relay opens) and on (relay closes again). If current is flowing through the load contacts it will cause arcing across the contacts when they open. The arcing can oxidize, pit and melt the contacts. This process can increase the contact resistance, superheat the relay and lead to fires. Power fault circuit interrupters are designed to prevent fires from low voltage across loads.

Interference with power line networking

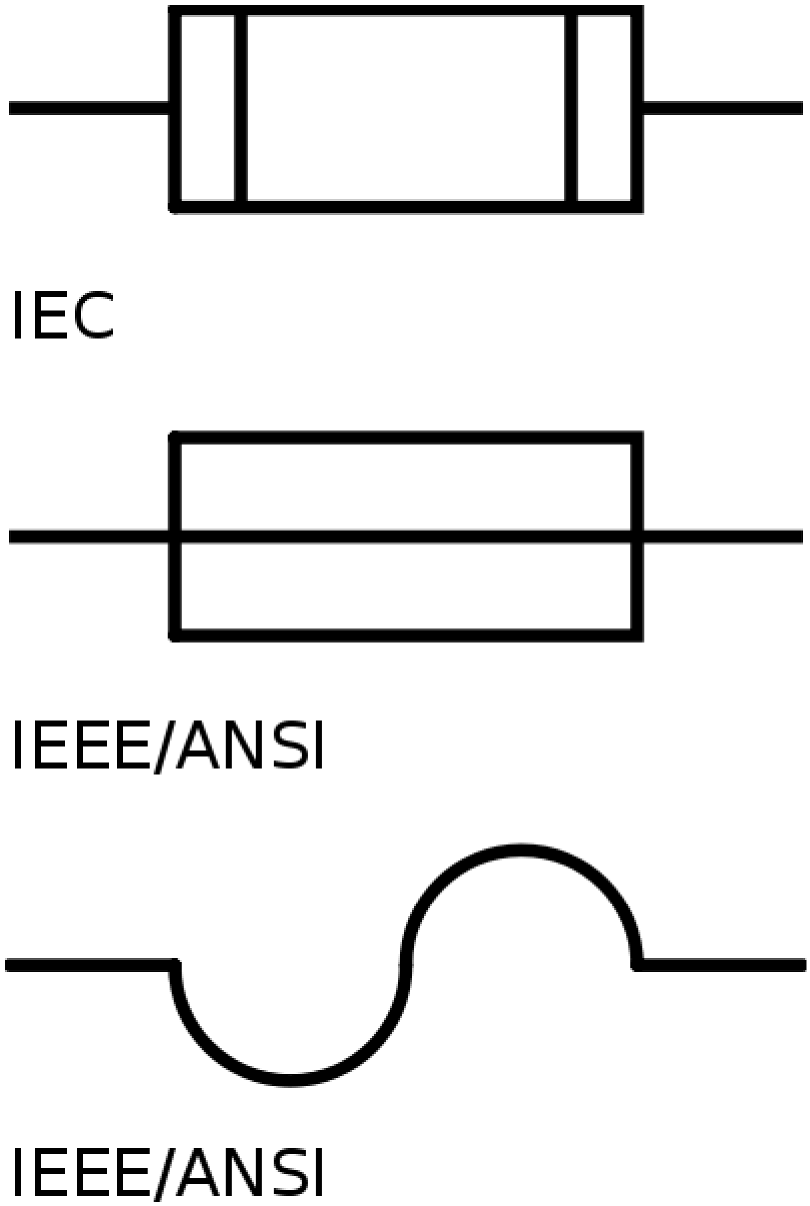
AFCIs may interfere with the operation of some power line communication technologies.

Chapter 4

Fuse (Electrical)

A miniature time-delay fuse used to protect electronic equipment, rated 0.3 amperes at 250 volts. 1.25 inches (about 32 mm) long.

200 A Industrial fuse. 80 kA breaking capacity.



Electronic symbols for a fuse. IEC (upper) and IEEE/ANSI American/Canadian (lower two) versions.

In electronics and electrical engineering a **fuse** (from the French *fusée*, Italian. *fuso*, "spindle") is a type of sacrificial overcurrent protection device. Its essential component is a metal wire or strip that melts when too much current flows, which interrupts the circuit in which it is connected. Short circuit, overload or device failure is often the reason for excessive current.

A fuse interrupts excessive current (blows) so that further damage by overheating or fire is prevented. Wiring regulations often define a maximum fuse current rating for particular circuits. Overcurrent protection devices are essential in electrical systems to limit threats to human life and property damage. Fuses are selected to allow passage of normal current and of excessive current only for short periods.

In 1847, Breguet recommended use of reduced-section conductors to protect telegraph stations from lightning strikes; by melting, the smaller wires would protect apparatus and wiring inside the building. A variety of wire or foil fusible elements were in use to protect telegraph cables and lighting installations as early as 1864.

A fuse was patented by Thomas Edison in 1890 as part of his successful electric distribution system.

Operation

A fuse consists of a metal strip or wire fuse element, of small cross-section compared to the circuit conductors, mounted between a pair of electrical terminals, and (usually) enclosed by a non-conducting and non-combustible housing. The fuse is arranged in series to carry all the current passing through the protected circuit. The resistance of the element generates heat due to the current flow. The size and construction of the element is (empirically) determined so that the heat produced for a normal current does not cause the element to attain a high temperature. If too high a current flows, the element rises to a higher temperature and either directly melts, or else melts a soldered joint within the fuse, opening the circuit.

When the metal conductor parts, an electric arc forms between the un-melted ends of the element. The arc grows in length until the voltage required to sustain the arc is higher than the available voltage in the circuit, terminating current flow. In alternating current circuits the current naturally reverses direction on each cycle, greatly enhancing the speed of fuse interruption. In the case of a current-limiting fuse, the voltage required to sustain the arc builds up quickly enough to essentially stop the fault current before the first peak of the AC waveform. This effect significantly limits damage to downstream protected devices.

The fuse element is made of zinc, copper, silver, aluminum, or alloys to provide stable and predictable characteristics. The fuse ideally would carry its rated current indefinitely, and melt quickly on a small excess. The element must not be damaged by minor harmless surges of current, and must not oxidize or change its behavior after possibly years of service.

The fuse elements may be shaped to increase heating effect. In large fuses, current may be divided between multiple strips of metal. A dual-element fuse may contain a metal strip that melts instantly on a short-circuit, and also contain a low-melting solder joint that responds to long-term overload of low values compared to a short-circuit. Fuse elements may be supported by steel or nichrome wires, so that no strain is placed on the element, but a spring may be included to increase the speed of parting of the element fragments.

The fuse element may be surrounded by air, or by materials intended to speed the quenching of the arc. Silica sand or non-conducting liquids may be used.

Characteristic parameters

Rated current I_N

A maximum current that the fuse can continuously conduct without interrupting the circuit.

Speed

The speed at which a fuse blows depends on how much current flows through it and the material of which the fuse is made. The operating time is not a fixed interval, but decreases as the current increases. Fuses have different characteristics of operating time compared to current, characterized as *fast-blow*, *slow-blow*, or *time-delay*, according to time required to respond to an overcurrent condition. A standard fuse may require twice its rated current to open in one second, a fast-blow fuse may require twice its rated current to blow in 0.1 seconds, and a slow-blow fuse may require twice its rated current for tens of seconds to blow.

Fuse selection depends on the load's characteristics. Semiconductor devices may use a fast or *ultrafast* fuse since semiconductor devices heat rapidly when excess current flows. The fastest blowing fuses are designed for the most sensitive electrical equipment, where even a short exposure to an overload current could be very damaging. Normal fast-blow fuses are the most general purpose fuses. The time delay fuse (also known as anti-surge, or slow-blow) are designed to allow a current which is above the rated value of the fuse to flow for a short period of time without the fuse blowing. These types of fuse are used on equipment such as motors, which can draw larger than normal currents for up to several seconds while coming up to speed.

The I^2t value

A measure of energy required to blow the fuse element and so a measure of the damaging effect of overcurrent on protected devices; sometimes known as the let-through energy. Unique I^2t parameters are provided by charts in manufacturer data sheets for each fuse family. The energy is mainly dependent on current and time for fuses.

Breaking capacity

The breaking capacity is the maximum current that can safely be interrupted by the fuse. Generally, this should be higher than the prospective short circuit current. Miniature fuses may have an interrupting rating only 10 times their rated current. Some fuses are designated High Rupture Capacity (HRC) and are usually filled with sand or a similar material. Fuses for small, low-voltage, usually residential, wiring systems are commonly rated, in North American practice, to interrupt 10,000 amperes. Fuses for larger power systems must have higher interrupting ratings, with some low-voltage current-limiting high interrupting fuses rated for 300,000 amperes. Fuses for high-voltage equipment, up to 115,000 volts, are rated by the total apparent power (megavolt-amperes, MVA) of the fault level on the circuit.

Rated voltage

Voltage rating of the fuse must be greater than or equal to what would become the open circuit voltage. For example, a glass tube fuse rated at 32 volts would not reliably interrupt current from a voltage source of 120 or 230 V. If a 32 V fuse attempts to interrupt the 120 or 230 V source, an arc may result. Plasma inside that glass tube fuse may continue to conduct current until current eventually so diminishes that plasma reverts to an insulating gas. Rated voltage should be larger than the maximum voltage source it would have to disconnect. This requirement applies to every type of fuse.

Rated voltage remains same for any one fuse, even when similar fuses are connected in series. Connecting fuses in series does not increase the rated voltage of the combination (nor of any one fuse).

Medium-voltage fuses rated for a few thousand volts are never used on low voltage circuits, because of their cost and because they cannot properly clear the circuit when operating at very low voltages.

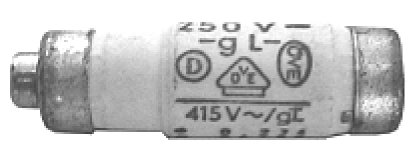
Voltage drop

A voltage drop across the fuse is usually provided by its manufacturer. Resistance may change when a fuse becomes hot due to energy dissipation while conducting higher currents. This resulting voltage drop should be taken into account, particularly when using a fuse in low-voltage applications. Voltage drop often is not significant in more traditional wire type fuses, but can be significant in other technologies such as resettable fuse (PPTC) type fuses.

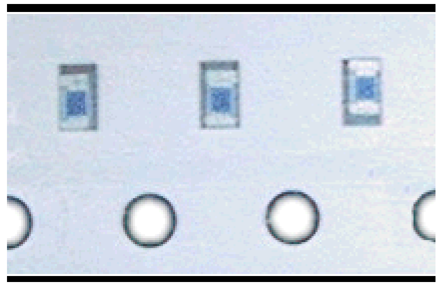
Temperature derating

Ambient temperature will change a fuse's operational parameters. A fuse rated for 1 A at 25 °C may conduct up to 10% or 20% more current at −40 °C and may open at 80% of its rated value at 100 °C. Operating values will vary with each fuse family and are provided in manufacturer data sheets.

Markings



A sample of the many markings that can be found on a fuse.



Surface Mount Fuses on 8 mm tape. Each fuse measures 1.6 mm × 0.79 mm and has no markings.

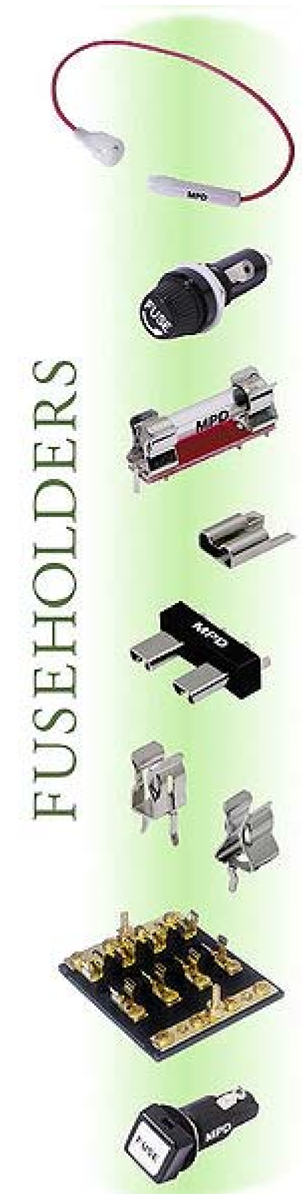
Most fuses are marked on the body or end caps with markings that indicate their ratings. Surface-mount technology "chip type" fuses feature few or no markings, making identification very difficult.

Similar appearing fuses may have significantly different properties, identified by their markings. Fuse markings will generally convey the following information, either explicitly as text, or else implicit with the approval agency marking for a particular type:

- Ampere rating of the fuse.
- Voltage rating of the fuse.
- Time-current characteristic; i.e. fuse speed.
- Approvals by national and international standards agencies.
- Manufacturer/part number/series.
- Breaking capacity

Packages and materials

Fuses come in a vast array of sizes and styles to serve in many applications, manufactured in standardised package layouts to make them easily interchangeable. Fuse bodies may be made of ceramic, glass, plastic, fiberglass, molded mica laminates, or molded compressed fibre depending on application and voltage class.



Multiple fuseholders

Cartridge (ferrule) fuses have a cylindrical body terminated with metal end caps. Some cartridge fuses are manufactured with end caps of different sizes to prevent accidental insertion of the wrong fuse rating in a holder, giving them a bottle shape.

Fuses for low voltage power circuits may have bolted blade or tag terminals which are secured by screws to a fuseholder. Some blade-type terminals are held by spring clips. Blade type fuses often require the use of a special purpose extractor tool to remove them from the fuse holder.

Renewable fuses have replaceable fuse elements, allowing the fuse body and terminals to be reused if not damaged after a fuse operation.

Fuses designed for soldering to a printed circuit board have radial or axial wire leads. Surface mount fuses have solder pads instead of leads.

High-voltage fuses of the expulsion type have fiber or glass-reinforced plastic tubes and an open end, and can have the fuse element replaced.

Semi-enclosed fuses are fuse wire carriers in which the fusible wire itself can be replaced. These are used in consumer units in some parts of the world, but are becoming less common.

While glass fuses have the advantage of a fuse element visible for inspection purposes, they have a low breaking capacity which generally restricts them to applications of 15 A or less at 250 V_{AC}. Ceramic fuses have the advantage of a higher breaking capacity, facilitating their use in circuits with higher current and voltage. Filling a fuse body with sand provides additional cooling of the arc and increases the breaking capacity of the fuse. Medium-voltage fuses may have liquid-filled envelopes to assist in the extinguishing of the arc. Some types of distribution switchgear use fuse links immersed in the oil that fills the equipment.

Fuse packages may include a rejection feature such as a pin, slot, or tab, which prevents interchange of otherwise similar appearing fuses. For example, fuse holders for North American class RK fuses have a pin that prevents installation of similar-appearing class H fuses, which have a much lower breaking capacity and a solid blade terminal that lacks the slot of the RK type.

Dimensions

Fuses can be built with different sized enclosures to prevent interchange of different ratings or types of fuse. For example, *bottle style* fuses distinguish between ratings with different cap diameters. Automotive glass fuses were made in different lengths, to prevent high-rated fuses being installed in a circuit intended for a lower rating.

Special features

Glass cartridge and plug fuses allow direct inspection of the fusible element. Other fuses have other indication methods including:

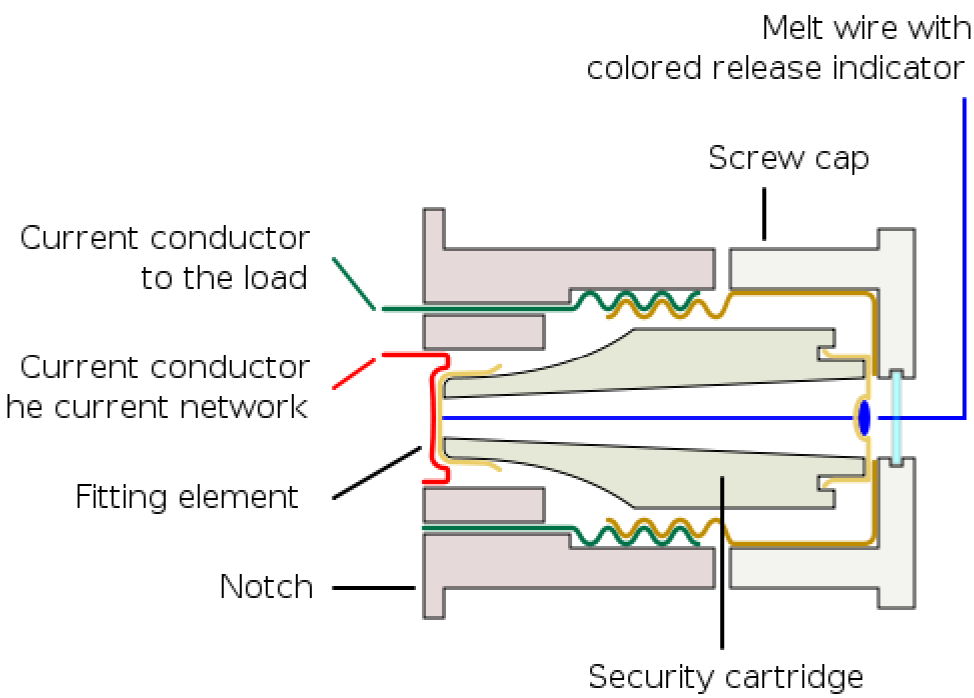
- Indicating pin or striker pin — extends out of the fuse cap when the element is blown.
- Indicating disc — a coloured disc (flush mounted in the end cap of the fuse) falls out when the element is blown.
- Element window — a small window built into the fuse body to provide visual indication of a blown element.
- External trip indicator — similar function to striker pin, but can be externally attached (using clips) to a compatible fuse.

Some fuses allow a special purpose micro switch or relay unit to be fixed to the fuse body. When the fuse element blows, the indicating pin extends to activate the micro switch or relay, which, in turn, triggers an event.

Some fuses for medium-voltage applications use two separate barrels and two fuse elements in parallel.

Fuse standards

IEC 60269 fuses



Cross section of a screw-type fuse holder with Diazed fuse

The International Electrotechnical Commission publishes standard 60269 for low-voltage power fuses. The standard is in four volumes, which describe general requirements, fuses for industrial and commercial applications, fuses for residential applications, and fuses to protect semiconductor devices. The IEC standard unifies several national standards, thereby improving the interchangeability of fuses in international trade. All fuses of different technologies tested to meet IEC standards will have similar time-current characteristics, which simplifies design and maintenance.

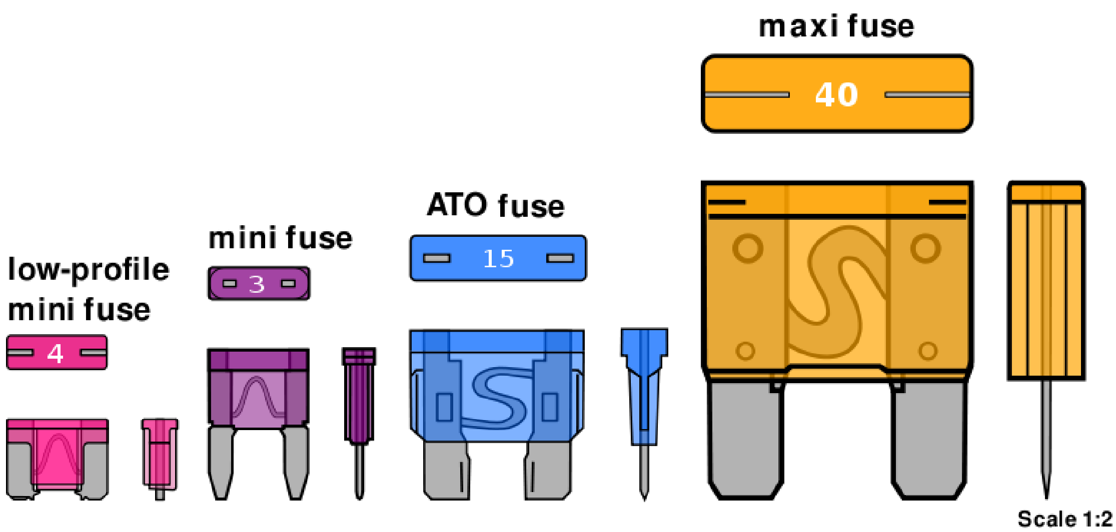
UL 248 fuses (North America)

In the United States and Canada, low-voltage fuses to 1 kV AC rating are made in accordance with Underwriters Laboratories standard UL 248 or the harmonized Canadian

Standards Association standard C22.2 No. 248. This standard applies to fuses rated 1 kV or less, AC or DC, and with breaking capacity up to 200 kA. These fuses are intended for installations following Canadian Electrical Code, Part I (CEC), or the National Electrical Code, NFPA 70 (NEC).

IEC and UL nomenclature varies slightly. IEC standards refer to a "fuse" as the assembly of a fuse link and fuse holder. In North American standards, the *fuse* is the replaceable portion of the assembly, and a *fuse link* would be a bare metal element for installation in a fuse.

Automotive fuses



Blade type fuses come in four physical sizes: low-profile mini, mini, regular and maxi

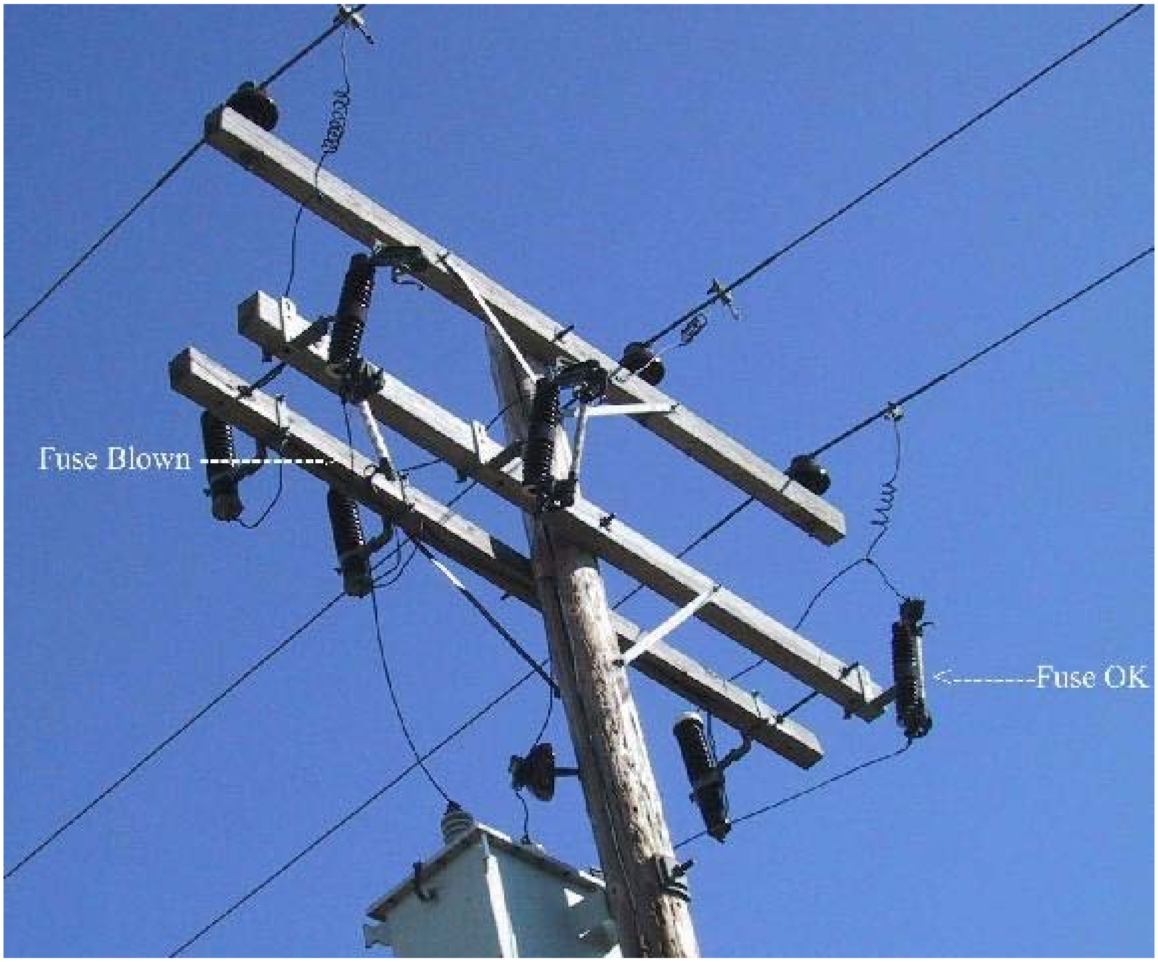
Automotive fuses are used to protect the wiring and electrical equipment for vehicles. There are several different types of automotive fuses and their usage is dependant upon the specific application, voltage, and current demands of the electrical circuit. Automotive fuses can be mounted in fuse blocks, inline fuse holders, or fuse clips. Some automotive fuses are occasionally used in non-automotive electrical applications. Standards for automotive fuses are published by SAE International (formerly known as the Society of Automotive Engineers).

Automotive fuses can be classified into four distinct categories:

- Blade fuses
- Glass tube or Bosch type
- Fusible links
- Fuse limiters

Most automotive fuses rated at 32 volts are used on circuits rated 24 volts DC and below. Some vehicles use a dual 12/42 V DC electrical system that will require a fuse rated at 58 V DC.

High voltage fuses



A set of pole-top fusible cutouts with one fuse blown, protecting a transformer- the white tube on the left is hanging down

Fuses are used on power systems up to 115,000 volts AC. High-voltage fuses are used to protect instrument transformers used for electricity metering, or for small power transformers where the expense of a circuit breaker is not warranted. For example, in distribution systems, a power fuse may be used to protect a transformer serving 1–3 houses. A circuit breaker at 115 kV may cost up to five times as much as a set of power fuses, so the resulting saving can be tens of thousands of dollars. Pole-mounted distribution transformers are nearly always protected by a fusible cutout, which can have the fuse element replaced using live-line maintenance tools.

Large power fuses use fusible elements made of silver, copper or tin to provide stable and predictable performance. High voltage *expulsion fuses* surround the fusible link with gasevolving substances, such as boric acid. When the fuse blows, heat from the arc causes the boric acid to evolve large volumes of gases. The associated high pressure (often greater than 100 atmospheres) and cooling gases rapidly quench the resulting arc. The hot gases are then explosively expelled out of the end(s) of the fuse. Such fuses can only be used outdoors.

A 115 kV high-voltage fuse in a substation near a hydroelectric power plant.

Older medium-voltage fuse for a 20 kV network

High voltage high power fuses are standalone protective switching devices used to 115 kV. They are used in power supply networks and for distribution uses. The most frequent application is in transformer circuits, with further uses in motor circuits and capacitor banks. These type of fuses may have an impact pin to operate a switch mechanism, so that all three phases are interrupted if any one fuse blows.

High-power fuse means that these fuses can interrupt several kiloamperes. Some manufacturers have tested their fuses for up to 63 kA cut-off current.

Fuses compared with circuit breakers

Fuses have the advantages of often being less costly and simpler than a circuit breaker for similar ratings. The blown fuse must be replaced with a new device which is less convenient than simply resetting a breaker and therefore likely to discourage people from ignoring faults. On the other hand, replacing a fuse without isolating the circuit first (most building wiring designs do not provide individual isolation switches for each fuse) can be dangerous in itself, particularly if the fault is a short circuit.

High rupturing capacity fuses can be rated to safely interrupt up to 300,000 amperes at 600 V AC. Special current-limiting fuses are applied ahead of some molded-case breakers to protect the breakers in low-voltage power circuits with high short-circuit levels.

Current-limiting fuses operate so quickly that they limit the total "let-through" energy that passes into the circuit, helping to protect downstream equipment from damage. These fuses open in less than one cycle of the AC power frequency; circuit breakers cannot match this speed.

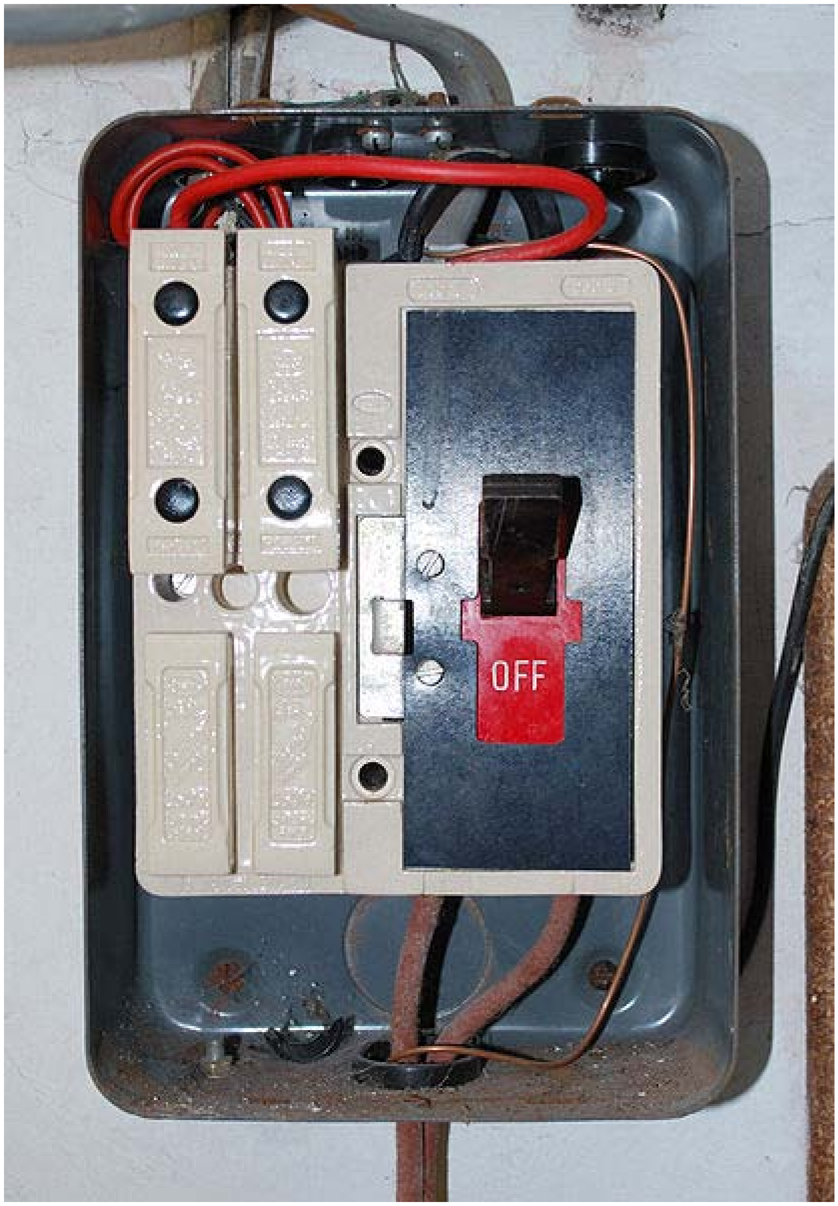
Some types of circuit breakers must be maintained on a regular basis to ensure their mechanical operation during an interruption. This is not the case with fuses, which rely on melting processes where no mechanical operation is required for the fuse to operate under fault conditions.

In a multi-phase power circuit, if only one fuse opens, the remaining phases will have higher than normal currents, and unbalanced voltages, with possible damage to motors. Fuses only sense overcurrent, or to a degree, over-temperature, and cannot usually be used independently with protective relaying to provide more advanced protective functions, for example, ground fault detection.

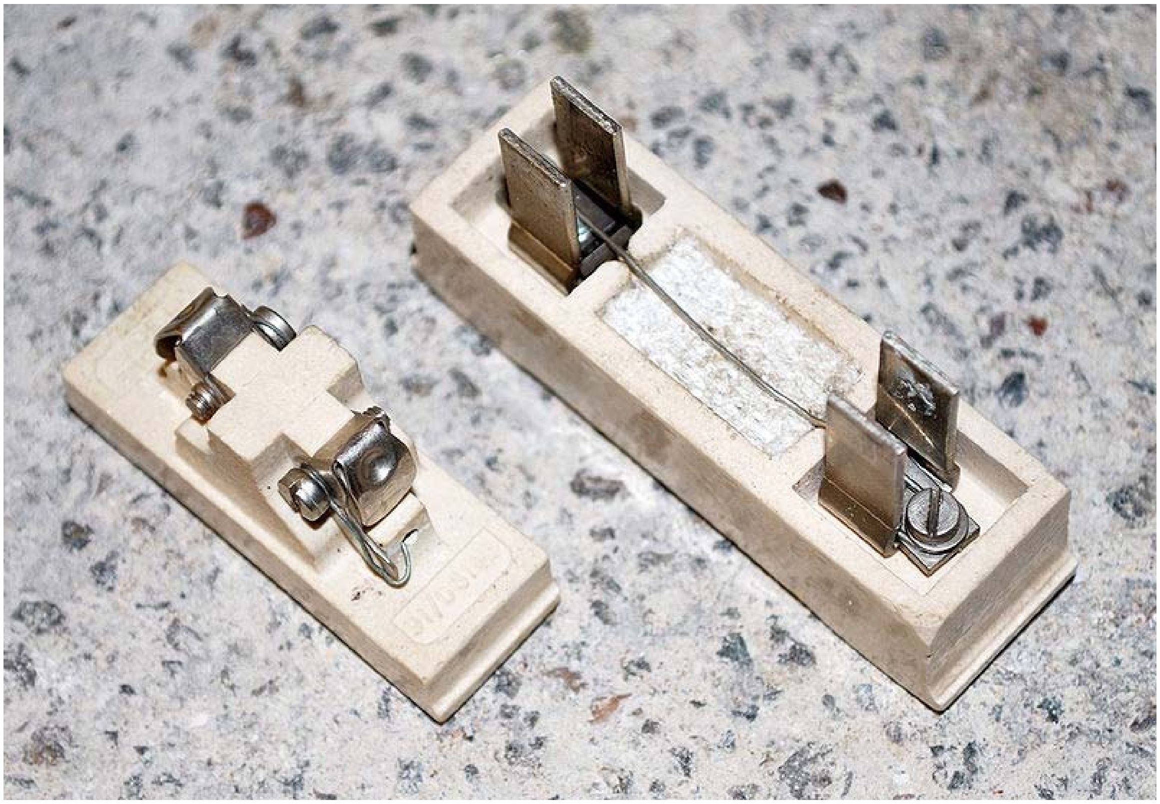
Some manufacturers of medium-voltage distribution fuses combine the overcurrent protection characteristics of the fusible element with the flexibility of relay protection by adding a pyrotechnic device to the fuse operated by external protective relays.

Fuse boxes

- Rewirable fuses

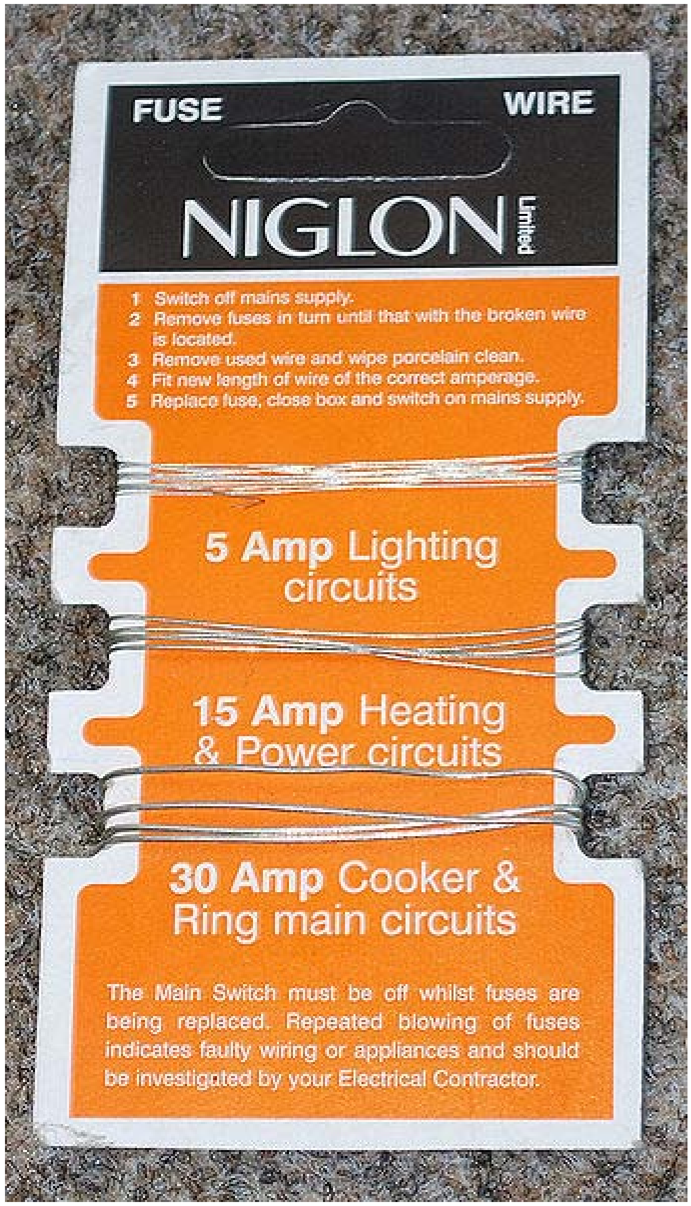


MEM rewirable fuse box



MEM rewirable fuse holders (30 A and 15 A)

Wylex fuse box



fuse wire as sold to UK consumers

In the UK, older electrical consumer units (also called fuse boxes) are fitted either with semi-enclosed (rewirable) fuses (BS 3036) or cartridge fuses (BS 1361). (Fuse wire is commonly supplied to consumers as short lengths of 5 A-, 15 A- and 30 A-rated wire wound on a piece of cardboard.) Modern consumer units usually contain miniature circuit breakers (MCBs) instead of fuses, though cartridge fuses are sometimes still used, as MCBs are prone to nuisance tripping.

Renewable fuses (rewirable or cartridge) allow user replacement, but this can be hazardous as it is easy to put a higher-rated or double fuse element (link or wire) into the holder (*overfusing*), or simply fitting it with copper wire or even a totally different type of conducting object (hairpins, paper clips, nails, etc.) to the existing carrier. Such tampering will not be visible without full inspection of the fuse. Fuse wire was never used in North America for this reason, although renewable fuses continue to be made for distribution boards.

The fuse boxes pictured in this section are (right) a MEM consumer unit with four rewirable fuse holders (two 30A and two 15A) installed c. 1957 (cover removed); a Wylex standard unit with eight rewirable fuse holders.

The *Wylex standard* consumer unit was very popular in the United Kingdom until the wiring regulations started demanding Residual-Current Devices (RCDs) for sockets that could feasibly supply equipment outside the equipotential zone. The design does not allow for fitting of RCDs or RCBOs. Some Wylex standard models were made with an RCD instead of the main switch, but (for consumer units supplying the entire installation) this is no longer compliant with the wiring regulations as alarm systems should **not** be RCD-protected. There are two styles of fuse base that can be screwed into these units: one designed for rewirable fusewire carriers and one designed for cartridge fuse carriers. Over the years MCBs have been made for both styles of base. In both cases, higher rated carriers had wider pins, so a carrier couldn't be changed for a higher rated one without also changing the base. Cartridge fuse carriers are also now available for DIN-rail enclosures.

In North America, fuses were used in buildings wired before 1960. These "Edison Base" fuses would screw into a fuse socket similar to Edison-base incandescent lamps. Ratings were 5, 10, 15, 20, 25, and 30 amperes. To prevent installation of fuses with an excessive current rating, later fuse boxes included rejection features in the fuseholder socket. Some installations use resettable miniature thermal circuit breakers, which screw into a fuse socket.

One form of fuse box abuse was to put a penny in the socket, which defeated overcurrent protection and resulted in a dangerous condition.

In the 1950s, fuses in new residential or industrial construction for branch circuit protection were superseded by low voltage circuit breakers.

Coordination of fuses in series

Where several fuses are connected in series at the various levels of a power distribution system, it is desirable to blow (clear) only the fuse (or other overcurrent device) electrically closest to the fault. This process is called "coordination" and may require the time-current characteristics of two fuses to be plotted on a common current basis. Fuses are selected so that the minor, branch, fuse disconnects its circuit well before the supplying, major, fuse starts to melt. In this way, only the faulty circuit is interrupted with minimal disturbance to other circuits fed by a common supplying fuse.

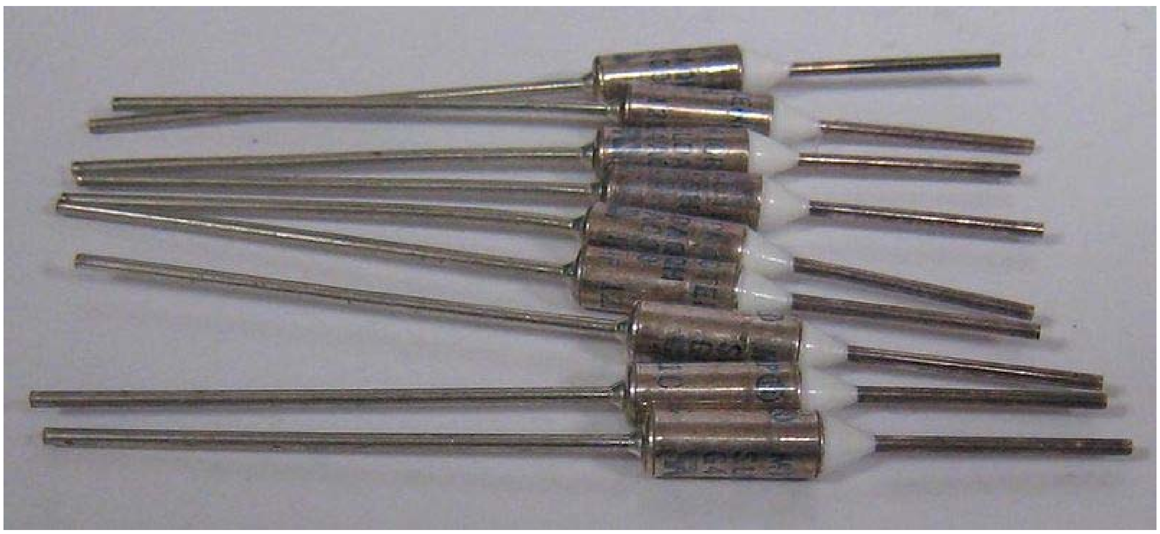
Where the fuses in a system are of similar types, simple rule-of-thumb ratios between ratings of the fuse closest to the load and the next fuse towards the source can be used.

Other fuse types

Resettable fuses

So-called self-resetting fuses use a thermoplastic conductive element known as a Polymeric Positive Temperature Coefficient (or PPTC) thermistor that impedes the circuit during an overcurrent condition (by increasing device resistance). The PPTC thermistor is self-resetting in that when current is removed, the device will cool and revert back to low resistance. These devices are often used in aerospace/nuclear applications where replacement is difficult, or on a computer motherboard so that a shorted mouse or keyboard does not cause motherboard damage.

Thermal fuses



thermal cutoff

A *thermal fuse* is often found in consumer equipment such as coffee makers or hair dryers or transformers powering small consumer electronics devices. They contain a fusible, temperature-sensitive alloy which holds a spring contact mechanism normally closed. When the surrounding temperature gets too high, the alloy melts and allows the spring contact mechanism to break the circuit. The device can be used to prevent a fire in a hair dryer for example, by cutting off the power supply to the heater elements when the air flow is interrupted (e.g., the blower motor stops or the air intake becomes accidentally blocked). Thermal fuses are a 'one shot', non-resettable device which must be replaced once they have been activated (blown).

Chapter 5

Electrical Ballast

"Choke ballast" (inductor) used in older lighting. This example is from a tanning bed. Requires a lamp starter (below) and capacitor.

Lamp starter, required with some inductor type ballasts. Connects both ends of the lamp together to "preheat" the lamp ends for 1 second before lighting.

An **electrical ballast** (sometimes called **control gear**) is a device intended to limit the amount of current in an electric circuit.

Ballasts vary greatly in complexity. They can be as simple as a series resistor as commonly used with small neon lamps or light-emitting diodes (LEDs). For higher-power installations, too much energy would be wasted in a resistive ballast, so alternatives are used that depend upon the reactance of inductors, capacitors, or both. Finally, ballasts can be as complex as the computerized, remote-controlled electronic ballasts now often used with fluorescent lamps.

Current limiting

Ballasts stabilize the current through an electrical load. These are most often used when an electrical circuit or device presents a negative (differential) resistance to the supply. If such a device were connected to a constant-voltage power supply, it would draw an increasing amount of current until it was destroyed or caused the power supply to fail. To prevent this, a ballast provides a positive resistance or reactance that limits the ultimate current to an appropriate level. In this way, the ballast provides for the proper operation of the negative-resistance device by appearing to be a legitimate, stable resistance in the circuit.

An example of a negative-resistance device is a gas-discharge lamp, where after lamp ignition, increasing arc current reduces the voltage drop.

Ballasts can also be used simply to deliberately reduce the current in an ordinary, positive-resistance circuit.

Prior to the advent of solid-state ignition, automobile ignition systems commonly included a ballast resistor to regulate the voltage applied to the ignition system.

Although LEDs are positive resistance devices, they have insufficient resistance to regulate their current consumption when operated from a voltage controlled source, so ballasts are used to control the current through the LED. Because the power dissipation is minuscule, simple resistor ballasts are normally used.

Resistors

A **ballast resistor** compensates for normal or incidental changes in the physical state of a system. It may be a fixed or variable resistor.

Fixed resistors

For simple, low-powered loads such as a neon lamp or LED, a fixed resistor is commonly used. Because the resistance of the ballast resistor is large it dominates the current in the circuit, even in the face of negative resistance introduced by the neon lamp.

The term also refers to an automobile engine component that lowers the supply voltage to the ignition system after the engine has been started. Because cranking the engine causes a very heavy load on the battery, the system voltage can drop quite low during cranking.

To allow the engine to start, the ignition system must be designed to operate on this lower voltage. But once cranking is completed, the normal operating voltage is regained; this voltage would overload the ignition system. To avoid this problem, a ballast resistor is inserted in series with the supply voltage feeding the ignition system. Occasionally, this ballast resistor will fail and the classic symptom of this failure is that the engine runs while being cranked (while the resistor is bypassed) but stalls immediately when cranking ceases (and the resistor is re-connected in the circuit).

Modern electronic ignition systems do not require a ballast resistor as they are flexible enough to operate on the low cranking voltage or the ordinary operating voltage.

In some old AC/DC receivers (universal sets), the vacuum tube heaters are connected in series. Since the voltage drop across all the filaments in series is sometimes less than the full mains voltage, it was often necessary to get rid of the excess voltage. A ballast resistor was often used for this purpose, as it was cheap and worked with both AC and DC.

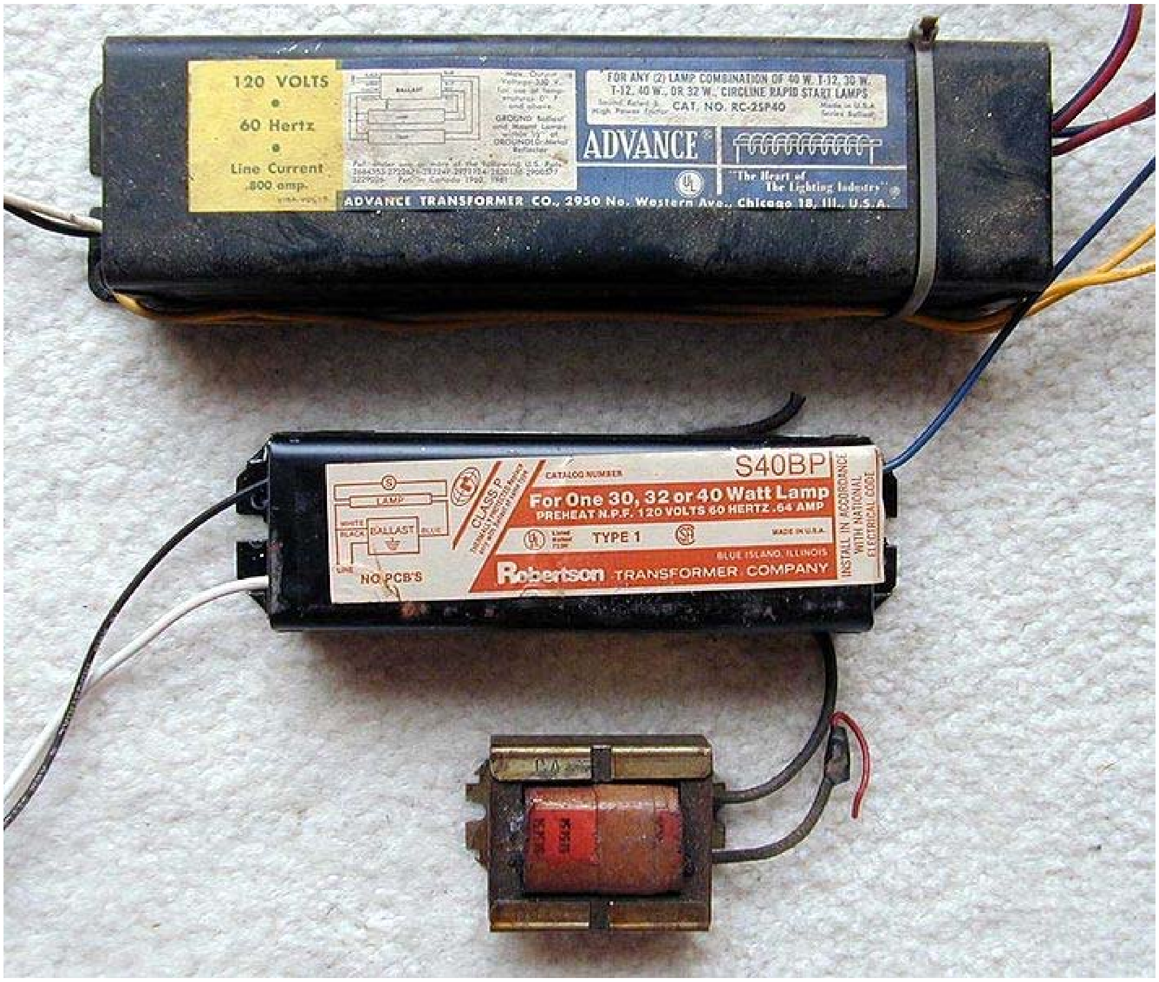
Self-variable resistors

Some ballast resistors have the property of increasing in resistance as current through them increases, and decreasing in resistance as current decreases. Physically, some such devices are often built quite like incandescent lamps. Like the tungsten filament of an ordinary incandescent lamp, if current increases, the ballast resistor gets hotter, its resistance goes up, and its voltage drop increases. If current decreases, the ballast resistor gets colder, its resistance drops, and the voltage drop decreases. Therefore the ballast resistor reduces variations in current, despite variations in applied voltage or changes in the rest of an electric circuit. These devices are sometimes termed barretters.

This property can lead to more precise current control than merely choosing an appropriate fixed resistor. The power lost in the resistive ballast is also reduced because a smaller portion of the overall power is dropped in the ballast compared to what might be required with a fixed resistor.

In times past, household clothes dryers sometimes incorporated a germicidal lamp in series with an ordinary incandescent lamp; the incandescent lamp operated as the ballast for the germicidal lamp. A commonly used light in the home in the 1960s in 220-240V countries was a circleline tube ballasted by an under-run regular mains filament lamp. Self ballasted mercury-vapor lamps incorporate ordinary tungsten filaments within the overall envelope of the lamp to act as the ballast, and it supplements the otherwise lacking red area of the light spectrum produced.

Reactive ballasts



Several typical magnetic ballasts for fluorescent lamps. The top is a high-power factor rapid start series ballast for two 30-40W lamps. The middle is a low power factor preheat ballast for a single 30-40W lamp while the bottom ballast is a simple inductor used with a 15W preheat lamp.

Because of the power that would be lost, resistors are not used as ballasts for lamps of more than about two watts. Instead, a reactance is used. Losses in the ballast due to its resistance and losses in its magnetic core may be significant, on the order of 5 to 25% of the lamp input wattage. Practical lighting design calculations must allow for ballast loss in estimating the running cost of a lighting installation.

An inductor is very common in line-frequency ballasts to provide the proper starting and operating electrical condition to power a fluorescent lamp, neon lamp, or high intensity discharge (HID) lamp. (Because of the use of the inductor, such ballasts are usually called *magnetic ballasts*.) The inductor has two benefits:

1. Its reactance limits the power available to the lamp with only minimal power losses in the inductor

2. The voltage spike produced when current through the inductor is rapidly interrupted is used in some circuits to first strike the arc in the lamp.

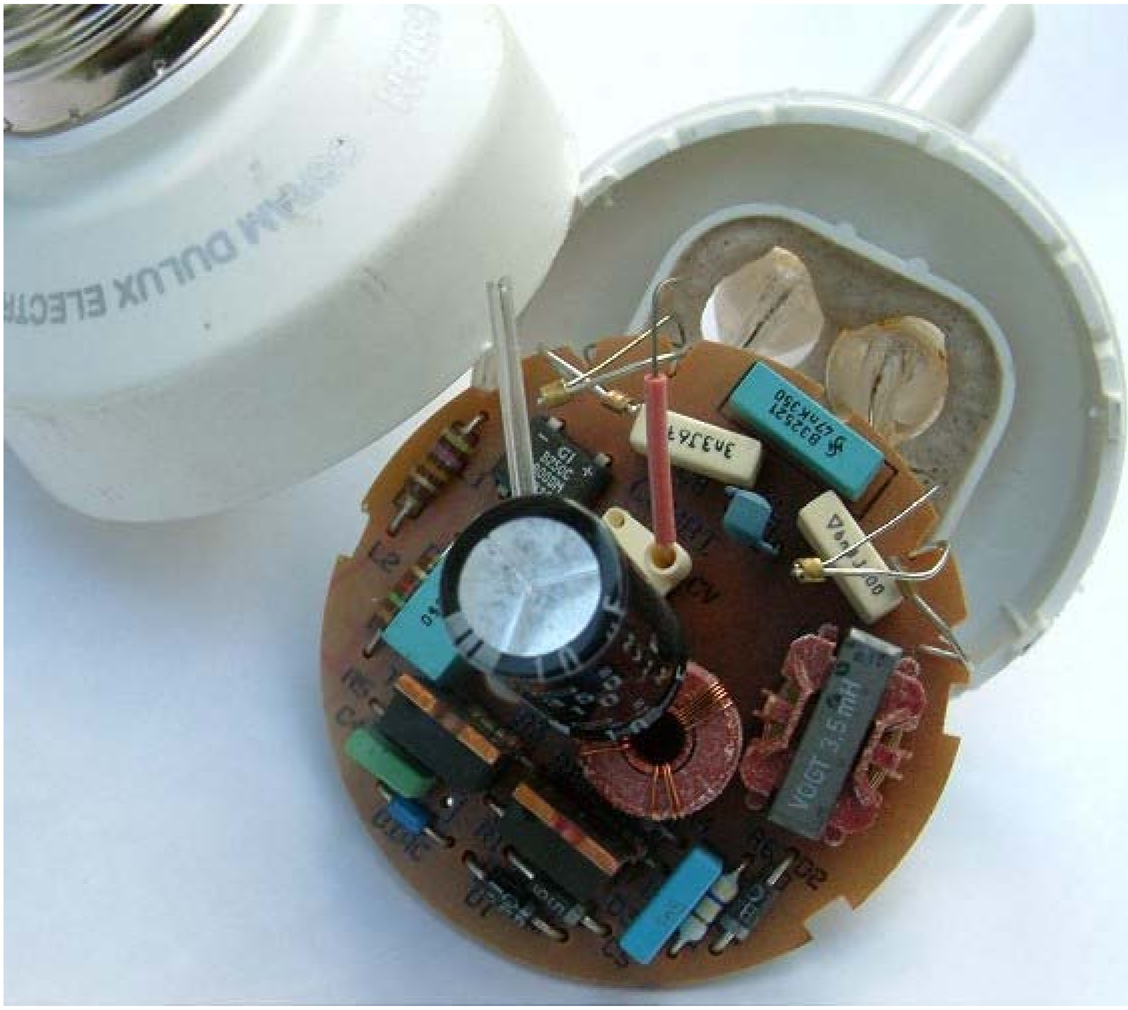
A disadvantage of the inductor is that current is shifted out of phase with the voltage, producing a poor power factor. In more expensive ballasts, a capacitor is often paired with the inductor to correct the power factor. In ballasts that control two or more lamps, line-frequency ballasts commonly use different phase relationships between the multiple lamps. This not only mitigates the flicker of the individual lamps, it also helps maintain a high power factor. These ballasts are often called *lead-lag* ballasts because the current in one lamp leads the mains phase and the current in the other lamp lags the mains phase.

For large lamps, line voltage may not be sufficient to start the lamp, so an autotransformer winding is included in the ballast to step up the voltage. The autotransformer is designed with enough leakage inductance so that the current is appropriately limited.

Because of the large inductors and capacitors that must be used, reactive ballasts operated at line frequency tend to be large and heavy. They commonly also produce acoustic noise (line-frequency hum).

Prior to 1980 in the United States, PCB-based oils were used as an insulating oil in many ballasts to provide cooling and electrical isolation.

Electronic ballasts



Electronic ballast of a compact fluorescent lamp

An **electronic lamp ballast** uses solid state electronic circuitry to provide the proper starting and operating electrical condition to power one or more fluorescent lamps and more recently HID lamps. Electronic ballasts usually change the frequency of the power from the standard mains (e.g., 60 Hz in U.S.) frequency to 20,000 Hz or higher, substantially eliminating the stroboscopic effect of flicker (a product of the line frequency) associated with fluorescent lighting. In addition, because more gas remains ionized in the arc stream, the lamps actually operate at about 9% higher efficacy above approximately 10 kHz. Lamp efficacy increases sharply at about 10 kHz and continues to improve until approximately 20 kHz. Because of the higher efficiency of the ballast itself and the improvement of lamp efficacy by operating at a higher frequency, electronic ballasts offer higher system efficacy for low pressure lamps like the fluorescent lamp. For HID lamps there is no improvement of the lamp efficacy in using higher frequency, but for these lamps the ballast losses are lower at higher frequencies and also the light depreciation is lower meaning more light after a given operating time of say 10 000 hours. Some HID lamp types like the Ceramic discharge metal halide lamp have reduced reliability when operated at high frequencies in the range of 20kHz to 200 kHz and for these lamps a square wave low frequency current drive is mostly used with frequency in the range of 100 to 400 Hz, with the same advantage of lower light depreciation. Electronic ballasts are often based on the SMPS topology, first rectifying the input power and then chopping it at a high frequency. Advanced electronic ballasts may allow dimming via pulse-width modulation or via changing the frequency to a higher value and remote control and monitoring via networks such as LonWorks, DALI, DMX-512, DSI or simple analog control using a 0-10V DC brightness control signal. Recently also systems remotely controlling the dim level via a wireless mesh network have been introduced.

Fluorescent lamp ballasts

Instant start

An instant start ballast starts lamps without heating the cathodes at all by using high voltage (around 600 V). It is the most energy efficient type, but gives the least number of starts from a lamp as emissive oxides are blasted from the cold cathode surfaces each time the lamp is started. This is the best type for installations where lamps are not turned on and off very often.

Rapid start

A rapid start ballast applies voltage and heats the cathodes simultaneously. It provides superior lamp life and more cycle life, but uses slightly more energy as the cathodes in each end of the lamp continue to consume heating power as the lamp operates. A dimming circuit can be used with a dimming ballast, which maintains the heating current while allowing lamp current to be controlled.

Programmed start

A programmed-start ballast is a more advanced version of rapid start. This ballast applies power to the filaments first, then after a short delay to allow the cathodes to preheat, applies voltage to the lamps to strike an arc. This ballast gives the best life and most starts from lamps, and so is preferred for applications with very frequent power cycling such as vision examination rooms and restrooms with a motion detector switch.

Ballast factor

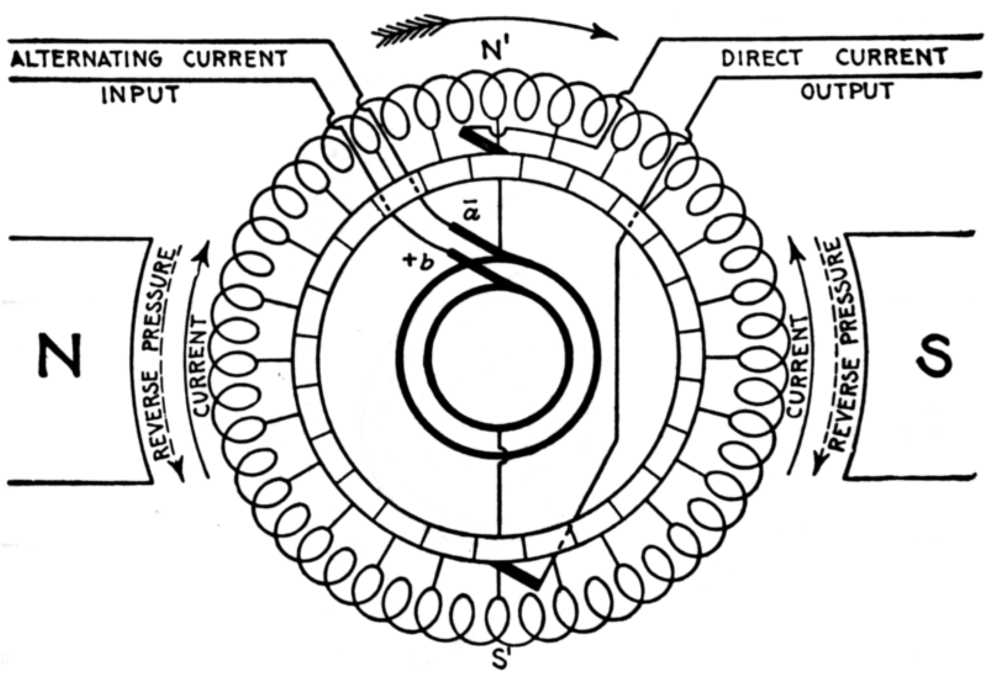
For a lighting ballast, the *ballast factor* is defined as the light output (in lumens) with a test ballast, compared to the light output with a laboratory reference ballast that operates the lamp at its specified nominal power rating. The ballast factor of practical ballasts must be considered in lighting design; a low ballast factor may save energy, but will produce less light. With fluorescent lamps, an electronic ballast may produce more light than the reference test ballast, which operates the lamp with line frequency current; such electronic ballasts have a ballast factor greater than one.

Chapter 6

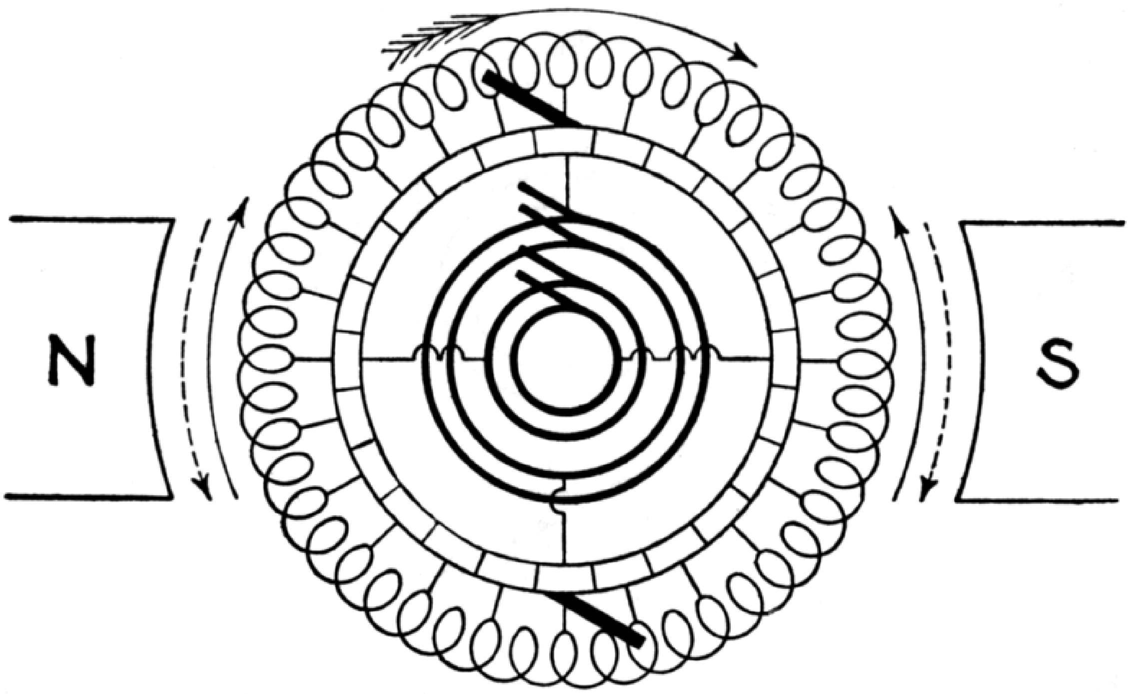
Rotary Converter

A **rotary converter** is a type of electrical machine which acts as a mechanical rectifier or inverter. It was used to convert AC to DC or DC to AC power before the advent of chemical or solid state power rectification. They were commonly used to provide DC power for commercial, industrial and railway electrification from an AC power source.

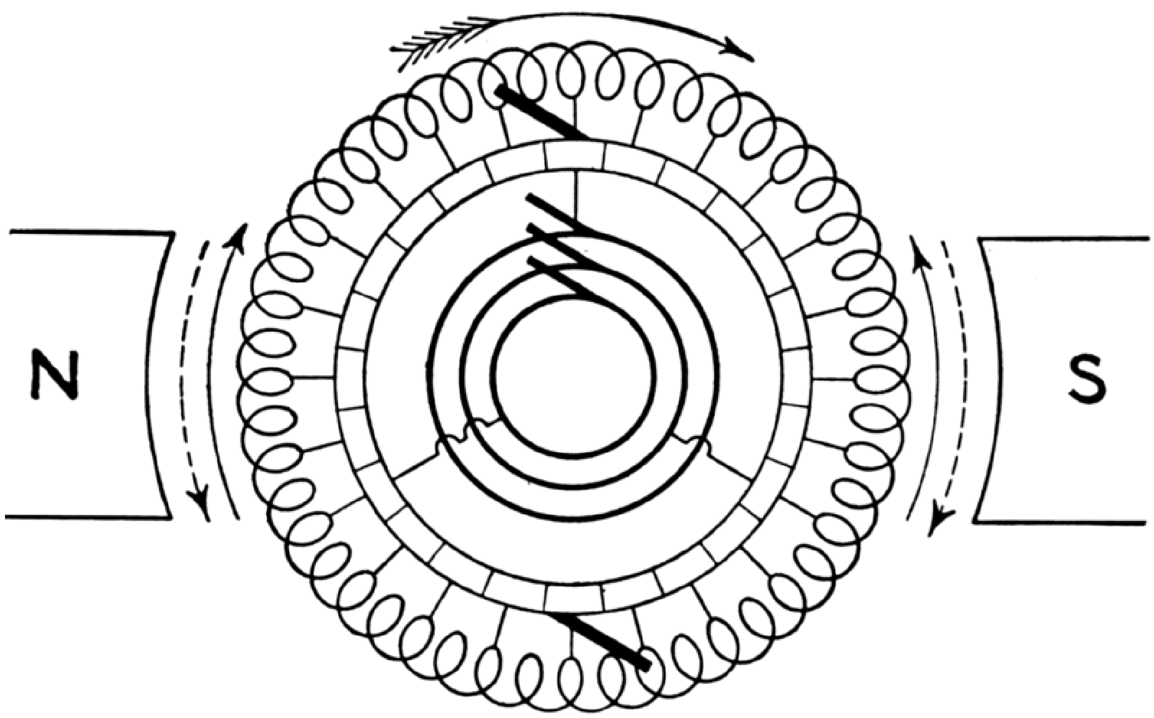
Principles of operation



Wiring schematic for a simplified bipolar field Gramme ring single-phase to direct current rotary converter. (In actual use, the converter is drum-wound and uses a multipolar field.)



Wiring schematic for a simpllfied two-phase to direct current rotary converter, with the second phase connected at right angles to the first.



Wiring schematic for a simpllfied three-phase to direct current rotary converter, with the phases separated by 120 degrees on the commutator.

The rotary converter can be thought of as a motor-generator where the two machines share a single rotating armature and set of field coils. The basic construction of the rotary converter consists of a DC generator (dynamo) with a set of slip rings tapped into its rotor windings at evenly spaced intervals. When a dynamo is spun the electric currents in its rotor windings alternate as it rotates in the magnetic field of the stationary field windings. This alternating current is rectified by means of a commutator which allows DC current to be extracted from the rotor. This principle is taken advantage of by energizing the same rotor windings with AC power which causes the machine to act as a synchronous AC motor. The rotation of the energized coils excites the stationary field windings producing part of the DC current. The other part is AC current from the slip rings which is directly rectified into DC by the commutator. This makes the rotary converter a hybrid dynamo and mechanical rectifier. When used in this way it is referred to as a synchronous rotary converter or simply a synchronous converter. The AC slip rings also allow the machine to act as an alternator. The device can be reversed and DC applied to the field and commutator windings to spin the machine and produce AC power. When operated as a DC to AC machine it is referred to as an inverted rotary converter.

One way to envision what is happening in an AC-to-DC rotary converter is to imagine a rotary reversing switch that is being driven at a speed that is synchronous with the power line. Such a switch could rectify the AC input waveform with no magnetic components at all save those driving the switch. The rotary converter is somewhat more complex than this trivial case because it delivers near-DC rather than the pulsating DC that would result from just the reversing switch, but the analogy may be helpful in understanding how the rotary converter avoids transforming all of the energy from electrical to mechanical and back to electrical.

The advantage of the rotary converter over the discrete motor-generator set is that the rotary converter avoids converting all of the power flow into mechanical energy and then back into electrical energy; some of the electrical energy instead flows directly from input to output, allowing the rotary converter to be much smaller and lighter than a motor-generator set of an equivalent power-handling capability. The advantages of a motor-generator set include adjustable voltage regulation which can compensate for voltage drop in the supply network; it also provided complete power isolation, harmonics isolation, greater surge and transient protection, and sag (brownout) protection through increased momentum.

In this first illustration of a single-phase to direct-current rotary converter, it may be used five different ways:

- If the coil is rotated, alternating currents can be taken from the collector rings, and it is called an alternator.
- if the coil is rotated, direct current can be taken from the commutator, and it is called a dynamo.
- If the coil is rotated, two separate currents can be taken from the armature, one providing direct current and the other providing alternating current. Such a machine is called a *double current generator*.

- If a direct current is applied to the commutator, the coil will begin to rotate as a commutated electric motor and an alternating current can be taken out of the collector rings. This is called an *inverted rotary converter*.
- If the machine is brought up to synchronous speed by external means and if the direction of the current through the armature has the correct relationship to the field coils, then the coil will continue to rotate in sychronism with the alternating current as a synchronous motor. A direct current can be taken from the commutator. When used this way, it is called a *rotary converter*.

Applications

Railroad Rotary Converter from Illinois Railway Museum

A typical use for an AC/DC converter was for railway electrification, where utility power was supplied as alternating current (AC) but the trains were designed to work on direct current (DC). Before the invention of mercury arc rectifiers and high-power semiconductor rectifiers, this conversion could only be accomplished using motor-generators or rotary converters.

Most machinery and appliances were operated by DC power at the turn of the century which was provided by rotary converter substations for residential, commercial and industrial consumption. Rotary converters provided high current DC power for industrial electrochemical processes such as electroplating. Steel mills needed large amounts of on site DC power for their main roll drive motors.

Obsolescence

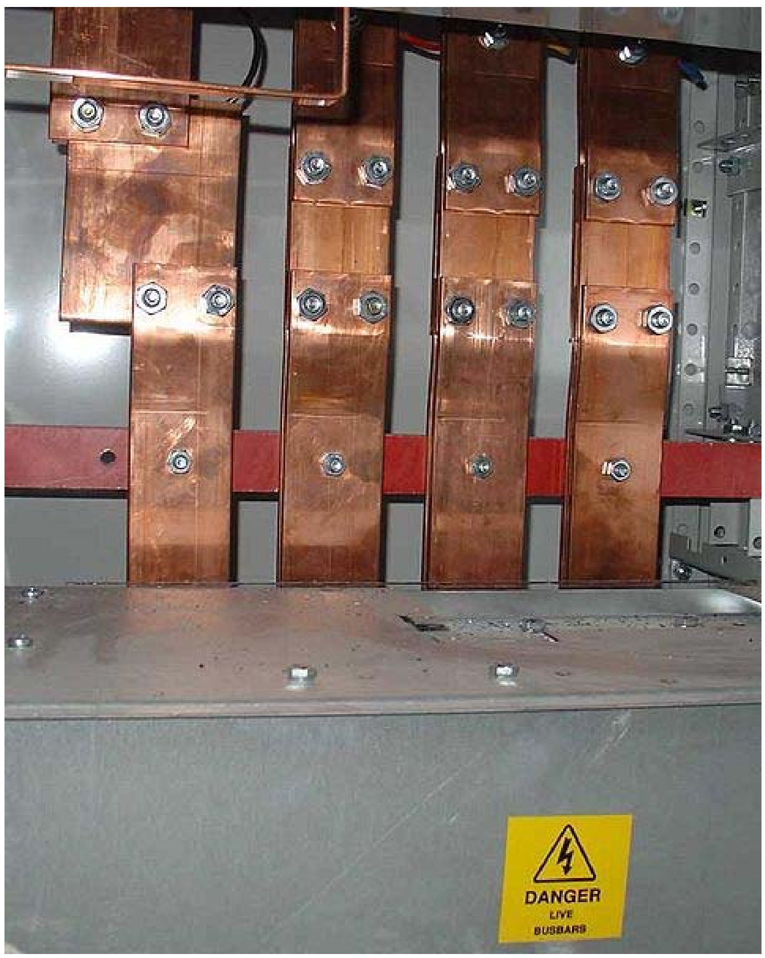
AC to DC synchronous rotary converters were made obsolete by mercury arc rectifiers in the 1930s and later on by semiconductor rectifiers in the 1960s. Some of the original New York City MTA railway substations using synchronous rotary converters operated until 1999. Compared to the rotary converter, the mercury arc and semiconductor rectifiers did not need daily maintenance, manual synchronizing for parallel operation, skilled personnel and they provided clean DC power. This enabled the new substations to be unmanned, only requiring periodic visits from a technician for inspection and maintenance. AC replaced DC in most applications and eventually the need for local DC substations diminished along with the need for rotary converters. Many DC customers converted to AC power, and on-site solid-state DC rectifiers were used to power the remaining DC equipment from the AC supply.

Self-balancing dynamo

The self-balancing dynamo is of similar construction to the single- and two-phase rotary converter. It was commonly used to create a completely balanced three-wire 120/240-volt DC electrical supply. The AC extracted from the slip rings was fed into a transformer with a single center-tapped winding. The center-tapped winding forms the DC neutral wire. It needed to be driven by a mechanical power source, such as a steam engine, diesel engine, or electric motor. It could be considered a rotary converter used as a double current generator; the AC current was used to balance the DC neutral wire.

Chapter 7

Busbar



1500 ampere busbars within a power distribution rack for a large building

In electrical power distribution, a **busbar** is a thick strip of copper or aluminium that conducts electricity within a switchboard, distribution board, substation or other electrical apparatus. Busbars are used to carry very large currents, or to distribute current to multiple devices within switchgear or equipment. For example, a household circuit breaker panel board will have bus bars at the back, arranged for the connection of multiple branch circuit breakers. An aluminum smelter will have very large bus bars used to carry tens of thousands of amperes to the electrochemical cells that produce aluminum from molten salts.

The size of the busbar is important in determining the maximum amount of current that can be safely carried. Busbars can have a cross-sectional area of as little as 10 mm^2 but electrical substations may use metal tubes of 50 mm in diameter (1,963 mm^2) or more as busbars.

Design and placement

Busbars are typically either flat strips or hollow tubes as these shapes allow heat to dissipate more efficiently due to their high surface area to cross-sectional area ratio. The skin effect makes 50–60 Hz AC busbars more than about 8 mm (1/3 in) thick inefficient, so hollow or flat shapes are prevalent in higher current applications. A hollow section has higher stiffness than a solid rod of equivalent current-carrying capacity, which allows a greater span between busbar supports in outdoor switchyards.

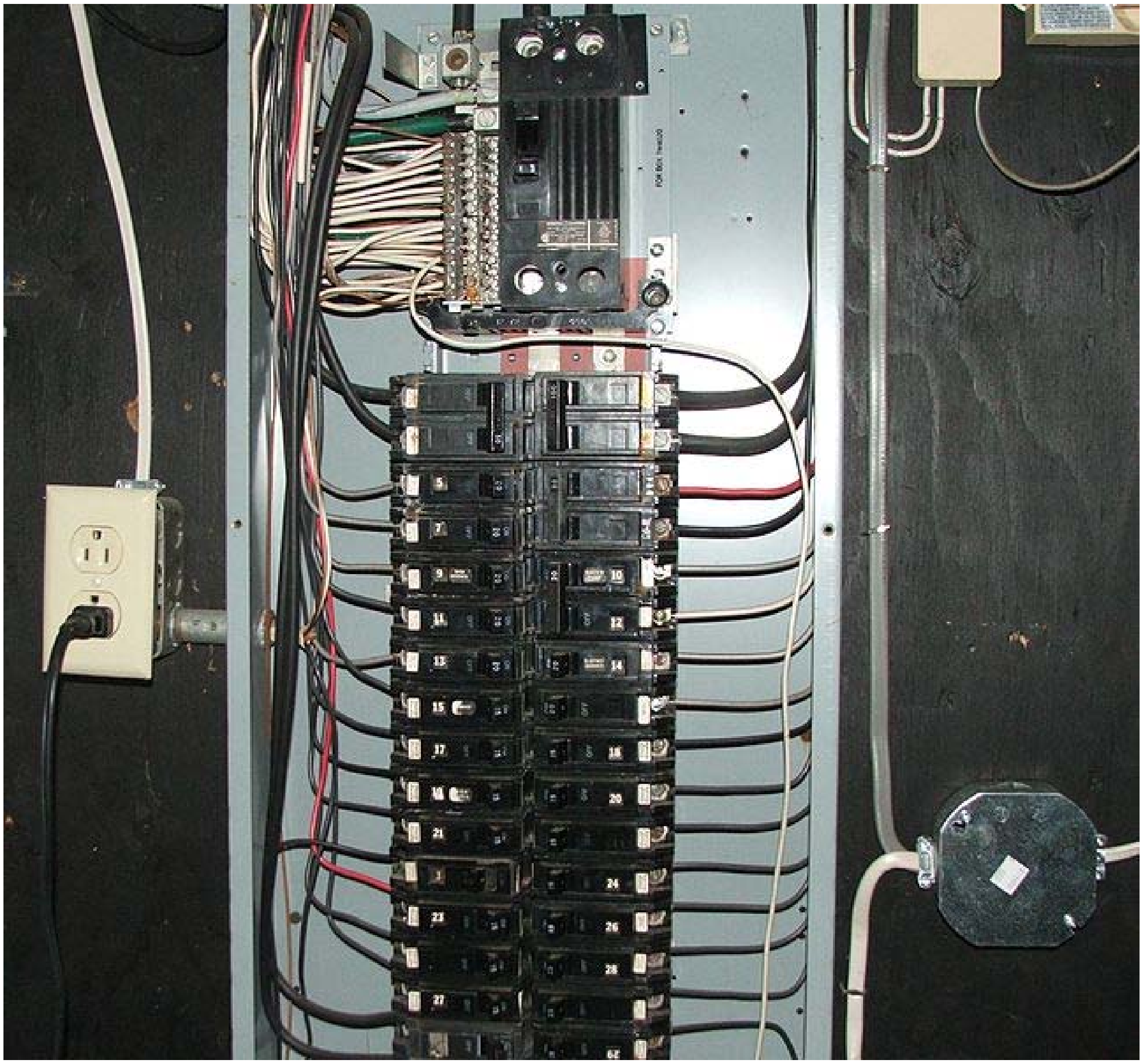
A busbar may either be supported on insulators, or else insulation may completely surround it. Busbars are protected from accidental contact either by a metal earthed enclosure or by elevation out of normal reach. Neutral busbars may also be insulated. Earth busbars are typically bolted directly onto any metal chassis of their enclosure. Busbars may be enclosed in a metal housing, in the form of bus duct or busway, segregated-phase bus, or isolated-phase bus.

Busbars may be connected to each other and to electrical apparatus by bolted or clamp connections. Often joints between high-current bus sections have matching surfaces that are silver-plated to reduce the contact resistance. At extra-high voltages (more than 300 kV) in outdoor buses, corona around the connections becomes a source of radio-frequency interference and power loss, so connection fittings designed for these voltages are used.

Busbars are typically contained inside of either a distribution board or busway.

Distribution boards

Distribution boards split the electrical supply into separate circuits at one location.



Two hot busbars are visible in this distribution board, traveling vertically from the main circuit breaker at top to feed the rows of breakers below it.

Bus ducts

Busways, or bus ducts, are long busbars with a protective cover. Rather than branching the main supply at one location, they allow new circuits to branch off anywhere along the route of the busway.

Westinghouse Bus Duct Section For Firestop Test: The left picture shows the exterior and the right section shows the interior of the bus duct, complete with mounting brackets for the bus bars and an internal firestop that had been chosen by the duct manufacturer for its electrical properties. The interior view shows that each individual bus bar had been tightly wrapped in the factory with electrical tape. Gaps between the internal firestop and the sheet metal shell indicated the unsuitability of such a thin firestop for this purpose. It was replaced with an 8" thickness of 3M Fire Barrier Mortar to avoid the shrinkage problem as well as to absorb more heat away from the copper bus bars in particular. The test resulted in a 2 hour rating.

The busbars contained within are visible in this opened busway, above the arrows at left and traveling horizontally at right. This busway section was used in a fire test of a firestop system, achieving a 2 hour fire-resistance rating.

Bus duct penetration, awaiting firestop.

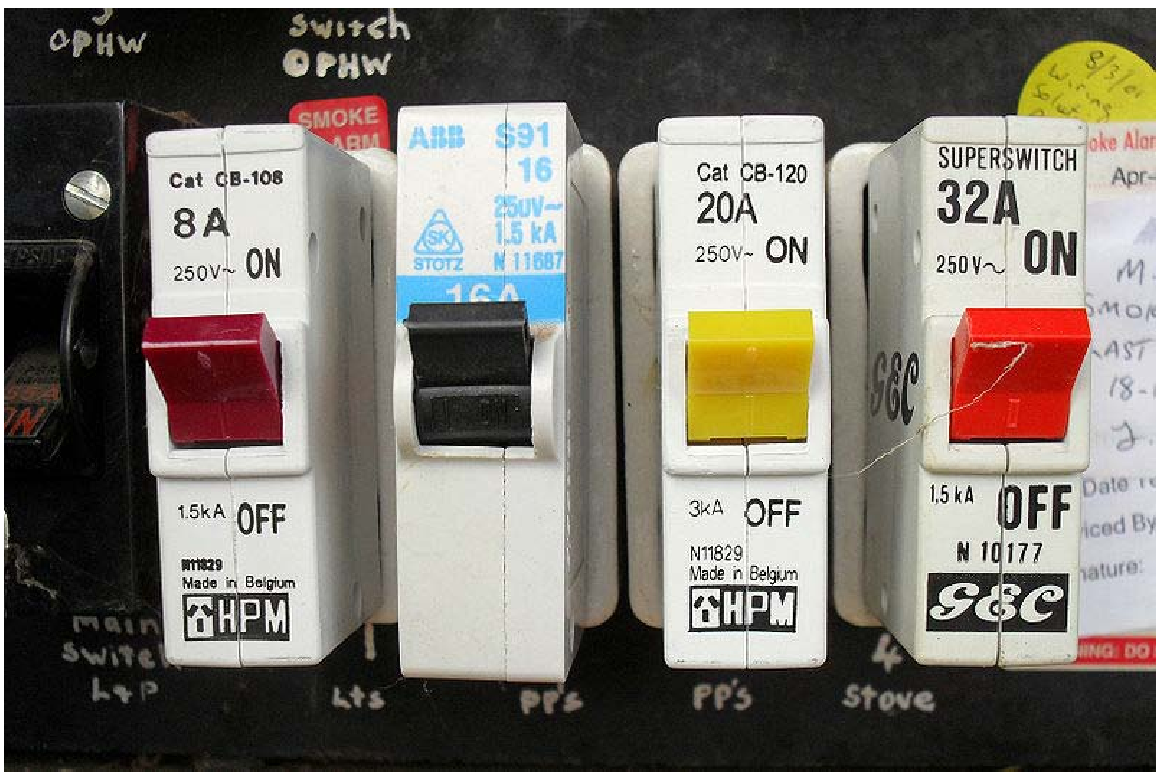
Electrical conduit and bus duct in a building at Texaco Nanticoke refinery in Nanticoke, Ontario, 1980s.

Chapter 8

Circuit Breaker

An air circuit breaker for low voltage (less than 1000 volts) power distribution switchgear

A 2 pole miniature circuit breaker



Four 1 pole circuit breakers

A **circuit breaker** is an automatically operated electrical switch designed to protect an electrical circuit from damage caused by overload or short circuit. Its basic function is to detect a fault condition and, by interrupting continuity, to immediately discontinue electrical flow. Unlike a fuse, which operates once and then has to be replaced, a circuit breaker can be reset (either manually or automatically) to resume normal operation. Circuit breakers are made in varying sizes, from small devices that protect an individual household appliance up to large switchgear designed to protect high voltage circuits feeding an entire city.

Origins

An early form of circuit breaker was described by Thomas Alva Edison in an 1879 patent application, although his commercial power distribution system used fuses. Its purpose was to protect lighting circuit wiring from accidental short-circuits and overloads.

Operation

All circuit breakers have common features in their operation, although details vary substantially depending on the voltage class, current rating and type of the circuit breaker.

The circuit breaker must detect a fault condition; in low-voltage circuit breakers this is usually done within the breaker enclosure. Circuit breakers for large currents or high voltages are usually arranged with pilot devices to sense a fault current and to operate the trip opening mechanism. The trip solenoid that releases the latch is usually energized by a separate battery, although some high-voltage circuit breakers are self-contained with current transformers, protection relays, and an internal control power source.

Once a fault is detected, contacts within the circuit breaker must open to interrupt the circuit; some mechanically-stored energy (using something such as springs or compressed air) contained within the breaker is used to separate the contacts, although some of the energy required may be obtained from the fault current itself. Small circuit breakers may be manually operated; larger units have solenoids to trip the mechanism, and electric motors to restore energy to the springs.

The circuit breaker contacts must carry the load current without excessive heating, and must also withstand the heat of the arc produced when interrupting the circuit. Contacts are made of copper or copper alloys, silver alloys, and other materials. Service life of the contacts is limited by the erosion due to interrupting the arc. Miniature and molded case circuit breakers are usually discarded when the contacts are worn, but power circuit breakers and high-voltage circuit breakers have replaceable contacts.

When a current is interrupted, an arc is generated. This arc must be contained, cooled, and extinguished in a controlled way, so that the gap between the contacts can again withstand the voltage in the circuit. Different circuit breakers use vacuum, air, insulating gas, or oil as the medium in which the arc forms. Different techniques are used to extinguish the arc including:

- Lengthening of the arc
- Intensive cooling (in jet chambers)

- Division into partial arcs
- Zero point quenching (Contacts open at the zero current time crossing of the AC waveform, effectively breaking no load current at the time of opening. The zero crossing occurs at twice the line frequency i.e. 100 times per second for 50Hz and 120 times per second for 60Hz AC)
- Connecting capacitors in parallel with contacts in DC circuits

Finally, once the fault condition has been cleared, the contacts must again be closed to restore power to the interrupted circuit.

Arc interruption

Miniature low-voltage circuit breakers use air alone to extinguish the arc. Larger ratings will have metal plates or non-metallic arc chutes to divide and cool the arc. Magnetic blowout coils deflect the arc into the arc chute.

In larger ratings, oil circuit breakers rely upon vaporization of some of the oil to blast a jet of oil through the arc.

Gas (usually sulfur hexafluoride) circuit breakers sometimes stretch the arc using a magnetic field, and then rely upon the dielectric strength of the sulfur hexafluoride (SF_6) to quench the stretched arc.

Vacuum circuit breakers have minimal arcing (as there is nothing to ionize other than the contact material), so the arc quenches when it is stretched a very small amount (<2–3 mm). Vacuum circuit breakers are frequently used in modern medium-voltage switchgear to 35,000 volts.

Air circuit breakers may use compressed air to blow out the arc, or alternatively, the contacts are rapidly swung into a small sealed chamber, the escaping of the displaced air thus blowing out the arc.

Circuit breakers are usually able to terminate all current very quickly: typically the arc is extinguished between 30 ms and 150 ms after the mechanism has been tripped, depending upon age and construction of the device.

Short-circuit current

Circuit breakers are rated both by the normal current that are expected to carry, and the maximum short-circuit current that they can safely interrupt.

Under short-circuit conditions, a current many times greater than normal can exist. When electrical contacts open to interrupt a large current, there is a tendency for an arc to form between the opened contacts, which would allow the current to continue. This condition can create conductive ionized gasses and molten or vaporized metal which can cause further continuation of the arc, or creation of additional short circuits, potentially resulting in the explosion of the circuit breaker and the equipment that it is installed in. Therefore, circuit breakers must incorporate various features to divide and extinguish the arc.

In air-insulated and miniature breakers an *arc chute* structure consisting (often) of metal plates or ceramic ridges cools the arc, and magnetic blowout coils deflect the arc into the arc chute. Larger circuit breakers such as those used in electrical power distribution may use vacuum, an inert gas such as sulphur hexafluoride or have contacts immersed in oil to suppress the arc.

The maximum short-circuit current that a breaker can interrupt is determined by testing. Application of a breaker in a circuit with a prospective short-circuit current higher than the breaker's interrupting capacity rating may result in failure of the breaker to safely interrupt a fault. In a worst-case scenario the breaker may successfully interrupt the fault, only to explode when reset.

Miniature circuit breakers used to protect control circuits or small appliances may not have sufficient interrupting capacity to use at a panelboard; these circuit breakers are called "supplemental circuit protectors" to distinguish them from distribution-type circuit breakers.

Standard current ratings

International Standard IEC 60898-1 and European Standard EN 60898-1 define the *rated current* I_n of a circuit breaker for low voltage distribution applications as the current that the breaker is designed to carry continuously (at an ambient air temperature of 30 °C). The commonly-available preferred values for the rated current are 6 A, 10 A, 13 A, 16 A, 20 A, 25 A, 32 A, 40 A, 50 A, 63 A, 80 A and 100 A (Renard series, slightly modified to include current limit of British BS 1363 sockets). The circuit breaker is labeled with the rated current in amperes, but without the unit symbol "A". Instead, the ampere figure is preceded by a letter "B", "C" or "D" that indicates the *instantaneous tripping current*, that is the minimum value of current that causes the circuit-breaker to trip without intentional time delay (i.e., in less than 100 ms), expressed in terms of I_n:

Type	Instantaneous tripping current
B	above 3 I_n up to and including 5 I_n
C	above 5 I_n up to and including 10 I_n
D	above 10 I_n up to and including 20 I_n
K	above 8 I_n up to and including 12 I_n For the protection of loads that cause frequent short duration (approximately 400 ms to 2 s) current peaks in normal operation.
Z	above 2 I_n up to and including 3 I_n for periods in the order of tens of seconds. For the protection of loads such as semiconductor devices or measuring circuits

using current transformers.

Types of circuit breaker

Front panel of a 1250 A air circuit breaker manufactured by ABB. This low voltage power circuit breaker can be withdrawn from its housing for servicing. Trip characteristics are configurable via DIP switches on the front panel.

Many different classifications of circuit breakers can be made, based on their features such as voltage class, construction type, interrupting type, and structural features.

Low voltage circuit breakers

Low voltage (less than 1000 V_{AC}) types are common in domestic, commercial and industrial application, and include:

- MCB (Miniature Circuit Breaker)—rated current not more than 100 A. Trip characteristics normally not adjustable. Thermal or thermal-magnetic operation. Breakers illustrated above are in this category.

- MCCB (Molded Case Circuit Breaker)—rated current up to 2500 A. Thermal or thermal-magnetic operation. Trip current may be adjustable in larger ratings.

- Low voltage power circuit breakers can be mounted in multi-tiers in LV switchboards or switchgear cabinets.

The characteristics of LV circuit breakers are given by international standards such as IEC 947. These circuit breakers are often installed in draw-out enclosures that allow removal and interchange without dismantling the switchgear.

Large low-voltage molded case and power circuit breakers may have electrical motor operators, allowing them to be tripped (opened) and closed under remote control. These may form part of an automatic transfer switch system for standby power.

Low-voltage circuit breakers are also made for direct-current (DC) applications, for example DC supplied for subway lines. Special breakers are required for direct current because the arc does not have a natural tendency to go out on each half cycle as for alternating current. A direct current circuit breaker will have blow-out coils which generate a magnetic field that rapidly stretches the arc when interrupting direct current.

Small circuit breakers are either installed directly in equipment, or are arranged in a breaker panel.

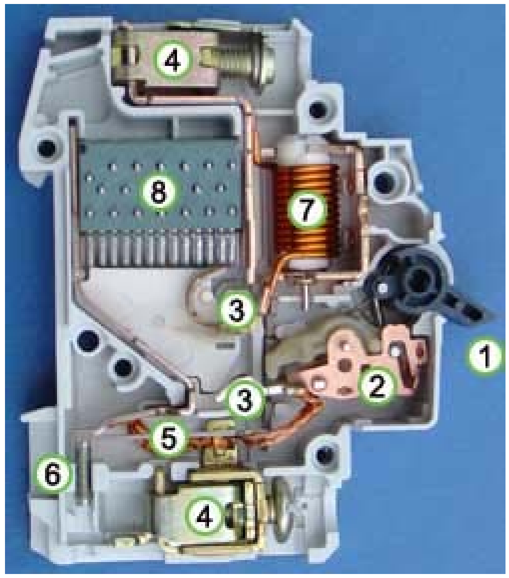


Photo of inside of a circuit breaker

The 10 ampere DIN rail-mounted thermal-magnetic miniature circuit breaker is the most common style in modern domestic consumer units and commercial electrical distribution boards throughout Europe. The design includes the following components:

1. Actuator lever - used to manually trip and reset the circuit breaker. Also indicates the status of the circuit breaker (On or Off/tripped). Most breakers are designed so they can still trip even if the lever is held or locked in the "on" position. This is sometimes referred to as "free trip" or "positive trip" operation.
2. Actuator mechanism - forces the contacts together or apart.
3. Contacts - Allow current when touching and break the current when moved apart.
4. Terminals
5. Bimetallic strip.
6. Calibration screw - allows the manufacturer to precisely adjust the trip current of the device after assembly.
7. Solenoid
8. Arc divider/extinguisher

Magnetic circuit breaker

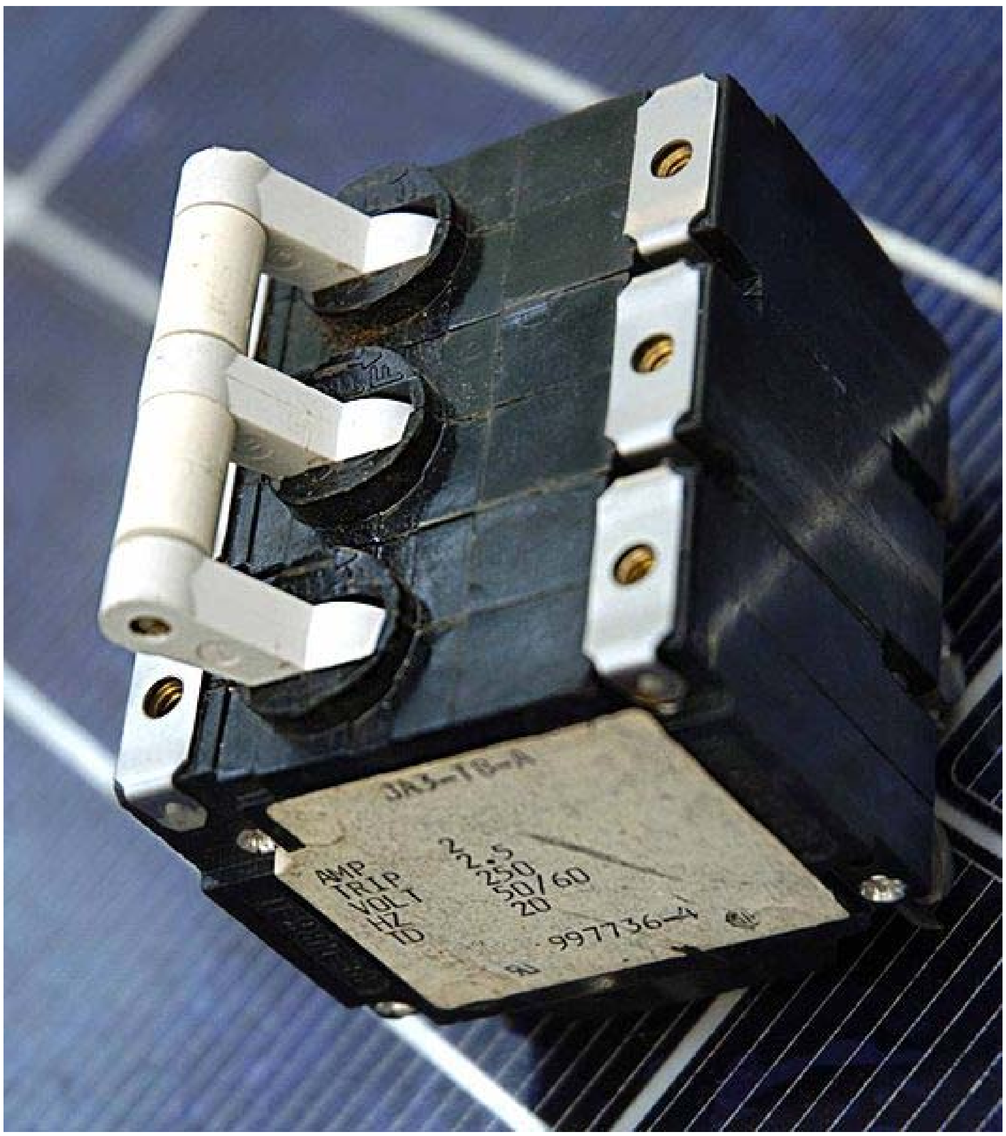
Magnetic circuit breakers use a solenoid (electromagnet) whose pulling force increases with the current. Certain designs utilize electromagnetic forces in addition to those of the solenoid. The circuit breaker contacts are held closed by a latch. As the current in the solenoid increases beyond the rating of the circuit breaker, the solenoid's pull releases the latch which then allows the contacts to open by spring action. Some types of magnetic breakers incorporate a hydraulic time delay feature using a viscous fluid. The core is restrained by a spring until the current exceeds the breaker rating. During an overload, the speed of the solenoid motion is restricted by the fluid. The delay permits brief current surges beyond normal running current for motor starting, energizing equipment, etc.

Short circuit currents provide sufficient solenoid force to release the latch regardless of core position thus bypassing the delay feature. Ambient temperature affects the time delay but does not affect the current rating of a magnetic breaker.

Thermal magnetic circuit breaker

Thermal magnetic circuit breakers, which are the type found in most distribution boards, incorporate both techniques with the electromagnet responding instantaneously to large surges in current (short circuits) and the bimetallic strip responding to less extreme but longer-term over-current conditions.

Common trip breakers



Three pole common trip breaker for supplying a three-phase device. This breaker has a 2 A rating

When supplying a branch circuit with more than one live conductor, each live conductor must be protected by a breaker pole. To ensure that all live conductors are interrupted when any pole trips, a "common trip" breaker must be used. These may either contain two or three tripping mechanisms within one case, or for small breakers, may externally tie the poles together via their operating handles. Two pole common trip breakers are common on 120/240 volt systems where 240 volt loads (including major appliances or further distribution boards) span the two live wires. Three-pole common trip breakers are typically used to supply three-phase electric power to large motors or further distribution boards.

Two and four pole breakers are used when there is a need to disconnect the neutral wire, to be sure that no current can flow back through the neutral wire from other loads connected to the same network when people need to touch the wires for maintenance. Separate circuit breakers must never be used for disconnecting live and neutral, because if the neutral gets disconnected while the live conductor stays connected, a dangerous condition arises: the circuit will appear de-energized (appliances will not work), but wires will stay live and RCDs will not trip if someone touches the live wire (because RCDs need power to trip). This is why only common trip breakers must be used when switching of the neutral wire is needed.

Medium-voltage circuit breakers

Medium-voltage circuit breakers rated between 1 and 72 kV may be assembled into metal-enclosed switchgear line ups for indoor use, or may be individual components installed outdoors in a substation. Air-break circuit breakers replaced oil-filled units for indoor applications, but are now themselves being replaced by vacuum circuit breakers (up to about 35 kV). Like the high voltage circuit breakers described below, these are also operated by current sensing protective relays operated through current transformers. The characteristics of MV breakers are given by international standards such as IEC 62271. Medium-voltage circuit breakers nearly always use separate current sensors and protective relays, instead of relying on built-in thermal or magnetic overcurrent sensors.

Medium-voltage circuit breakers can be classified by the medium used to extinguish the arc:

- Vacuum circuit breaker—With rated current up to 3000 A, these breakers interrupt the current by creating and extinguishing the arc in a vacuum container. These are generally applied for voltages up to about 35,000 V, which corresponds roughly to the medium-voltage range of power systems. Vacuum circuit breakers tend to have longer life expectancies between overhaul than do air circuit breakers.

- Air circuit breaker—Rated current up to 10,000 A. Trip characteristics are often fully adjustable including configurable trip thresholds and delays. Usually electronically controlled, though some models are microprocessor controlled via an integral electronic trip unit. Often used for main power distribution in large industrial plant, where the breakers are arranged in draw-out enclosures for ease of maintenance.

- SF_6 circuit breakers extinguish the arc in a chamber filled with sulfur hexafluoride gas.

Medium-voltage circuit breakers may be connected into the circuit by bolted connections to bus bars or wires, especially in outdoor switchyards. Medium-voltage circuit breakers in switchgear line-ups are often built with draw-out construction, allowing the breaker to be removed without disturbing the power circuit connections, using a motor-operated or hand-cranked mechanism to separate the breaker from its enclosure.

High-voltage circuit breakers

Russian 110 kV oil circuit breaker

115 kV bulk oil circuit breaker

400 kV SF_6 live tank circuit breakers

Electrical power transmission networks are protected and controlled by high-voltage breakers. The definition of *high voltage* varies but in power transmission work is usually thought to be 72.5 kV or higher, according to a recent definition by the International Electrotechnical Commission (IEC). High-voltage breakers are nearly always solenoid-operated, with current sensing protective relays operated through current transformers. In substations the protective relay scheme can be complex, protecting equipment and buses from various types of overload or ground/earth fault.

High-voltage breakers are broadly classified by the medium used to extinguish the arc.

- Bulk oil
- Minimum oil
- Air blast
- Vacuum
- SF_6

Some of the manufacturers are ABB, GE (General Electric) , Tavrida Electric, Alstom, Mitsubishi Electric, Pennsylvania Breaker, Siemens, Toshiba, Končar HVS, BHEL, CGL, Square D (Schneider Electric).

Due to environmental and cost concerns over insulating oil spills, most new breakers use SF_6 gas to quench the arc.

Circuit breakers can be classified as *live tank*, where the enclosure that contains the breaking mechanism is at line potential, or *dead tank* with the enclosure at earth potential. High-voltage AC circuit breakers are routinely available with ratings up to 765 kV. 1200KV breakers are likely to come into market very soon.

High-voltage circuit breakers used on transmission systems may be arranged to allow a single pole of a three-phase line to trip, instead of tripping all three poles; for some classes of faults this improves the system stability and availability.

Sulfur hexafluoride (SF_6) high-voltage circuit-breakers

A sulfur hexafluoride circuit breaker uses contacts surrounded by sulfur hexafluoride gas to quench the arc. They are most often used for transmission-level voltages and may be incorporated into compact gas-insulated switchgear. In cold climates, supplemental heating or de-rating of the circuit breakers may be required due to liquefaction of the SF_6 gas.

Other breakers

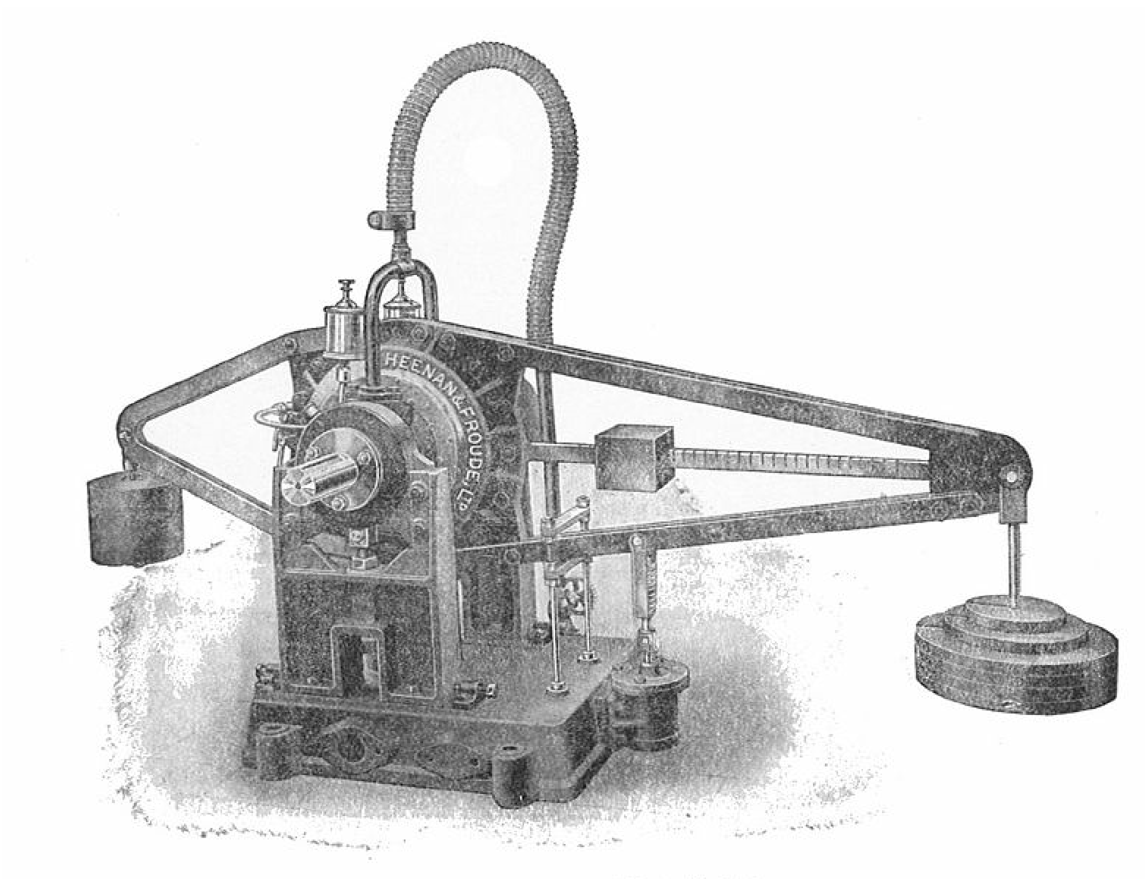
The following types are described in separate articles.

- Breakers for protections against earth faults too small to trip an over-current device:
  - Residual-current device (RCD, formerly known as a *residual current circuit breaker*) — detects current imbalance, but does not provide over-current protection.
  - Residual current breaker with over-current protection (RCBO) — combines the functions of an RCD and an MCB in one package. In the United States and Canada, panel-mounted devices that combine ground (earth) fault detection and over-current protection are called Ground Fault Circuit Interrupter (GFCI) breakers; a wall mounted outlet device providing ground fault detection only is called a GFI.
  - Earth leakage circuit breaker (ELCB) — This detects earth current directly rather than detecting imbalance. They are no longer seen in new installations for various reasons.
- Autorecloser — A type of circuit breaker which closes again after a delay. These are used on overhead power distribution systems, to prevent short duration faults from causing sustained outages.

- Polyswitch (polyfuse) — A small device commonly described as an automatically resetting fuse rather than a circuit breaker.

Chapter 9

Dynamometer



Early hydraulic dynamometer, with dead-weight torque measurement.

A **dynamometer** or **"dyno"** for short, is a device for measuring force, moment of force (torque), or power. For example, the power produced by an engine, motor or other rotating prime mover can be calculated by simultaneously measuring torque and rotational speed (RPM).

A dynamometer can also be used to determine the torque and power required to operate a driven machine such as a pump. In that case, a *motoring* or *driving* dynamometer is used.

A dynamometer that is designed to be driven is called an *absorption* or *passive* dynamometer. A dynamometer that can either drive or absorb is called a *universal* or *active* dynamometer.

In addition to being used to determine the torque or power characteristics of a machine under test (MUT), dynamometers are employed in a number of other roles. In standard emissions testing cycles such as those defined by the US Environmental Protection Agency (US EPA), dynamometers are used to provide simulated road loading of either the engine (using an engine dynamometer) or full powertrain (using a chassis dynamometer). In fact, beyond simple power and torque measurements, dynamometers can be used as part of a testbed for a variety of engine development activities such as the calibration of engine management controllers, detailed investigations into combustion behavior and tribology.

In the medical terminology, hand dynamometers are used for routine screening of grip strength and initial and ongoing evaluation of patients with hand trauma and dysfunction. They are also used to measure grip strength in patients where compromise of the cervical nerve roots or peripheral nerves is suspected.

In the rehabilitation, kinesiology, and ergonomics realms, force dynamometers are used for measuring the back, grip, arm, and/or leg strength of athletes, patients, and workers to evaluate physical status, performance, and task demands. Typically the force applied to a lever or through a cable are measured and then converted to a moment of force by multiplying by the perpendicular distance from the force to the axis of the level.

Principles of operation of torque power (absorbing) dynamometers

An absorbing dynamometer acts as a load that is driven by the prime mover that is under test (e.g. Pelton wheel). The dynamometer must be able to operate at any speed and load to any level of torque that the test requires.

Absorbing dynamometers are not to be confused with "inertia" dynamometers, which calculate power solely by measuring power required to accelerate a known mass drive roller and provide no variable load to the prime mover.

An Absorption dynamometer is usually equipped with some means of measuring the operating torque and speed.

The dynamometer's Power Absorption Unit absorbs the power developed by the prime mover. The power absorbed by the dynamometer is converted into heat and the heat generally dissipates into the ambient air or transfers to cooling water that dissipates into the air. Regenerative dynamometers, in which the prime mover drives a DC motor as a generator to create load, make excess DC power and potentially, using a DC/AC inverter, can feed AC power back into the commercial electrical power grid - where the power produced is eventually converted back into heat (as in an oven or light bulb, etc.).

Absorption dynamometers can be equipped with two types of control systems to provide different main test types.

Constant Force

The dynamometer has a "braking" torque regulator, the PAU (Power Absorption Unit) is configured to provide a set braking force torque load while the prime mover is configured to operate at whatever throttle opening, fuel delivery rate or any other variable it is desired to test. The prime mover is then allowed to accelerate the engine through the desired speed or RPM range. Constant Force test routines require the PAU to be set slightly torque deficient as referenced to prime mover output to allow some rate of acceleration. Power is calculated based on torque x RPM / 5252 + calculated power required for the acceleration rate that occurred.

Constant Speed

If the dynamometer has a speed regulator (human or computer), the PAU provides a variable mount of braking force (torque) that is necessary to cause the prime mover to operate at the desired single test speed or RPM. The PAU braking load applied to the prime mover to can be manually controlled or determined by a computer. Most systems employ eddy current, oil hydraulic or DC motor produced loads because of their linear and quick load change ability.

Power is calculated based on torque x RPM / 5252.

A motoring dynamometer acts as a motor that drives the equipment under test. It must be able to drive the equipment at any speed and develop any level of torque that the test requires. In common usage, AC or DC motors are used to drive the equipment or "load" device.

In most dynamometers power (P) is not measured directly; it must be calculated from torque (τ) and angular velocity (ω) values or force (F) and linear velocity (v):

$$P = \tau \cdot \omega$$

or

$$P = F \cdot v$$

where

P is the power in watts

τ is the torque in newton metres

ω is the angular velocity in radians per second

F is the force in newtons

v is the linear velocity in metres per second

Division by a conversion constant may be required depending on the units of measure used.

For imperial units,

$$P_{\mathrm{hp}} = \frac{\tau_{\mathrm{lb \cdot ft}} \cdot \omega_{\mathrm{rpm}}}{5252}$$

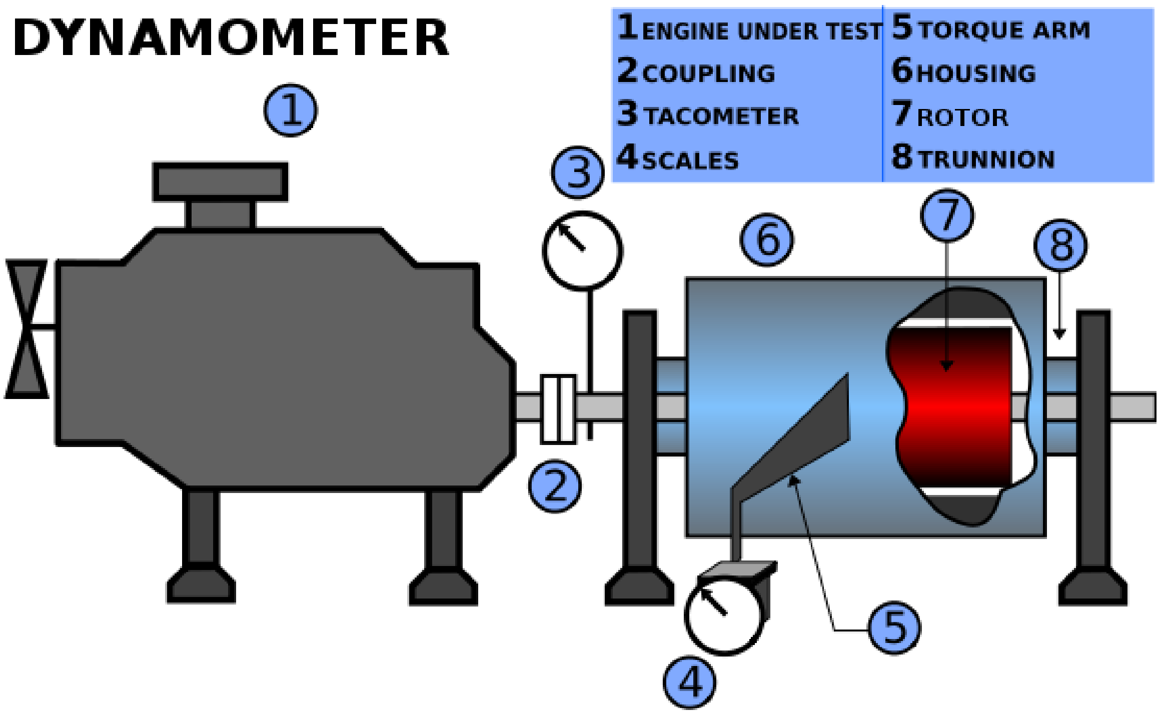
where
P_{hp} is the power in horsepower
$\tau_{\mathrm{lb \cdot ft}}$ is the torque in pound-feet
ω_{RPM} is the rotational velocity in revolutions per minute

For metric units,

$$P_{\mathrm{kW}} = \frac{\tau_{\mathrm{N \cdot m}} \cdot \omega_{\mathrm{rpm}}}{9549}$$

where
P_{kW} is the power in kilowatts
$\tau_{\mathrm{N \cdot m}}$ is the torque in newton metres
ω_{rpm} is the rotational velocity in revolutions per minute

Detailed dynamometer description



Electrical dynamometer setup showing engine, torque measurement arrangement and tachometer

A dynamometer consists of an absorption (or absorber/driver) unit, and usually includes a means for measuring torque and rotational speed. An absorption unit consists of some type of rotor in a housing. The rotor is coupled to the engine or other equipment under test and is free to rotate at whatever speed is required for the test. Some means is provided to develop a braking torque between dynamometer's rotor and housing. The means for developing torque can be frictional, hydraulic, electromagnetic etc. according to the type of absorption/driver unit.

One means for measuring torque is to mount the dynamometer housing so that it is free to turn except that it is restrained by a torque arm. The housing can be made free to rotate by using trunnions connected to each end of the housing to support the dyno in pedestal mounted trunnion bearings. The torque arm is connected to the dyno housing and a weighing scale is positioned so that it measures the force exerted by the dyno housing in attempting to rotate. The torque is the force indicated by the scales multiplied by the length of the torque arm measured from the center of the dynamometer. A load cell transducer can be substituted for the scales in order to provide an electrical signal that is proportional to torque.

Another means for measuring torque is to connect the engine to the dynamometer through a torque sensing coupling or torque transducer. A torque transducer provides an electrical signal that is proportional to torque.

With electrical absorption units, it is possible to determine torque by measuring the current drawn (or generated) by the absorber/driver. This is generally a less accurate method and not much practiced in modern times, but it may be adequate for some purposes.

When torque and speed signals are available, test data can be transmitted to a data acquisition system rather than being recorded manually. Speed and torque signals can also be recorded by a chart recorder or plotter.

Types of dynamometers

In addition to classification as *Absorption*, *Motoring* or *Universal* as described above, dynamometers can be classified in other ways.

A dyno that is coupled directly to an engine is known as an *engine dyno*.

A dyno that can measure torque and power delivered by the power train of a vehicle directly from the drive wheel or wheels (without removing the engine from the frame of the vehicle), is known as a *chassis dyno*.

Dynamometers can also be classified by the type of absorption unit or absorber/driver that they use. Some units that are capable of absorption only can be combined with a motor to construct an absorber/driver or universal dynamometer. The following types of absorption/driver units have been used:

Types of absorption/driver units

- Eddy current or electromagnetic brake (absorption only)
- Magnetic Powder brake (absorption only)
- Hysteresis Brake (absorption only)
- Electric motor/generator (absorb or drive)
- Fan brake (absorption only)
- Hydraulic brake (absorption only)
- Mechanical friction brake or Prony brake (absorption only)
- Water brake (absorption only)
- Compound dyno (usually an absorption dyno in tandem with an electric/motoring dyno)

Eddy current type absorber

EC dynamometers are currently the most common absorbers used in modern chassis dynos. The EC absorbers provide the quick load change rate for rapid load settling. Most are air cooled, but some are designed to require external water cooling systems.

Eddy current dynamometers require an electrically conductive core, shaft or disc, moving across a magnetic field to produce resistance to movement. Iron is a common material, but copper, aluminum and other conductive materials are usable.

In current (2009) applications, most EC brakes use cast iron discs, similar to vehicle disc brake rotors, and use variable electromagnets to change the magnetic field strength to control the amount of braking.

The electromagnet voltage is usually controlled by a computer, using changes in the magnetic field to match the power output being applied.

Sophisticated EC systems allow steady state and controlled acceleration rate operation.

Powder dynamometer

A powder dynamometer is similar to an eddy current dynamometer, but a fine magnetic powder is placed in the air gap between the rotor and the coil. The resulting flux lines create "chains" of metal particulate that are constantly built and broken apart during rotation creating great torque. Powder dynamometers are typically limited to lower RPM due to heat dissipation issues.

Hysteresis dynamometers

Hysteresis dynamometers, use a steel rotor that is moved through flux lines generated between magnetic pole pieces. This design, as in the usual "disc type" eddy current absorbers, allows for full torque to be produced at zero speed, as well as at full speed. Heat dissipation is assisted by forced air. Hysteresis and "disc type" EC dynamometers are one of the most efficient technologies in small (200 hp (150 kW) and less) dynamometers. A hysteresis brake is an eddy current absorber that, unlike most "disc type" eddy current absorbers, puts the electromagnet coils inside a vented and ribbed cylinder and rotates the cylinder, instead of rotating a disc between electromagnets. The potential benefit for the hysteresis absorber is that the diameter can be decreased and operating RPM of the absorber may be increased.

Electric motor/generator dynamometer

Electric motor/generator dynamometers are a specialized type of adjustable-speed drives. The absorption/driver unit can be either an alternating current (AC) motor or a direct current (DC) motor. Either an AC motor or a DC motor can operate as a generator that is driven by the unit under test or a motor that drives the unit under test. When equipped with appropriate control units, electric motor/generator dynamometers can be configured as universal dynamometers. The control unit for an AC motor is a variable-frequency drive and the control unit for a DC motor is a DC drive. In both cases, regenerative control units can transfer power from the unit under test to the electric utility. Where permitted, the operator of the dynamometer can receive payment (or credit) from the utility for the returned power.

In engine testing, universal dynamometers can not only absorb the power of the engine but also, drive the engine for measuring friction, pumping losses and other factors.

Electric motor/generator dynamometers are generally more costly and complex than other types of dynamometers.

Fan brake

A fan is used to blow air to provide engine load. Changing gearing or fan or simply measuring the max RPM attained.

Hydraulic brake

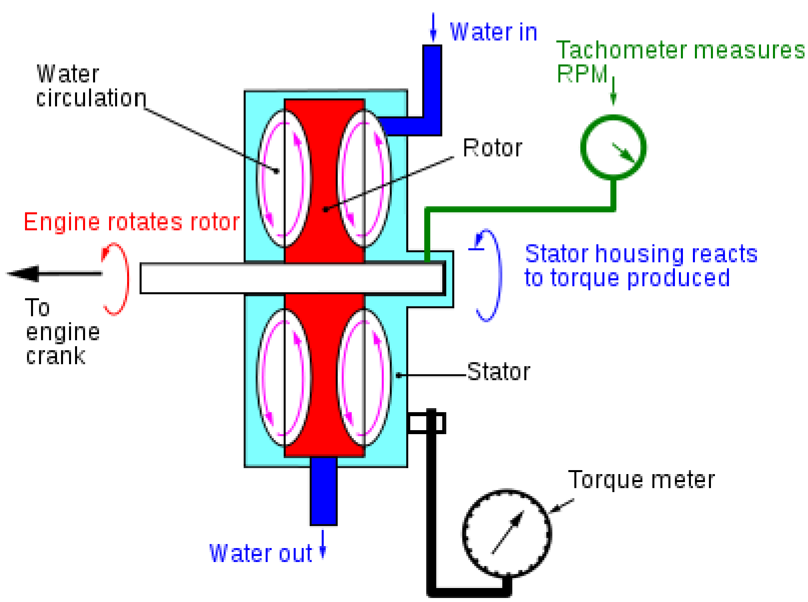
The hydraulic brake system consists of a hydraulic pump (usually a gear type pump), a fluid reservoir and piping between the two parts. Inserted in the piping is an adjustable valve and between the pump and the valve is a gauge or other means of measuring hydraulic pressure. Usually, the fluid used was hydraulic oil, but recent synthetic multi-grade oils may be a better choice. In simplest terms, the engine is brought up to the desired RPM and the valve is incrementally closed and as the pumps outlet is restricted, the load increases and the throttle is simply opened until at the desired throttle opening. Unlike most other systems, power is calculated by factoring flow volume (calculated from pump design specs), hydraulic pressure and RPM. Brake HP, whether figured with pressure, volume and RPM or with a different load cell type brake dyno, should produce essentially identical power figures. Hydraulic dynos are renowned for having the absolute quickest load change ability, just slightly surpassing the eddy current absorbers. The downside is that they require large quantities of hot oil under high pressure and the requirement for an oil reservoir.

Water brake type absorber

The water brake absorber is sometimes mistakenly called a "hydraulic dynamometer." Water brake absorbers are relatively common, having been manufactured for many years and noted for their high power capability, small package, light weight, and relatively low manufacturing cost as compared to other, quicker reacting "power absorber" types.

Their drawbacks are that they can take a relatively long period of time to "stabilize" their load amount and the fact that they require a constant supply of water to the "water brake housing" for cooling. In many parts of the country, environmental regulations now prohibit "flow through" water and large water tanks must be installed to prevent contaminated water from entering the environment.

The schematic shows the most common type of water brake, the variable level type. Water is added until the engine is held at a steady RPM against the load. Water is then kept at that level and replaced by constant draining and refilling, which is needed to carry away the heat created by absorbing the horsepower. The housing attempts to rotate in response to the torque produced but is restrained by the scale or torque metering cell that measures the torque.



This schematic shows a water brake, which is actually a fluid coupling with a housing restrained from rotating—similar to a water pump with no outlet.

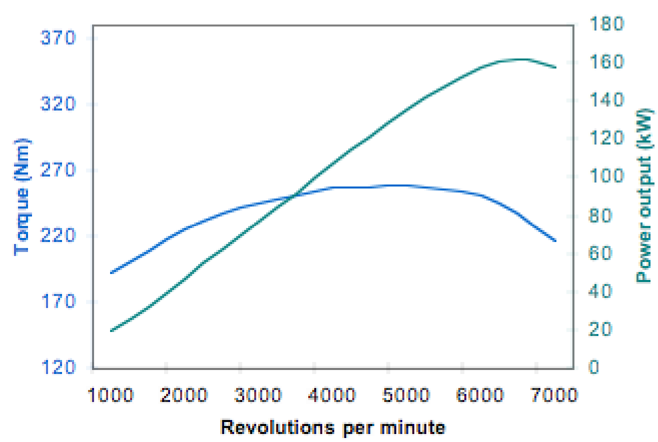
Compound Dynamometers

In most cases, motoring dynamometers are symmetrical; a 300 kW AC dynamometer can absorb 300 kW as well as motor at 300 kW. This is an uncommon requirement in engine testing and development. Sometimes, a more cost-effective solution is to attach a larger absorption dynamometer with a smaller motoring dynamometer; alternatively, a larger absorption dynamometer and a simple AC or DC motor may be used in a similar manner with the electric motor only providing motoring power when required and no absorption. The (cheaper) absorption dynamometer is sized for the maximum required absorption, whereas the motoring dynamometer is sized for motoring. A typical size ratio for common emission test cycles and most engine development is approximately 3:1. Torque measurement is somewhat complicated since there are two machines in tandem; an inline torque transducer is the preferred method of torque measurement in this case. An eddy-current or waterbrake dynamometer with electronic control combined with a variable frequency drive and AC induction motor is a commonly used configuration of this type. Disadvantages include requiring a second set of test cell services (electrical power and cooling), and a slightly more complicated control system. Attention must be paid to the transition between motoring and braking in terms of control stability.

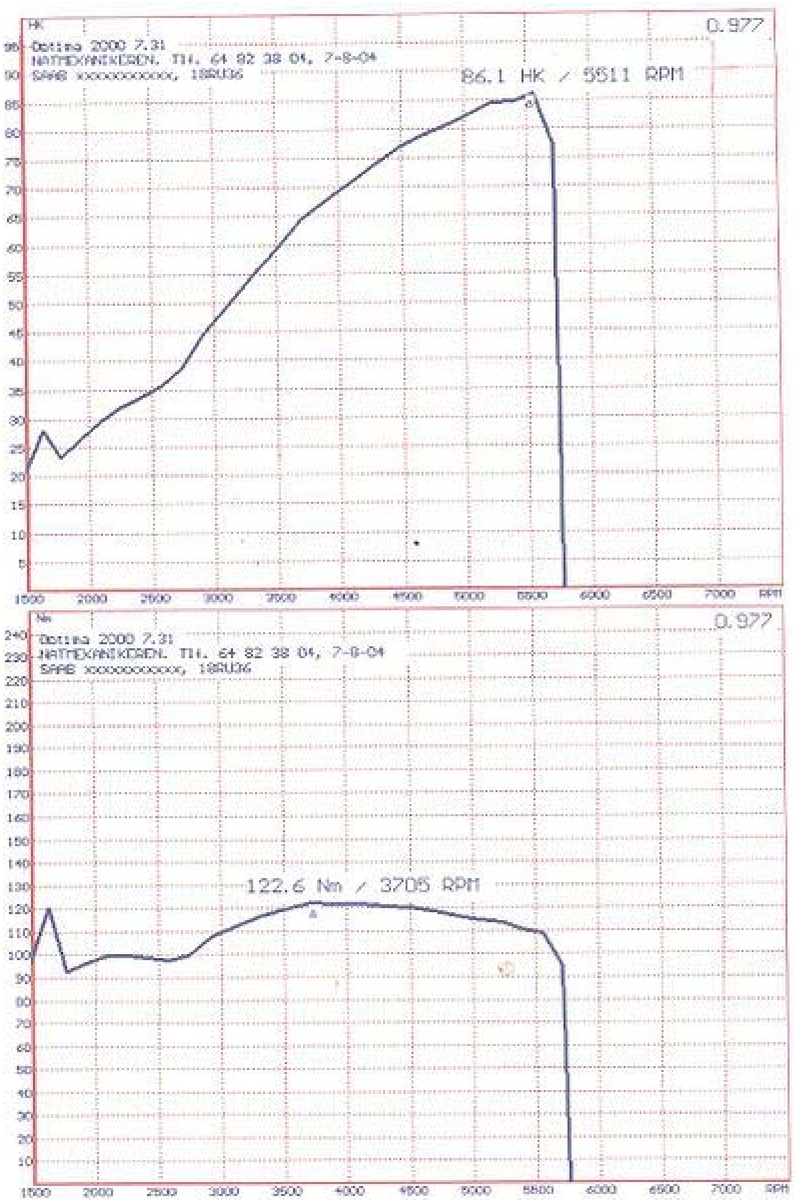
How dynamometers are used for engine testing

Dynamometers are useful in the development and refinement of modern day engine technology. The concept is to use a dyno to measure and compare power transfer at different points on a vehicle, thus allowing the engine or drivetrain to be modified to get more efficient power transfer. For example, if an engine dyno shows that a particular engine achieves 400 N·m (300 lbf·ft) of torque, and a chassis dynamo shows only 350 N·m (260 lbf·ft), one would know to look to the drivetrain for the major improvements. Dynamometers are typically very expensive pieces of equipment, reserved for certain fields that rely on them for a particular purpose.

Types of dynamometer systems



Dyno graph 1



Dyno graph 2

A **brake** dynamometer applies variable load on the Prime Mover (PM) and measures the PM's ability to move or hold the RPM as related to the "braking force" applied. It is usually connected to a computer that records applied braking torque and calculates engine power output based on information from a "load cell" or "strain gauge" and RPM (speed sensor).

An **inertia** dynamometer provides a fixed inertial mass load and calculates the power required to accelerate that fixed, known mass and uses a computer to record RPM and acc. rate to calculate torque. The engine is generally tested from somewhat above idle to its maximum RPM and the output is measured and plotted on a graph.

A **motoring** dynamometer provides the features of a brake dyne system, but in addition, can "power" (usually with an AC or DC motor) the Prime Mover (PM) and allow testing of very small power small outputs. Example, duplicating speeds and loads that are experienced when operating a vehicle traveling downhill or on/off throttle operations.

There are essentially 3 types of dynamometer test procedures

1. Steady state (only on brake dynamometers), where the engine is held at a specified RPM (or series of usually sequential RPMs) for a desired amount of time by the variable brake loading as provided by the PAU (power absorber unit)
2. Sweep test (on inertia or brake dynamometers), where the engine is tested under a load (inertia or brake loading), but allowed to "sweep" up in RPM in a continuous fashion, from a specified lower "starting" RPM to a specified "end" RPM
3. Transient test (usually on AC or DC dynamometers), where the engine power and speed are varied throughout the test cycle. Different test cycles are used in different jurisdictions. Chassis test cycles include the US light-duty UDDS, HWFET, US06, SC03, ECE, EUDC, and CD34. Engine test cycles include ETC, HDDTC, HDGTC, WHTC, WHSC, and ED12.

Types of Sweep Tests:

1. **Inertia sweep**: An inertia dyno system provides a fixed inertial mass flywheel and computes the power required to accelerate the flywheel (load) from the starting to the ending RPM. The actual rotational mass of the engine or engine and vehicle in the case of a chassis dyno is not known and the variability of even tire mass will skew power results. The inertia value of the flywheel is "fixed," so low power engines are under load for a much longer time and internal engine temperatures are usually too high by the end of the test, skewing optimal "dyno" tuning settings away from the outside world's optimal tuning settings. Conversely, high powered engines, commonly complete a common "4th gear sweep" test in less than 10 seconds, which is not a reliable load condition as compared to operation in the outside world. By not providing enough time under load, internal combustion chamber temps are unrealistically low and power readings, especially past the power peak, are skewed low.

1. **Loaded Sweep Tests** (brake dyno type) consist of 2 types:
    1. **Simple fixed Load Sweep Test**: A fixed load, of somewhat less than the engine's output, is applied during the test. The engine is allowed to accelerate from its starting RPM to its ending RPM, varying in its own acceleration rate, depending on power output at any particular RPM point Power is calculated using torque * RPM / 5252 + the power required to accelerate the dyno and engine's / vehicle's rotating mass.
    2. **Controlled Acceleration Sweep Test**: Similar in basic usage as the above Simple fixed Load Sweep Test, but with the addition of active load control that targets a specific rate of acceleration. Commonly, 20fps/ps is used.

Controlled Acceleration Rate test is that the acc. rate used is controlled from low power to high power engines and over extension and contraction of "test duration" is avoided, providing more repeatable tests and tuning results.

In every Sweep Test, there is still the remaining issue of potential power reading error due to the variable engine / dyno / vehicle total rotating mass. Many modern computer controlled brake dyno systems are capable of deriving that "inertial mass" value to eliminate the error.

Interestingly, A "sweep test" will always be suspect, as many "sweep" users ignore the rotating mass factor and prefer to use a blanket "factor" on every test, on every engine or vehicle. Simple inertia dyne systems aren't capable of deriving "inertial mass" and are forced to use the same assumed inertial mass on every vehicle.

Using Steady State testing eliminates a Sweep Test rotating inertial mass error , as there is no acceleration during a Steady State test.

Transient Test Characteristics: Aggressive throttle movements, engine speed changes, and engine motoring are characteristics of most transient engine tests. The usual purpose of these tests are for vehicle emissions development and homologation. In some cases, the lower-cost eddy-current dynamometer is used to test one of the transient test cycles for early development and calibration. An eddy current dyne system offers fast load response, which allows rapid tracking of speed and load, but does not allow motoring. Since most required transient tests contain a significant amount of motoring operation, a transient test cycle with an eddy-current dyno will generate different emissions test results. Final adjustments are required to be done on a motoring-capable dyno.

Engine dynamometer

HORIBA engine dynamometer TITAN

An engine dynamometer measures power and torque directly from the engine's crankshaft (or flywheel), when the engine is removed from the vehicle. These dynos do not account for power losses in the drivetrain, such as the gearbox, transmission or differential etc.

Chassis dynamometer

Saab 96 on chassis dynamometer

AVL ROADSIM Light and medium duty vehicle chassis dynamometer for exhaust emission testing (Homologation) and other applications

A chassis dynamometer measures power delivered to the surface of the "drive roller" by the drive wheels. The vehicle is often parked on the roller or rollers, which the car then turns and the output is measured.

Modern roller type chassis dyne systems use the Salvisberg roller, which improved traction and repeatability over smooth or knurled drive rollers.

On a motorcycle, typical power loss at higher power levels, mostly through tire flex, is about 10% and gearbox chain and other power transferring parts are another 2% to 5%.

Other types of chassis dynamometers are available that eliminate the potential wheel slippage on old style drive rollers and attach directly to the vehicle's hubs for direct torque measurement from the axle. Hub mounted dynos include units made by Dynapack and Rototest.

Chassis dynos can be fixed or portable.

Modern chassis dynamometers can do much more than display RPM, horsepower, and torque. With modern electronics and quick reacting, low inertia dyne systems, it is now possible to tune to best power and the smoothest runs, in realtime.

In retail settings it is also common to "tune the air fuel ratio" , using a wideband oxygen sensor that is graphed along with RPM.

Some, dyne systems can also add vehicle diagnostic information to the dyno graph as well. This is done by gathering data directly from the vehicle using on-board diagnostics communication.

Emissions development and homologation dynamometer test systems often integrate emissions sampling, measurement, engine speed and load control, data acquisition, and safety monitoring into a complete test cell system. These test systems usually include complex emissions sampling equipment (such as constant volume samplers or raw exhaust gas sample preparation systems), and exhaust emissions analyzers. These analyzers are much more sensitive and much faster than a typical portable exhaust gas analyzer. Response times of well under one second are common and required by many transient test cycles.

Integration of the dynamometer control system along with automatic calibration tools for engine system calibration is often found in development test cell systems. In these test cell systems, the dynamometer load and engine speed are varied to many engine operating points, and selected engine management parameters are varied and the results recorded automatically. Later analysis of this data may then be used to generate engine calibration data used by the engine management software.

Because of frictional and mechanical losses in the various drivetrain components, the measured rear wheel brake horsepower is generally 15-20 percent less than the brake horsepower measured at the crankshaft or flywheel on an engine dynamometer. Other sources, after researching several different "engine" dyno software packages, found that the engine dyno user can integrally add "frictional loss" channel factors of +10% to +15% to the flywheel power, raising the claim that 20% to 25% or even more power is actually lost between the crankshaft at high power outputs.

Common misconceptions about dynos

Drag racing: 1/4 mile prediction based on dynamometer measured power

Horsepower figures are a strong predictor but do not guarantee a specific 0-60 mph, 1/4 mile elapsed time (ET) or 1/4 mile speed. An engine accelerating in a vehicle experiences different conditions than on a dyno. G forces and different temperatures as well as different modes of vibration in a vehicle can cause significant differences in power output.

Inexpensive "inertia dynamometers" commonly provide insufficient loading, and complete their "test" in less time than the real world 1/4 mile takes, causing inherent power value errors, due to unrealistic internal engine temperatures.

More sophisticated dyne systems are capable of "loaded testing," which can potentially recreate the same temperatures as on the drag strip.

In engineering units, the power figures used should be "True" or "Effective" horsepower scale.

Engine damage: Can dyno testing damage engines?

A brake dyno, in steady state mode only provides a load that is equal the amount of power that the engine is making at any specifically selected RPM point. If the engine makes 200 brake HP at 5000 RPM, the dynamometer's brake or power absorber will provide exactly 200 hp (150 kW) of load against it, keeping the RPM at 5000 RPM.

That's a realistic load that simulates a vehicle pulling a large trailer up a hill. It should be no problem on the dyno if there's no problem on the road.

Apprehension over dyno testing and engine damage has solid roots in fact. Old style dynamometers commonly used an inexpensive water brake type of power absorber. Load was increased or decreased by filling and draining water in the housing to change the amount of internal water volume to change the load, all the while draining and refilling the water to keep the water from boiling. It would sometimes take some time for the operator or computer to stabilize inflow and outflow rates. That extra time could pose a risk to engines.

Water brakes are still commonly used in applications where their small size and light weight are important and engine torque curves are relatively straight, as in large automotive and boats.

Engine testing may damage engines primarily due to insufficient instrumentation, insufficient safety monitoring systems, and insufficient cooling. An engine on a dyno does not receive air cooling due to engine speeds. Automotive engines are not typically designed for wide-open throttle operation for extended periods of time; internal components may overheat and fail.

History

Gaspard de Prony invented the de Prony brake in 1821. The de Prony brake (or Prony brake) is considered to be one of the earliest dynamometers.

Froude Hofmann of Worcester, UK, manufactures engine and vehicle dynamometers. They credit William Froude with the invention of the hydraulic dynamometer in 1877 and say that the first commercial dynamometers were produced in 1881 by their predecessor company, Heenan & Froude.

In 1928, the German company "*Carl Schenck Eisengießerei & Waagenfabrik*" built the first vehicle dynamometers for brake tests with the basic design of the today's vehicle test stands.

The eddy current dynamometer was invented by Martin and Anthony Winther in about 1931. At that time, DC Motor/generator dynamometers had been in use for many years. A company founded by the Winthers, Dynamatic Corporation, manufactured dynamometers in Kenosha, Wisconsin until 2002. Dynamatic was part of Eaton Corporation from 1946 to 1995. In 2002, Dyne Systems of Jackson, Wisconsin acquired the Dynamatic dynamometer product line. Starting in 1938, Heenan & Froude manufactured eddy current dynamometers for many years under license from Dynamatic and Eaton.

Chapter 10

Inverter (Electrical)

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

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

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

The inverter performs the opposite function of a rectifier.

Applications

DC power source utilization

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

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

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

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

Uninterruptible power supplies

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

Induction heating

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

HVDC power transmission

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

Variable-frequency drives

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

Electric vehicle drives

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

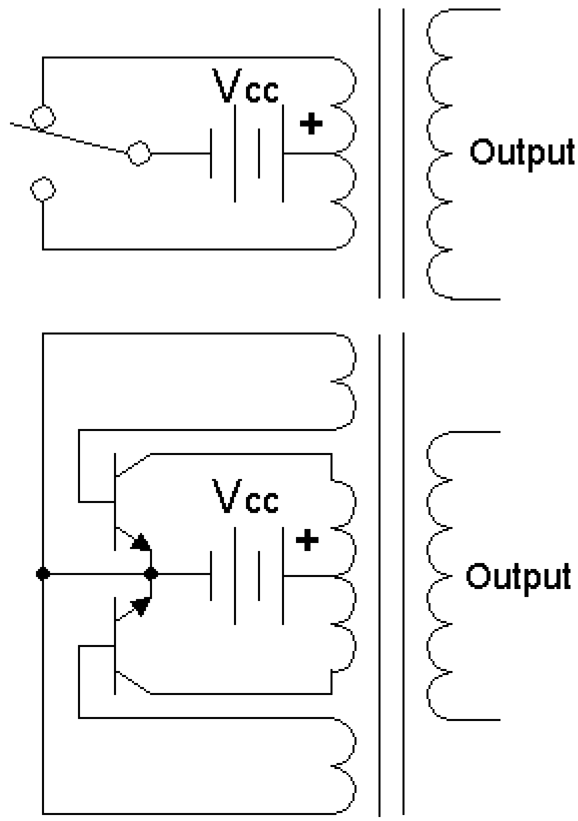
Air conditioning

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

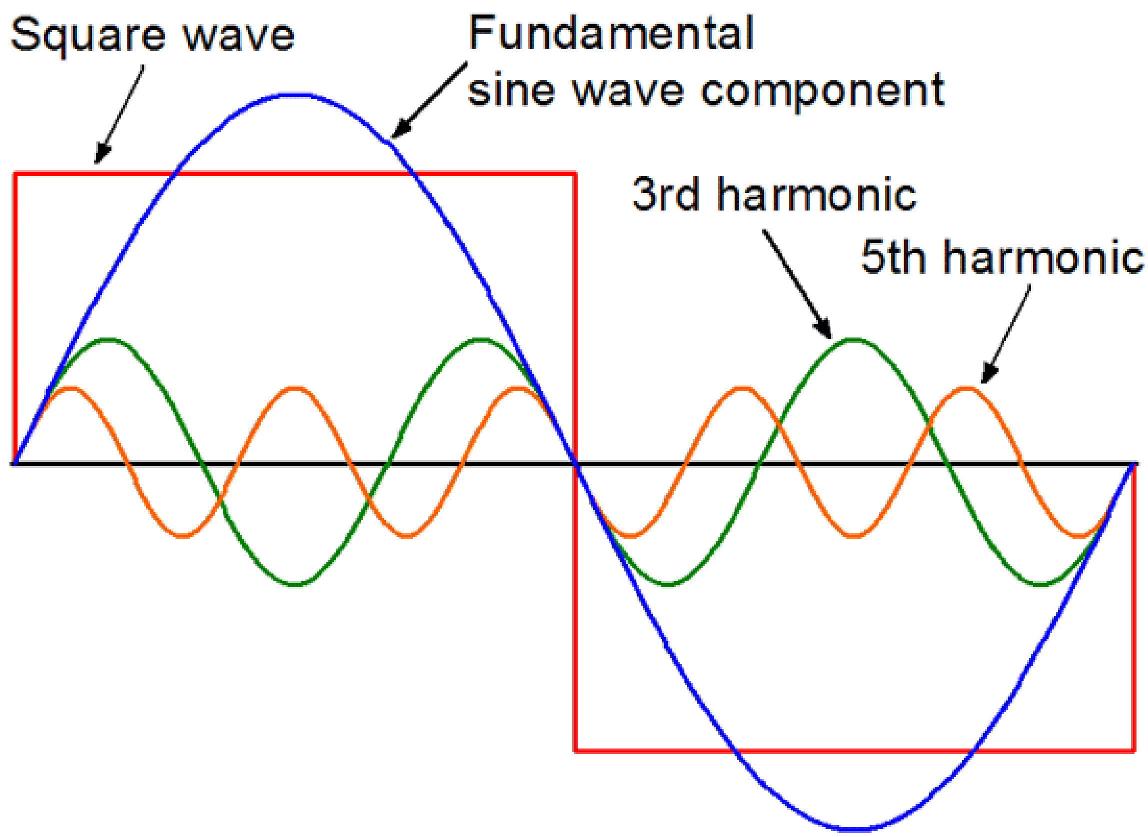
The general case

A transformer allows AC power to be converted to any desired voltage, but at the same frequency. Inverters, plus rectifiers for DC, can be designed to convert from any voltage, AC or DC, to any other voltage, also AC or DC, at any desired frequency. The output power can never exceed the input power, but efficiencies can be high, with a small proportion of the power dissipated as waste heat.

Circuit description



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



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

Basic designs

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

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

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

Output waveforms

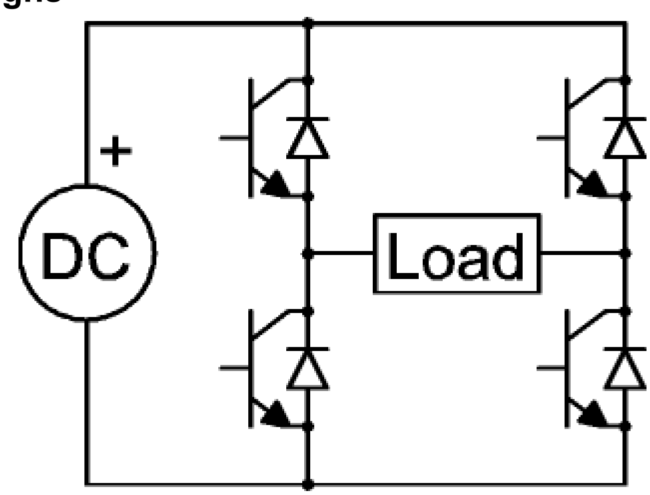
The switch in the simple inverter described above, when not coupled to an output transformer, produces a square voltage waveform due to its simple off and on nature as opposed to the sinusoidal waveform that is the usual waveform of an AC power supply. Using Fourier analysis, periodic waveforms are represented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

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

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

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

Advanced designs

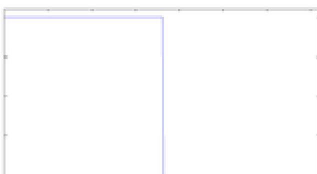
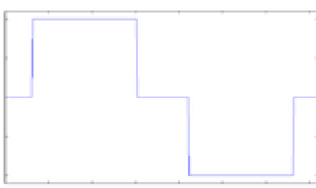
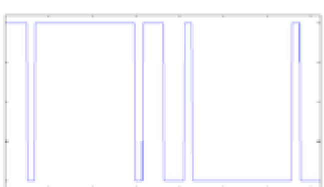
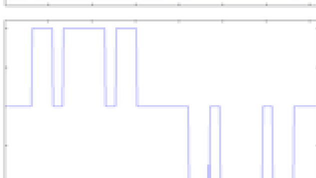


H-bridge inverter circuit with transistor switches and antiparallel diodes

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

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

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

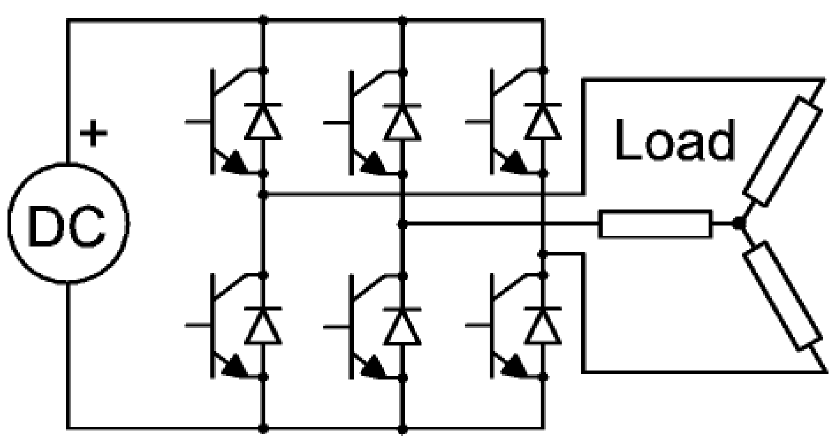
waveform	**signal transitions per period**	**harmonics eliminated**	**harmonics amplified**	**System Description**	**THD**
	2	-	-	2-level square wave	~45%
	4	3, 9, 27,...	-	3-level "modified square wave"	> 23.8%
	8			5-level "modified square wave"	> 6.5%
	10	3, 5, 9, 27	7, 11,...	2-level very slow PWM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

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

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

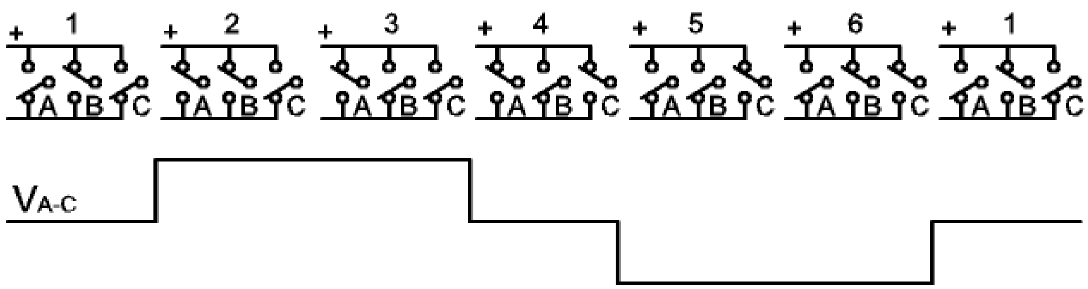
Multilevel inverters provide another approach to harmonic cancellation. Multilevel inverters provide an output waveform that exhibits multiple steps at several voltage levels. For example, it is possible to produce a more sinusoidal wave by having split-rail direct current inputs at two voltages, or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

Three phase inverters



3-phase inverter with wye connected load

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

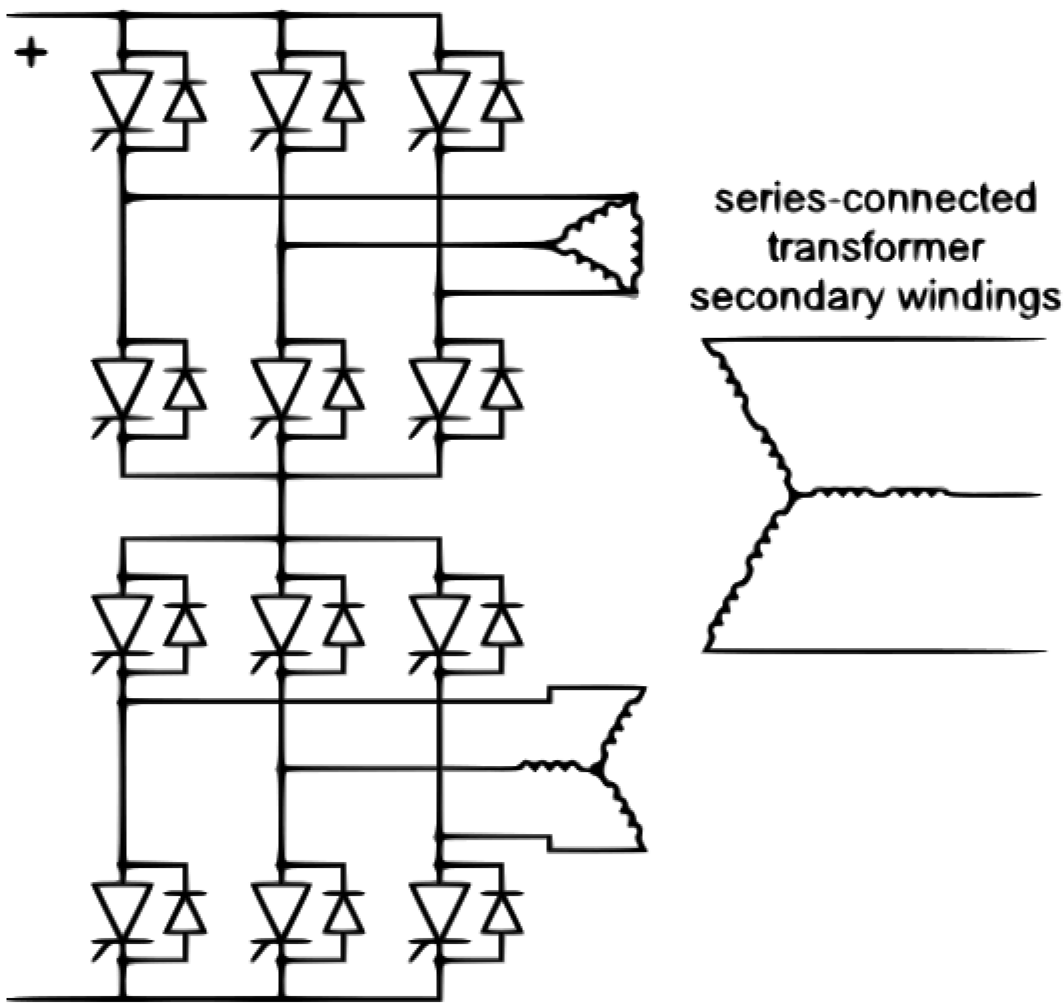
Early inverters

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.

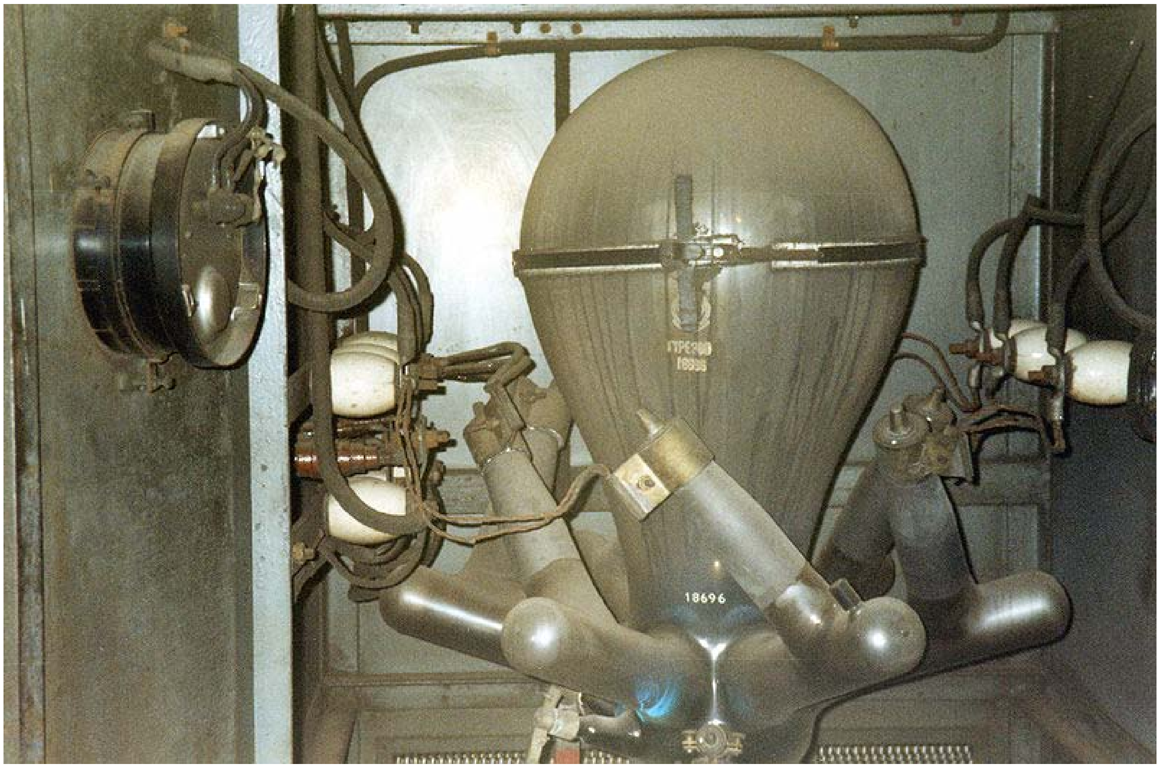
Chapter 11

Mercury Arc Valve

Mercury rectifier on display in Beromünster, Switzerland before being decommissioned

A **mercury arc valve** (**mercury vapor rectifier**) is a type of electrical rectifier used for converting high-voltage or high-current alternating current (AC) into direct current (DC). Rectifiers of this type were used to provide power for industrial motors, electric railways, streetcars, and electric locomotives, as well as for high-voltage direct current power transmission. They were the primary method of rectification before the advent of semiconductor rectifiers such as diodes and gate turn-off thyristor (GTOs).

History



Glass bulb mercury arc rectifier from the 1940s

The mercury arc rectifier was invented by Peter Cooper Hewitt in 1902 and further developed throughout the 1920s and 1930s by researchers in both Europe and North America. Before the advent of solid-state devices, mercury arc rectifiers were one of the most efficient rectifiers. Mercury arc rectifiers or "converters" were used for charging storage batteries and in arc lighting systems where they were found to be more efficient than rotary converters.

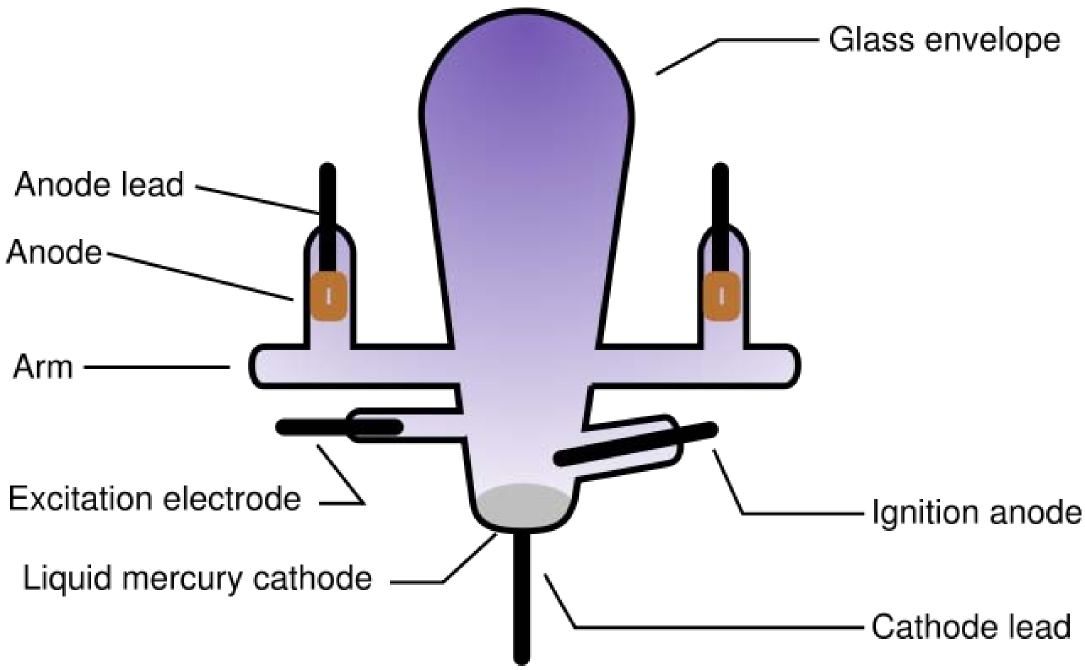
Since about 1975, high-voltage solid state devices such as the silicon diode and thyristor have made mercury arc rectifiers largely obsolete, even in some high-voltage DC applications.

Applications

Mercury arc valves were widely used until the 1960s for the conversion of alternating current into direct current. Applications included power supply for streetcars, electric railways, and variable-voltage power supplies for large radio transmitters. Mercury arc stations were used to provide DC power to legacy Edison-style DC power grids in urban centers until the 1950s.

They remain in use, for example, in some South African mines, on the Manx Electric Railway on the Isle of Man, the Inter-Island HVDC (high voltage direct current) link between the North and South Islands of New Zealand, and the HVDC Vancouver Island link between Vancouver Island and the Canadian mainland.

Design



A glass envelope mercury arc rectifier valve

One type of mercury vapor electric rectifier consists of an evacuated glass bulb, with a pool of liquid mercury sitting in the bottom as the cathode. Over it curves the glass bulb, which condenses mercury evaporated in the course of operation of the device. The glass envelope has one or more arms with graphite rods as anodes. Their number depends on the application. If direct current is to be produced from single-phase alternating current, then two anodes are used, each connected to the outer ends of a centre-tapped transformer secondary winding. With three-phase alternating current three or six anodes are used, to provide a smoother direct current. Six-phase operation can improve the efficiency of the transformer as well as providing smoother DC, by enabling two anodes to conduct simultaneously. During operation, the arc transfers to the anodes at the highest positive potential (with respect to the cathode). Design of the arms and envelope is intended to prevent an arc from forming between the anodes; such a condition is called "backfire" and is a critical factor in the design of mercury arc rectifiers.

Glass envelope rectifiers can produce hundreds of kilowatts of direct-current power in a single unit. A 6-phase rectifier rated 150 amperes has a glass envelope approximately 600 mm (24 inches) high by 300 mm (12 inches) outside diameter. These rectifiers will contain several pounds of liquid mercury. The large size of the envelope is required due to the low thermal conductivity of glass. Mercury vapor in the upper part of the envelope must give up heat through the glass envelope to condense and return to the cathode pool.

The current-carrying capacity of a rectifier is limited in part by the size of the wires fused into the glass envelope for connection of the anodes and cathode. Development of high-current rectifiers required leadwire materials and glass with very similar coefficients of thermal expansion in order to prevent leakage of air into the envelope.

For larger valves, a metal tank with ceramic insulators for the electrodes is used, with a vacuum pump system to counteract slight leakage of air into the tank around imperfect seals. The design patented by Uno Lamm of ASEA is one example of this type which includes grading electrodes between the anode and cathode to prevent backfire. Metal-tank rectifiers were built with ratings of 2000 A and 125 kV per unit.

Both glass and metal envelope rectifiers may have control grids inserted between the anode and cathode. This allows the conduction of the rectifier to be controlled, for example to delay the instant at which the arc transfers to the anode on the alternating current waveform, thereby giving control of the mean output voltage produced by the rectifier. Such grid-controlled valves are an essential part of a static inverter.

The temperature of the envelope must be carefully controlled, since the working pressure within the envelope is set by the coolest spot on the enclosure wall. A typical design maintains temperature at 40 degrees Celsius and a mercury vapor pressure of 7 millipascals.

Function

Principle

Operation of the rectifier relies on an electrical arc discharge between electrodes in a sealed envelope containing mercury vapor. A pool of liquid mercury acts as a self-renewing cathode that does not deteriorate with time. The mercury emits electrons freely, whereas the carbon anodes emit very few electrons even when heated, thus rectifying action occurs.

Once an arc is formed, electrons are emitted from the surface of the pool, causing ionization of mercury vapor along the path towards the anodes. The mercury ions are attracted towards the cathode, and the resulting ionic bombardment of the pool maintains the temperature of the 'emission spot', so long as a current of a few amperes continues.

The mercury ions emit light at characteristic wavelengths, the relative intensities of which are determined by the pressure of the vapor. At the low pressure within a rectifier, the light appears pale blue-violet and contains much ultraviolet light.

The cathode is connected to the DC load, which in turn is connected to the center tap of an AC transformer, which always remains at zero potential. For each AC phase, a wire from each of the two end taps is connected to an anode "arm" on the mercury arc rectifier. As the voltage on each anode goes positive, it will begin to conduct through the mercury vapor to the cathode. As the anodes of each AC phase are fed from opposite ends of the transformer winding, one will be positive, and the other negative, and thus a current will always be maintained from one or more positive anodes to the cathode.

Single-phase mercury arc rectifiers were infrequently used because every time the AC voltage dropped to zero the arc would be extinguished. The direct current produced by a single-phase rectifier contains a varying component (ripple) at twice the power supply frequency, which was undesirable in many applications for DC. The solution was to use 2, 3 or even 6 phase AC power supplies so that the rectified current would maintain a more constant voltage level. Polyphase rectifiers also balanced the load on the phases of a polyphase supply system, which is desirable for reasons of system performance and economy.

Starting

A conventional mercury arc rectifier is started by a brief high-voltage arc within the rectifier, between the cathode pool and a starting electrode. By one of a number of means, the starting electrode is brought into contact with the pool and allowed to pass current through an inductive circuit. The contact with the pool is then broken, resulting in a high emf.

The momentary contact between the starting electrode and the pool may be achieved by allowing an external electromagnet to pull the electrode into contact with the pool; the electromagnet can also serve as the starting inductance. Alternatively, the electromagnet may be arranged to tip the bulb of a small rectifier, just enough to allow mercury from the pool to reach the starting electrode. An alternative system provides a narrow neck of mercury between two pools, and by passing a very high current at negligible voltage through the neck, displaces it by magnetostriction, thus opening the circuit.

Excitation

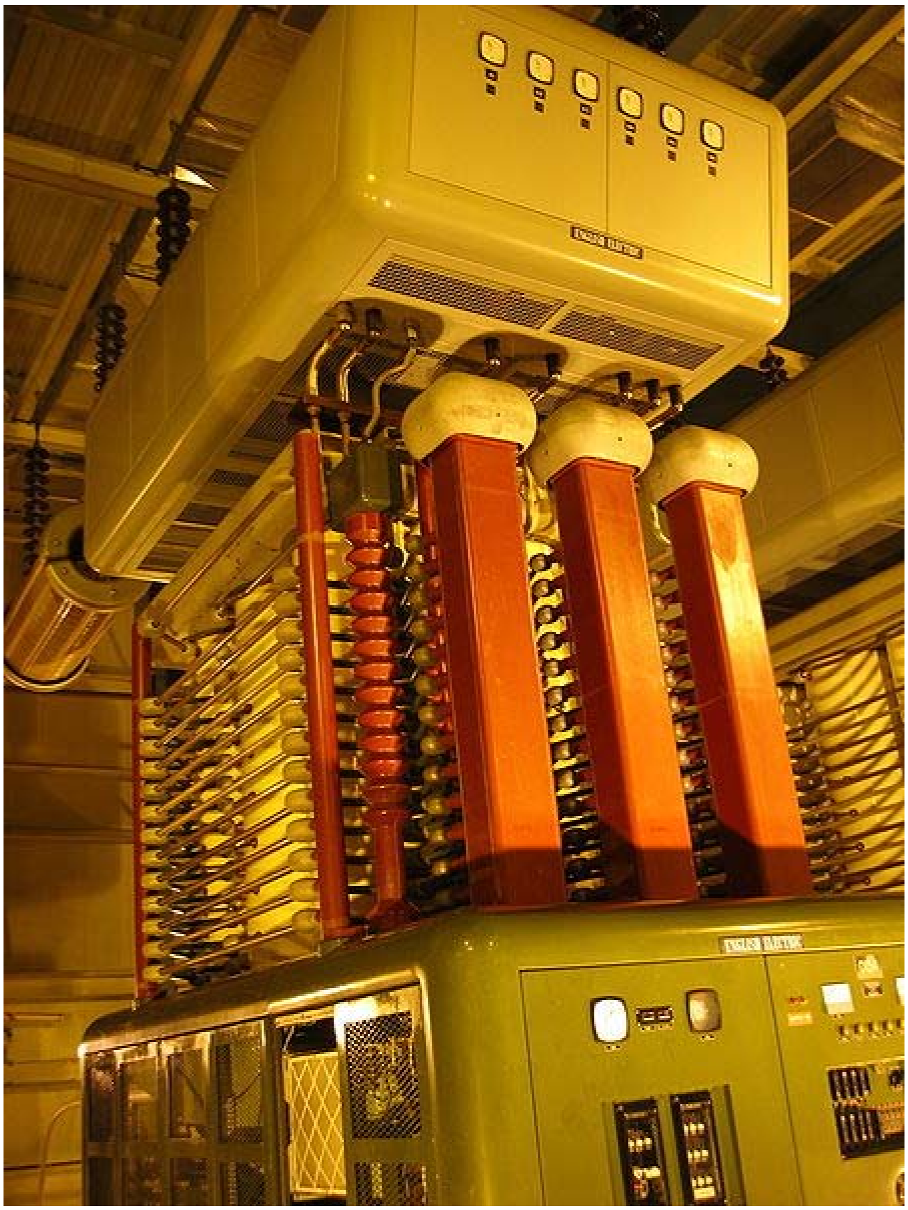
Since momentary interruptions or reductions of output current may cause the cathode spot to extinguish, many rectifiers incorporate an additional electrode to maintain an arc whenever the plant is in use. Typically, a two or three phase supply of a few amperes passes through small 'excitation' anodes. A magnetically shunted transformer of a few hundred VA rating is commonly used to provide this supply.

This excitation or *keep-alive* circuit was absolutely necessary for mercury arc rectifiers used in the high voltage supply of radiotelegraphy transmitters, as current flow was regularly interrupted every time the morse key was released.

Control

Installation of a control grid between the anode and the pool cathode allows control of the conduction of the valve. Start of the current flow can be delayed past the point at which the arc would form in an uncontrolled valve. This allows the output voltage of a valve group to be adjusted by delaying the firing point, and allows controlled mercury arc valves to form the active switching elements in an inverter converting direct current into alternating current.

Others



A 150 kV mercury arc valve at Manitoba Hydro's Radisson converter station, August 2003

The largest ever mercury arc rectifiers were used until 2004 at the Nelson River Bipole high-voltage DC power transmission project.

Special types of mercury arc rectifiers are the Ignitron and the Excitron.

In 1919 the book "Cyclopedia of Telephony & Telegraphy Vol. 1" described an amplifier for telephone signals that used a magnetic field to modulate an arc in a mercury rectifier tube. This pre-dated the application of the vacuum tube to amplification of audio signals but was never commercially important.

Environmental hazard

Mercury compounds are toxic, highly persistent in the environment, and present a danger to humans and the environment. The use of large quantities of mercury in fragile glass envelopes presents a hazard of potential release of mercury to the environment should the glass bulb be broken. Some HVDC static inverter stations have required expensive clean-up to eliminate traces of mercury emitted from the station over its service life. Steel tank rectifiers frequently required vacuum pumps which continually emitted small amounts of mercury vapor.

Chapter 12

Motor-Generator and Phasor Measurement Unit

Motor-generator

Radio station motor-generator set, converting from low to the high voltage power supply. This device is also called *umformer*. Dübendorf Museum of Military Aviation

A **motor-generator** (an **M-G set** or a **dynamotor** for dynamo-motor) is a device for converting electrical power to another form. In some contexts, the other form is mechanical energy; in other contexts, it is a different form of electricity. The two senses refer to different types of equipment.

The Motor-generator set is used to convert frequency, voltage, and phase of power. They may also be used to provide complete line isolation in addition to the various types of power conversion and control. Large motor-generators were widely used to convert industrial amounts of power while smaller motor-generators (such as the one shown in the picture) were used to convert battery power to higher DC voltages.

By comparison, simple, low-powered consumer electronics devices like vacuum tube car radios did not use motor-generators. Instead, they would typically use an inverter circuit consisting of a vibrator (a self-exciting relay) and a transformer to produce the B+ voltages required for the vacuum tubes.

A **motor-generator** is physically different from a normal electric motor attached to a separate generator, in that both rotor coils of the motor and the generator are wound around a single rotor, and both coils share the same outer field coils or magnets. Typically the motor coils are driven from a commutator on one end of the shaft, when the generator coils output to another commutator on the other end of the shaft. The entire rotor and shaft assembly is only slightly larger in size than in a normal electric motor, and may not have any exposed drive shafts.

Electrical power handling

In the context of electric power generation and large fixed electrical power systems, a **motor-generator** consists of an electric motor mechanically coupled to an electric generator (or alternator). The motor runs on the electrical input current while the generator creates the electrical output current, with power flowing between the two machines as a mechanical torque; this provides electrical isolation and some buffering of the power between the two electrical systems. One use of this type of motor-generator is to eliminate spikes and variations in "dirty power" or to provide phase matching between different electrical system; another is to buffer extreme loads on the power system. For example, tokamak fusion devices impose very large peak loads, but relatively low average loads, on the electrical grid. The DIII-D and Princeton Large Torus (PLT) tokamaks and Nimrod synchrotron used a large flywheel on multiple motor-generator rigs to level the load imposed on the electrical system: the motor side slowly accelerated a large flywheel to store energy, which was consumed rapidly during a fusion experiment as the generator side acted as a brake on the flywheel. Similarly, the next generation U.S. Navy aircraft carrier Electromagnetic Aircraft Launch System (EMALS) will use a flywheel motor-generator rig to supply power instantaneously for aircraft launches at greater than the ship's installed generator capacity.

Conversions

Motor-generators may be used for various conversions including:

- Alternating current (AC) to direct current (DC)
- DC to AC
- DC at one voltage to DC at another voltage
- AC at one frequency to AC at another harmonically-related frequency

High-frequency machines

An Alexanderson alternator is a motor-driven, high-frequency alternator which provides radio frequency power. In the early days of radio communication, the high frequency carrier wave had to be produced mechanically using an Alternator with many poles driven at high speeds. The Alexanderson alternator produced upward of 100 kHz with power outputs upward of 200 kW. While electromechanical converters were regularly used for long wave transmissions in the first three decades of the 20th century, electronic techniques were required at higher frequencies. The Alexanderson alternator was largely replaced by the vacuum tube oscillator in the 1920s.

Motor-generators used to increase Ride-Through

Motor-generators have even been used where the input and output currents are essentially the same. In this case, the mechanical inertia of the M-G set is used to filter out transients in the input power. The output's electric current can be very clean (noise free) and will be able to *ride-through* brief blackouts and switching transients at the input to the M-G set. This may enable, for example, the flawless cut-over from mains power to AC power provided by a diesel generator set.

The motor-generator set may contain a large flywheel to improve its ride-through; however, consideration must be taken in this application as the motor-generator will require a large amount of current on re-closure, if prior to the pull-out torque is achieved, resulting in a shut down. The in-rush current during re-closure will depend on many factors, however. As an example, a 250 kVA motor generator operating at 300 ampere of full load current will require 1550 ampere of in-rush current during a re-closure after 5 seconds. This example used a fixed mounted flywheel sized to result in a 1/2 Hz per second slew rate. The motor-generator was a vertical type 2 bearing machine with oil bath bearings.

The motor-generator today

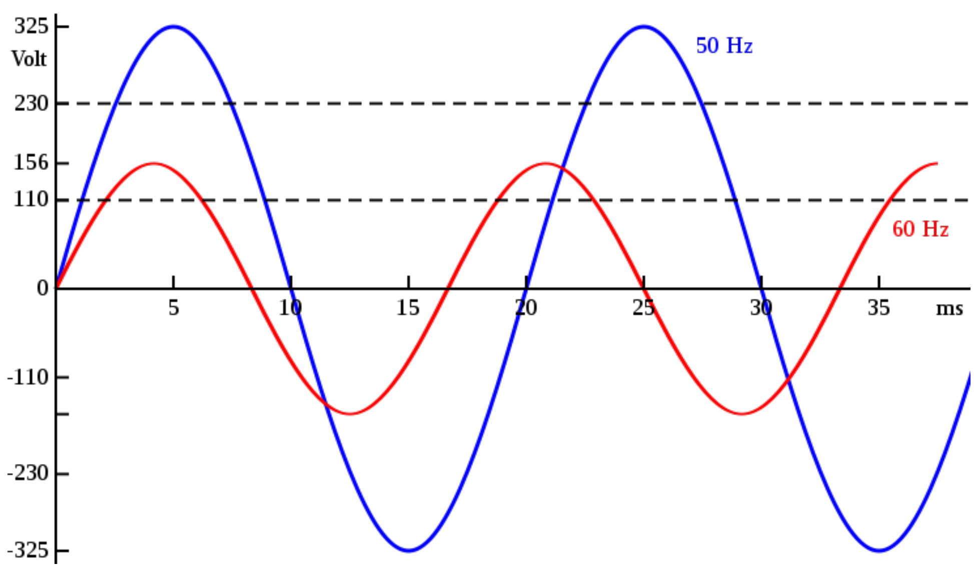
Motor-generators have been replaced by semiconductor devices for some purposes. In industrial settings where harmonic cancellation, frequency conversion, or line isolation is needed, MG sets remain a popular solution.

A useful feature of the motor-generator is that they can handle large short-term overloads better than semiconductor devices of the same average load rating. Consider that the thermally current-limited components of a large semiconductor inverter are solid-state switches massing a few grams with a thermal time constant to their heat sinks of likely more than 100 ms, whereas the thermally current limited components of an MG are copper windings massing some hundreds of kilos which are intrinsically attached to their own large thermal mass. They also have inherently excellent resistance to electrostatic discharge (ESD).

Modern use of the term motor-generator

In the context of hybrid vehicles and other lightweight power systems, a **motor-generator** can be used to describe a single power transducer that can be used as either an electric motor or a generator, converting between electrical power and mechanical power. In principle, any electrical generator can also serve as an electric motor, or vice versa. A device that is specifically designed for use in either mode may be called a "motor-generator"; the literature distributed by Toyota to describe the Hybrid Synergy Drive is an example of this newer usage.

Phasor measurement unit



Using a PMU, it is simple to detect abnormal waveform shapes. A waveform shape described mathematically is called a phasor.

A **phasor measurement unit** (PMU) measures the electrical waves on an electricity grid to determine the health of the system. In power engineering, these are also commonly referred to as synchrophasors and are considered one of the most important measuring devices in the future of power systems. A PMU can be a dedicated device, or the PMU function can be incorporated into a protective relay or other device.

Technical overview

A phasor is a complex number that represents both the magnitude and phase angle of the sine waves found in electricity. Phasor measurements that occur at the same time are called "synchrophasors", as are the PMU devices that allow their measurement. In typical applications phasor measurement units are sampled from widely dispersed locations in the power system network and synchronized from the common time source of a global positioning system (GPS) radio clock. Synchrophasor technology provides a tool for system operators and planners to measure the state of the electrical system and manage power quality. Synchrophasors measure voltages and currents at diverse locations on a power grid and can output accurately time-stamped voltage and current phasors. Because these phasors are truly synchronized, synchronized comparison of two quantities is possible, in real time. These comparisons can be used to assess system conditions.

The technology has the potential to change the economics of power delivery by allowing increased power flow over existing lines. Synchrophasor data could be used to allow power flow up to a line's dynamic limit instead of to its worst-case limit.

History

In 1893, Charles Proteus Steinmetz presented a paper on simplified mathematical description of the waveforms of alternating electricity. Steinmetz called his representation a phasor. With the invention of phasor measurement units (PMU) in 1988 by Dr. Arun G. Phadke and Dr. James S. Thorp at Virginia Tech, Steinmetz's technique of phasor calculation evolved into the calculation of real time phasor measurements that are synchronized to an absolute time reference provided by the Global Positioning System. Early prototypes of the PMU were built at Virginia Tech, and Macrodyne built the first PMU (model 1620) in 1992.

Phasor networks

A phasor network consists of phasor measurement units (PMUs) dispersed throughout the electricity system, Phasor Data Concentrators (PDC) to collect the information and a Supervisory Control And Data Acquisition (SCADA) system at the central control facility. Such a network is used in Wide Area Measurement Systems (WAMS), the first of which was begun in 2000 by the Bonneville Power Administration . The complete network requires rapid data transfer within the frequency of sampling of the phasor data. GPS time stamping can provide a theoretical accuracy of synchronization better than 1 microsecond. "Clocks need to be accurate to ± 500 nanoseconds to provide the one microsecond time standard needed by each device performing synchrophasor measurement." For 60Hz systems, PMUs must deliver between 10 and 30 synchronous reports per second depending on the application. The PDC correlates the data, and controls and monitors the PMUs (from a dozen up to 60). At the central control facility, the SCADA system presents system wide data on all generators and substations in the system every 2 to 10 seconds. PMUs often use phone lines to connect to PDC, which then send data to the SCADA and/or Wide Area Measurement System (WAMS) server.

PMUs from multiple vendors can yield inaccurate readings. In one test, readings differed by 47 microseconds- or a difference of 1 degree of at 60Hz- an unacceptable variance. China's solution to the problem was to build all its own PMUs adhering to its own specifications and standards so there would be no multi-vendor source of conflicts, standards, protocols, or performance characteristics.

Implementations

- The Bonneville Power Administration (BPA) is the first utility to implement comprehensive adoption of synchrophasors in its wide-area monitoring system. Today there are several implementations underway.
- The FNET project operated by Virginia Tech and the University of Tennessee utilizes a network of approximately 80 low-cost, high-precision Frequency Disturbance Recorders to collect syncrophasor data from the U.S. power grid.
- In 2006, China's Wide Area Monitoring Systems (WAMS) for its 6 grids had 300 PMUs installed mainly at 500 kV and 330 kV substations and power plants. By 2012, China plans to have PMUs at all 500kV substations and all powerplants of 300MW and above. Since 2002, China has built its own PMUs to its own national standard. One type has higher sampling rates than typical and is used in power plants to measure rotor angle of the generator, reporting excitation voltage, excitation current, valve position, and output of the power system stabilizer (PSS). All PMUs are connected via private network, and samples are received within 40 ms on average.
- The North American Synchrophasor Initiative (NASPI), previously known as The Eastern Interconnect Phasor Project (EIPP), has over 120 connected phasor measurement units collecting data into a "Super Phasor Data Concentrator" system centered at Tennessee Valley Authority (TVA). This data concentration system is now an open source project known as the openPDC.
- The DOE has sponsored several related research projects, including GridStat at Washington State University.

Applications

1. Power system automation, as in smart grids
2. Load shedding and other load control techniques such as demand response mechanisms to manage a power system. (i.e. Directing power where it is needed in real-time)
3. Increase the reliability of the power grid by detecting faults early, allowing for isolation of operative system, and the prevention of power outages.
4. Increase power quality by precise analysis and automated correction of sources of system degradation.
5. Wide Area measurement and control, in very wide area super grids, regional transmission networks, and local distribution grids.

Standards

The IEEE 1344 standard for synchrophasors was completed in 1995, and reaffirmed in 2001. In 2005, it was replaced by IEEE Standard C37.118-2005, which was a complete revision and dealt with issues concerning use of PMUs in electric power systems. The specification describes standards for measurement, the method of quantifying the measurements, testing & certification requirements for verifying accuracy, and data transmission format and protocol for real-time data communication. The standard is not yet comprehensive- it does not attempt to address all factors that PMUs can detect in power system dynamic activity.

Other standards used with PMU interfacing:

- OPC-DA / OPC-HDA - A Microsoft Windows based interface protocol that is currently being generalized to use XML and run on non Windows computers.
- IEC 61850 a standard for electrical substation automation
- BPA PDCStream - a variant of IEEE 1344 used by the Bonneville Power Administration (BPA) PDCs and user interface software.

Chapter 13

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.

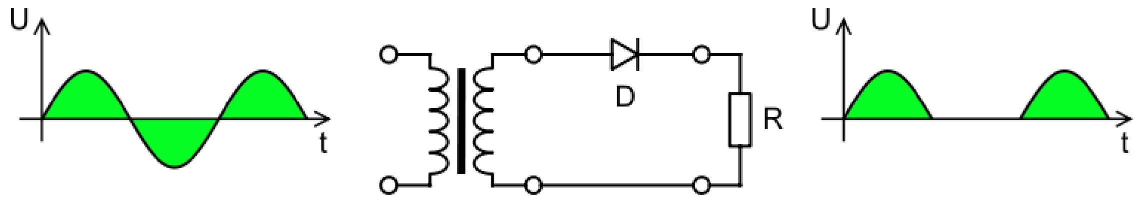
A device which performs the opposite function (converting DC to AC) is known as an inverter.

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.



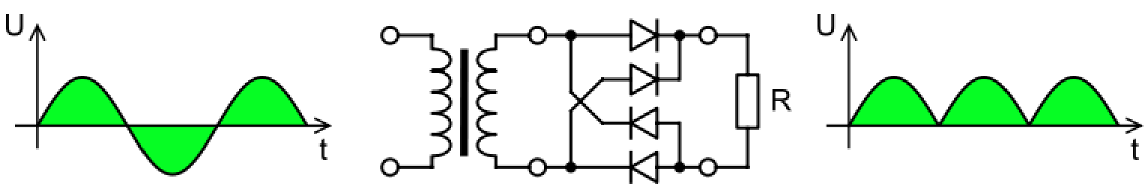
The output DC voltage of a half wave rectifier can be calculated with the following two ideal equations:

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

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

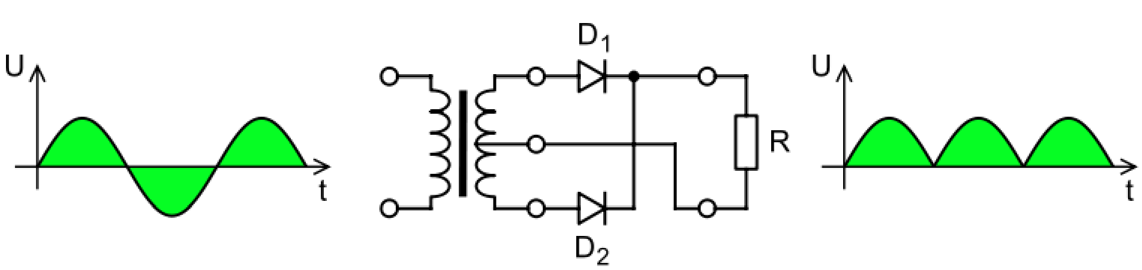
Full-wave rectification

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.

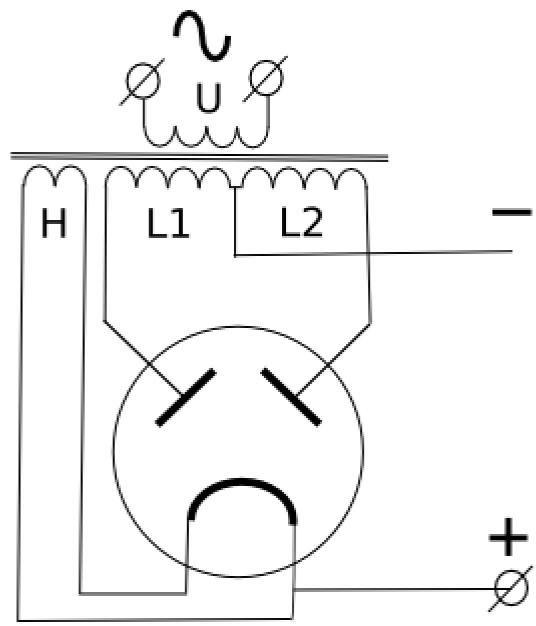


Graetz bridge rectifier: a full-wave rectifier using 4 diodes.

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.

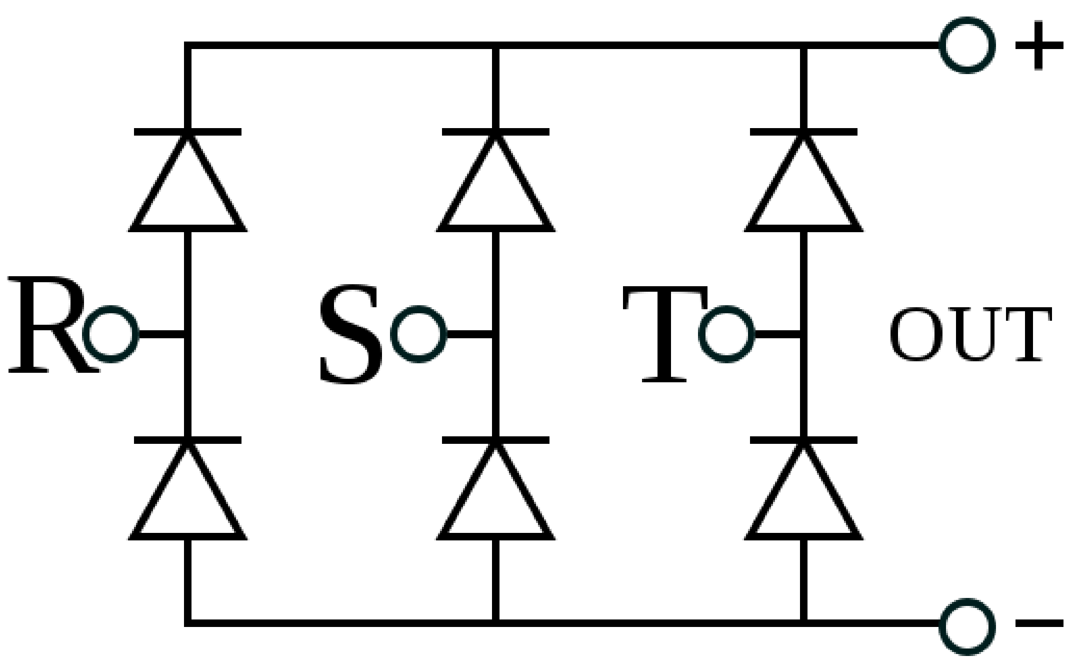


Full-wave rectifier using a center tap transformer and 2 diodes.

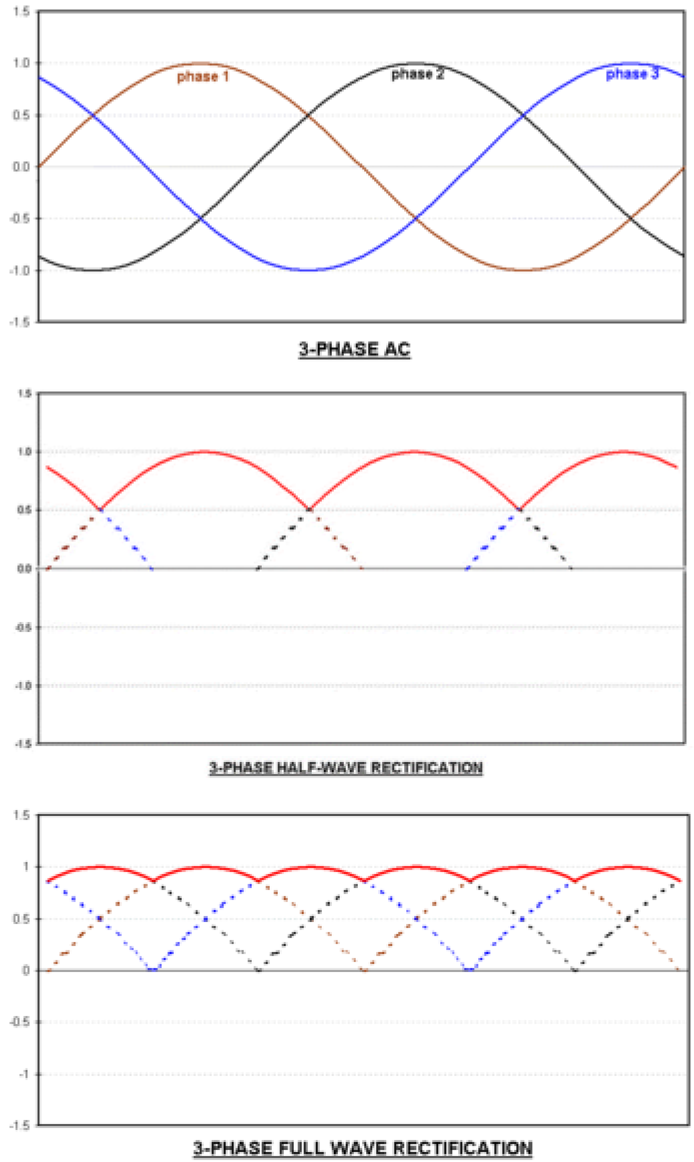


Full-wave rectifier, with vacuum tube having two anodes.

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.

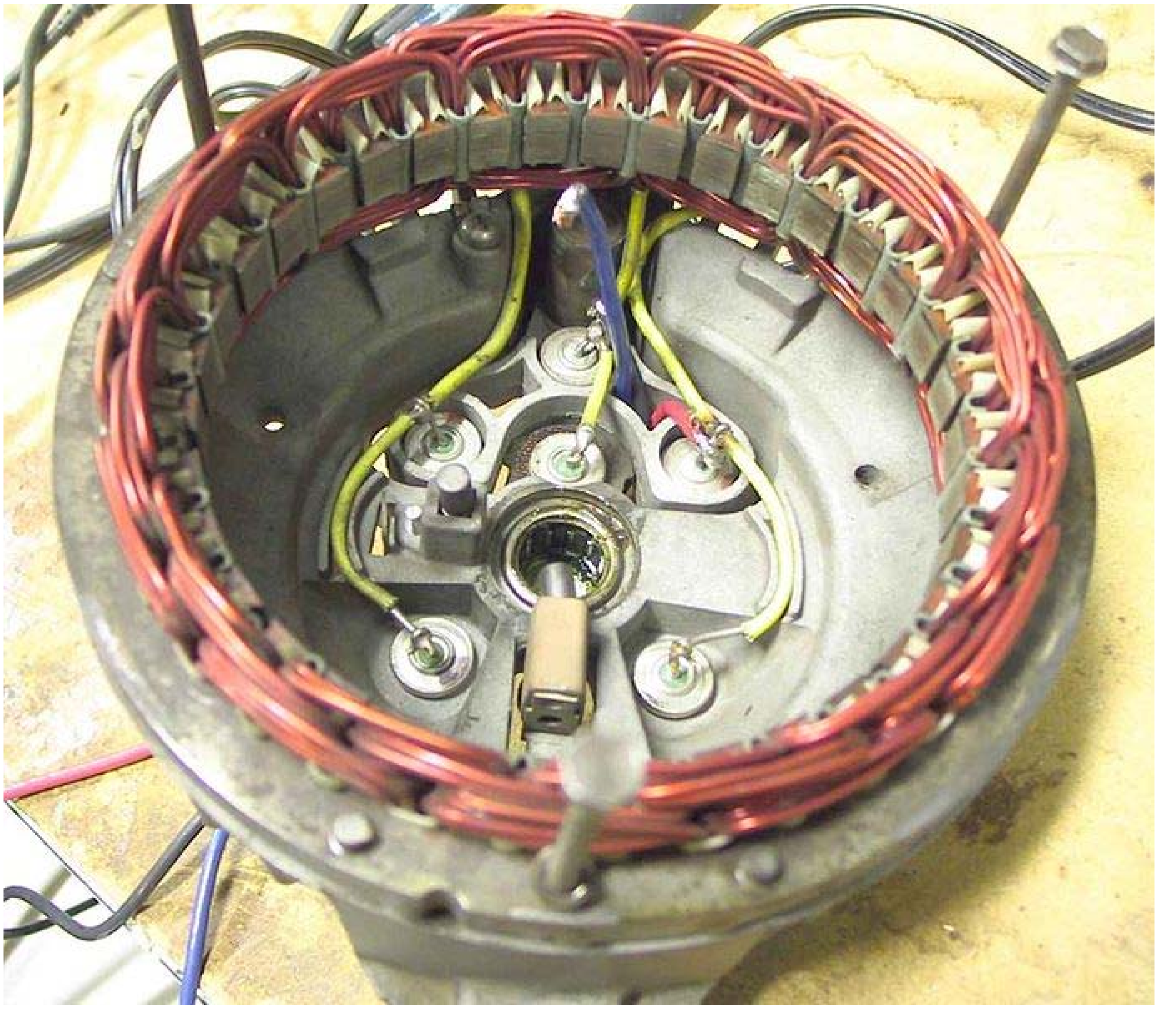


A three-phase bridge rectifier.



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:

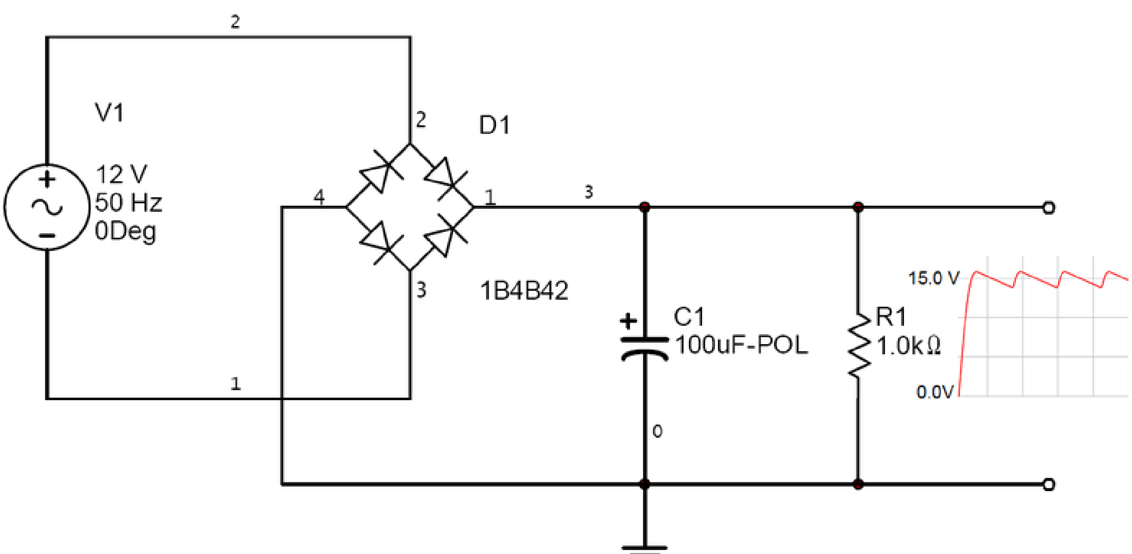
> $\mathbf{V_{dc}, V_{av}}$ - the average or DC output voltage,
> $\mathbf{V_p}$ - the peak value of half wave,
> $\mathbf{V_{rms}}$ - the root-mean-square value of output voltage.
> $\boldsymbol{\pi}$ = ~ 3.14159

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.

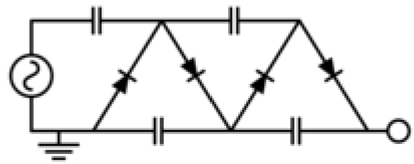
To further reduce this ripple, a capacitor-input filter can be used. This complements the reservoir capacitor with a choke (inductor) and a second filter capacitor, so that a steadier DC output can be obtained across the terminals of the filter capacitor. The choke presents a high impedance to the ripple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



Cockcroft Walton Voltage multiplier

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.

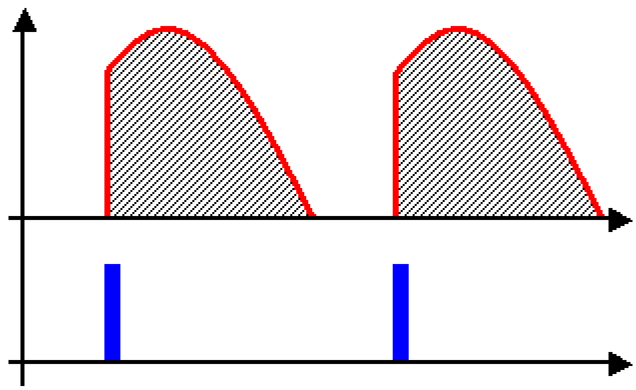
Applications

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

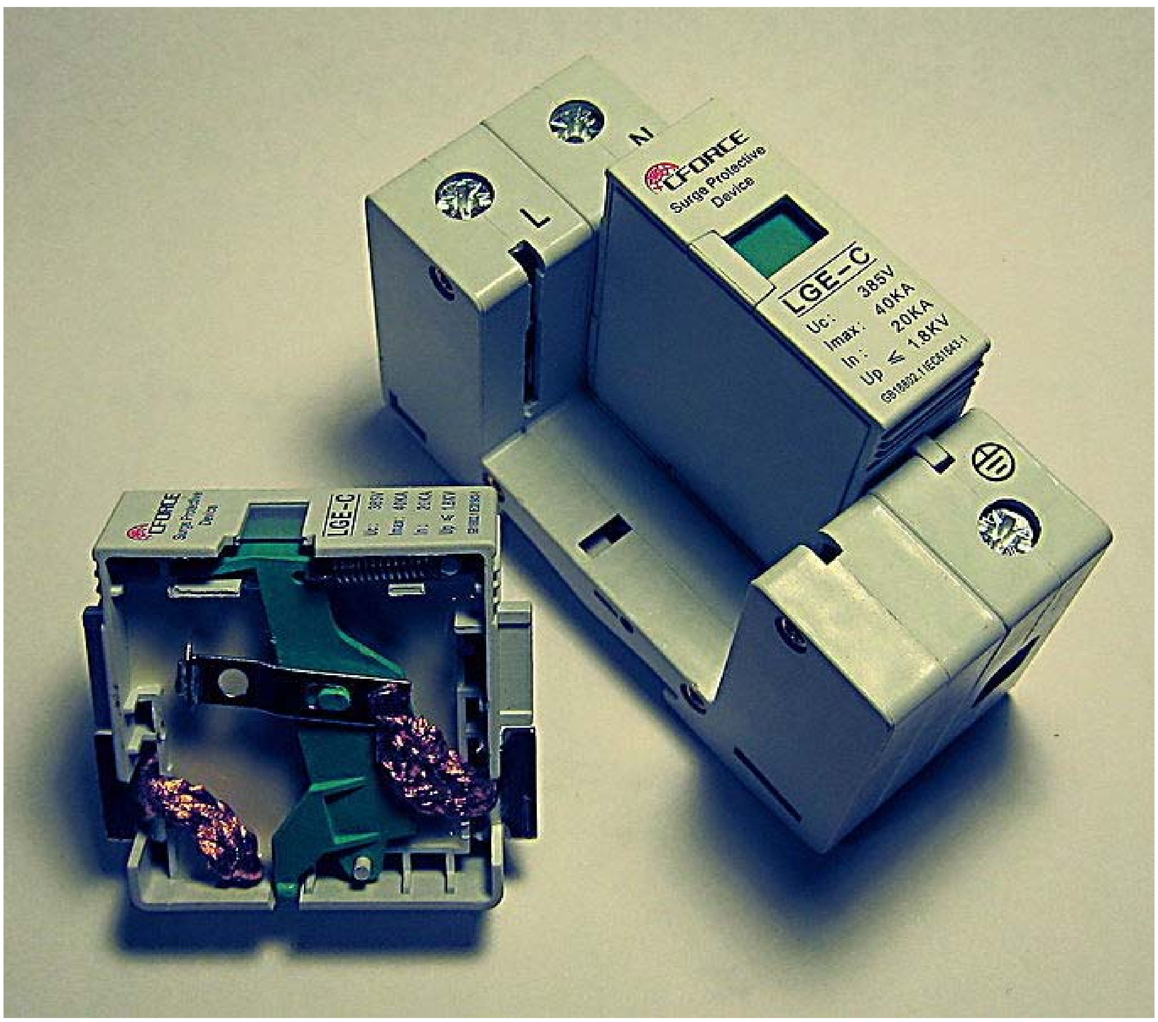
Researchers at Idaho National Laboratory (INL) have proposed high-speed rectifiers that would sit at the center of spiral nanoantennas and convert infrared frequency electricity from AC to DC. Infrared frequencies range from 0.3 to 400 terahertz.

Unimolecular rectifiers

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

Chapter 14

Surge Protector



A 2-pole surge protector for installation in distribution boards

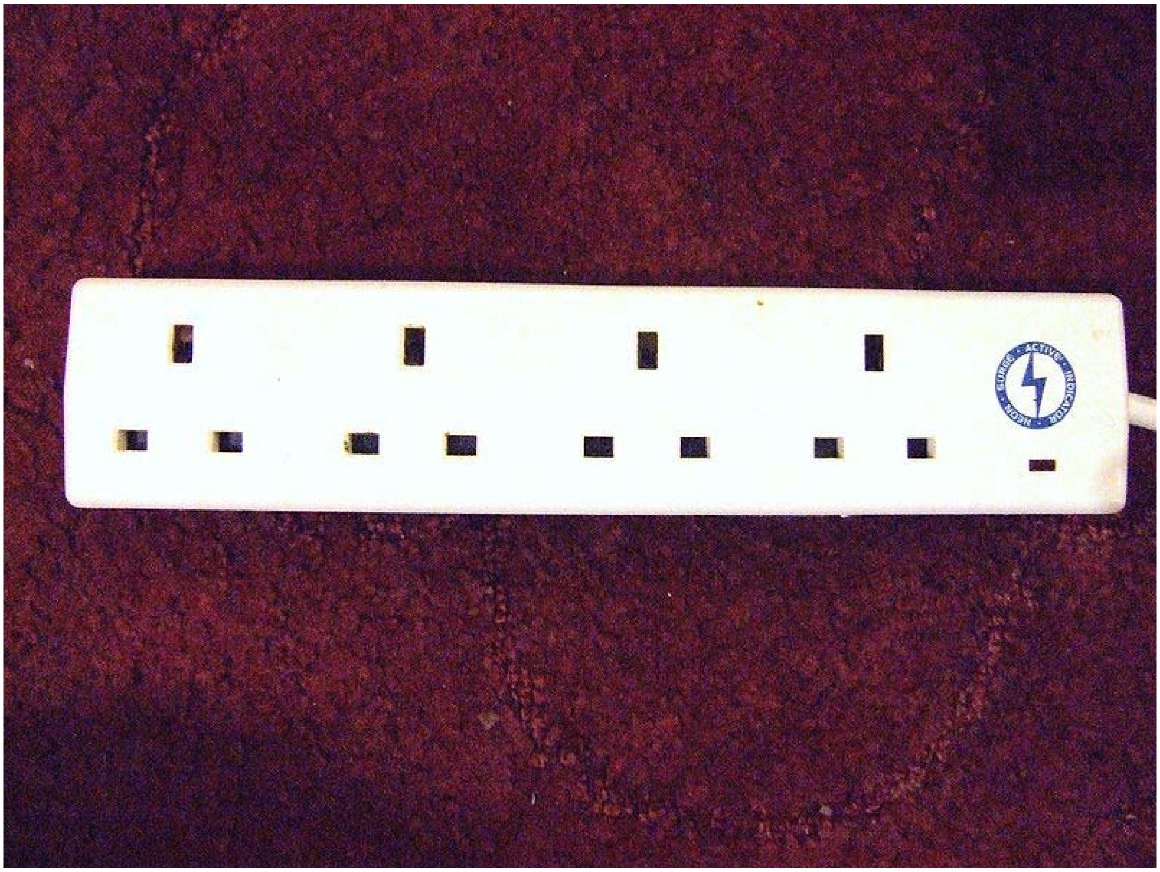
A **surge protector** (or **surge suppressor**) is an appliance designed to protect electrical devices from voltage spikes. A surge protector attempts to limit the voltage supplied to an electric device by either blocking or by shorting to ground any unwanted voltages above a safe threshold. Here we, primarily discusses specifications and components relevant to the type of protector that diverts (shorts) a voltage spike to ground; however, there is some coverage of other methods.

The terms **surge protection device (SPD)**, or the obsolescent term **transient voltage surge suppressor (TVSS)**, are used to describe electrical devices typically installed in power distribution panels, process control systems, communications systems, and other heavy-duty industrial systems, for the purpose of protecting against electrical surges and spikes, including those caused by lightning. Scaled-down versions of these devices are sometimes installed in residential service entrance electrical panels, to protect equipment in a household from similar hazards.

Many power strips have basic surge protection built in; these are typically clearly labeled as such. However, power strips that do *not* provide surge protection are sometimes erroneously referred to as "surge protectors" by persons who do not understand their purpose and function.

Important specifications

Many surge and noise protectors have multiple outlets



UK type G socket adaptor with surge protector

These are some of the most prominently featured specifications which define a surge protector for AC mains, as well as for some data communications protection applications:

Clamping voltage

Also known as the **let-through voltage**. This specifies what spike voltage will cause the protective components inside a surge protector to divert unwanted energy from the protected line. A lower clamping voltage indicates better protection, but can sometimes result in a shorter life expectancy for the overall protective system. The lowest three levels of protection defined in the UL rating are 330 V, 400 V and 500 V. The standard let-through voltage for 120 V AC devices is 330 volts.

Joules rating

This number defines how much energy the surge protector can theoretically absorb in a single event, without failure. Counter-intuitively, a lower number may indicate longer life expectancy if the device can divert more energy elsewhere and thus will need to absorb less energy. In other words, a protective device offering a lower clamping voltage while diverting the same surge current will cause more of the surge energy to be dissipated elsewhere in the system. Better protectors exceed peak ratings of 1000 Joules and 40,000

Amperes. It is often claimed that a lower joule rating is undersized protection, since the total energy in harmful spikes can be significantly larger than this. However, if properly installed, for every joule absorbed by a protector, another 4 to 30 joules may be dissipated harmlessly into ground. A MOV-based protector with a higher let-through voltage can receive a higher joule rating, even though it lets more surge energy through to the device to be protected.

The joule rating is a commonly-quoted but very misleading parameter for comparing surge protectors. A surge of any arbitrary ampere and voltage combination can occur in time, but surges commonly last only for microseconds to nanoseconds, and experimentally modeled surge energy has been far under 100 Joules. Well-designed surge protectors should not rely on MOVs to only *absorb* surge energy, but use them instead to survive the process of harmlessly *redirecting* it. An overwhelmingly overloaded MOV should fail gracefully like a fuse, while diverting most of the surge energy to ground thus sacrificing itself, if needed, to protect equipment plugged into the surge protector. As an additional consideration, since energy in a MOV is stored as potential energy and is released as kinetic energy, a lower joule rating reduces fire and explosion hazards.

Some manufacturers commonly design higher joule rated surge protectors by connecting multiple MOVs in parallel. Since individual MOVs have slightly different non-linear responses when exposed to the same overvoltage, any given MOV might be more sensitive than others. This can cause one MOV in a group to conduct more (a phenomenon called **current-hogging**), leading to overuse and eventually premature failure of that component. If a single inline fuse is placed in series with the MOVs as a power-off safety feature, it will open and fail the surge protector even if remaining MOVs are intact. Thus, the *effective* surge energy absorption capacity of the entire system is dependent on the MOV with the lowest clamping voltage, and the additional MOVs do not provide any further benefit. This limitation can be surmounted by using carefully *matched sets* of MOVs, but this matching must be carefully coordinated with the original manufacturer of the MOV components.

Response time

Surge protectors don't operate instantaneously; a slight delay exists. The longer the response time, the longer the connected equipment will be exposed to the surge. However, surges don't happen instantly either. Surges usually take around a few microseconds to reach their peak voltage, and a surge protector with a nanosecond response time would kick in fast enough to suppress the most damaging portion of the spike.

Therefore, response time under standard testing is not a useful measure of a surge protector's ability when comparing MOV devices. All MOVs have response times measured in nanoseconds, while test waveforms usually used to design and calibrate surge protectors are all based on modeled waveforms of surges measured in microseconds. As a result, MOV-based protectors have no trouble producing impressive response-time specs.

Slower-responding technologies (notably, GDTs) may have difficulty protecting against against fast spikes. Therefore, good designs incorporating slower but otherwise useful technologies usually combine them with faster-acting components, to provide more comprehensive protection.

Standards

Some frequently-listed standards include:

- IEC 61643-1
- EN 61643-11 and 61643-21
- Telcordia Technologies Technical Reference TR-NWT-001011
- ANSI/IEEE C62.xx
- Underwriters Laboratories (UL) 1449

Each standard defines different protector characteristics, test vectors, or operational purpose.

The UL1449 (3rd Edition) standard for SPDs is a major rewrite of previous editions, and has also been accepted as an ANSI standard for the first time.

EN 62305 and ANSI/IEEE C62.xx define what spikes a protector might be expected to divert. EN 61643-11 and 61643-21 specify both the product's performance and safety requirements. In contrast, the IEC only writes standards and does not certify any particular product as meeting those standards. IEC Standards are used by members of the CB Scheme of international agreements to test and certify products for safety compliance.

None of those standards guarantee that a protector will provide proper protection in a given application. Each standard defines what a protector should do or might accomplish, based on standardized tests that may or may not correlate to conditions present in a particular real-world situation. A specialized engineering analysis may be needed to provide sufficient protection, especially in situations of high lightning risk.

Primary components

Systems used to reduce or limit high voltage surges can include one or more of the following types of electronic components. Some surge suppression systems use multiple technologies, since each method has its strong and weak points. The first six methods listed operate primarily by diverting unwanted surge energy away from the protected load, through a protective component connected in a *parallel* (or shunted) topology. The last two methods also block unwanted energy by using a protective component connected in *series* with the power feed to the protected load, and additionally may shunt the unwanted energy like the earlier systems.

Single-outlet surge protector, with visible connection and protection lights

Metal oxide varistor (MOV)

A metal oxide varistor consists of a bulk semiconductor material (typically sintered granular zinc oxide) that can conduct large currents (effectively short-circuits) when presented with a voltage above its rated voltage. MOVs typically limit voltages to about 3 to 4 times the normal circuit voltage by diverting surge current elsewhere than the protected load. MOVs may be connected in parallel to increase current capability and life expectancy, providing they are *matched sets* (unmatched MOVs have a tolerance of approximately ±20% on voltage ratings, which is not sufficient).

MOVs have finite life expectancy and "degrade" when exposed to a few large transients, or many more smaller transients. As a MOV degrades, its triggering voltage falls lower and lower. Eventually, the MOV behaves as a part-time effective short circuit on the AC power line, which will cause it to heat up. As the MOV heats up, it may degrade further, causing a runaway catastrophic failure that can result in a small explosion if the line current is not otherwise limited.

MOVs usually are thermal fused or otherwise protected to avoid persistent short circuits and other fire hazards. In a typical power strip, the visible circuit breaker may be distinct from the internal thermal fuse, which is not normally visible to the end user. If a surge current is so excessively large as to exceed the MOV parameters and blow the thermal fuse, then a light found on some protectors would indicate unacceptable failure. Even adequately sized MOV protectors will eventually degrade beyond acceptable limits with or without a failure light indication. Therefore, all MOV-based protectors should have an indicator that the protective components have failed, and this indication must be checked on a regular basis to insure that protection is still functioning.

Because of their good price/performance ratio, MOVs are the most common protector component in low-cost basic AC power protectors.

Transient voltage suppression (TVS) diode

A TVS diode is a type of zener diode, also called an avalanche diode or **silicon avalanche diode (SAD)**, which can limit voltage spikes. These components provide the fastest limiting action of protective components (theoretically in picoseconds), but have a relatively low energy absorbing capability. Voltages can be clamped to less than twice the normal operation voltage. If current impulses remain within the device ratings, life expectancy is exceptionally long. If component ratings are exceeded, the diode may fail as a permanent short circuit; in such cases, protection may remain but normal circuit operation is terminated in the case of low-power signal lines. Due to their relatively-limited current capacity, TVS diodes are often restricted to circuits with smaller current spikes. TVS diodes are also used where spikes occur significantly more often than once a year, since this component will not degrade when used within its ratings. A unique type of TVS diode (trade names Transzorb or Transil) contains reversed paired *parallel* avalanche diodes for bi-polar operation.

TVS diodes are often used in high-speed but low power circuits, such as occur in data communications. These devices can be paired in *series* with another diode to provide low capacitance as required in communication circuits.

Thyristor surge protection device (TSPD)

A Trisil is a type of **thyristor surge protection device (TSPD)**, a specialized solid-state electronic device used in crowbar circuits to protect against overvoltage conditions. A SIDACtor is another thyristor type device used for similar protective purposes.

These thyristor-family devices can be viewed as having characteristics much like a spark gap or a GDT, but can operate much faster. They are related to TVS diodes, but can "breakover" to a low clamping voltage analogous to an ionized and conducting spark gap. After triggering, the low clamping voltage allows large current surges to flow while limiting heat dissipation in the device.

Gas discharge tube (GDT)

Typical low-power lightning protection circuit. Note MOVs (blue disks) and GDTs (small silver spools)

A **gas discharge tube (GDT)** is a sealed glass-enclosed device containing a special gas mixture trapped between two electrodes, which becomes ionized by a high voltage spike to conduct electric current. GDTs can conduct more current for their size than other components. Like MOVs, GDTs have a finite life expectancy, and can handle a few very large transients or a greater number of smaller transients. GDTs take a relatively long time to trigger, permitting a higher voltage spike to pass through before the GDT conducts significant current. It is not uncommon for a GDT to let through pulses of 500 V or more of 100 ns in duration. In some cases, additional protective components are necessary to prevent damage due to high-speed **let-through** voltage which occurs before the GDT begins to operate.

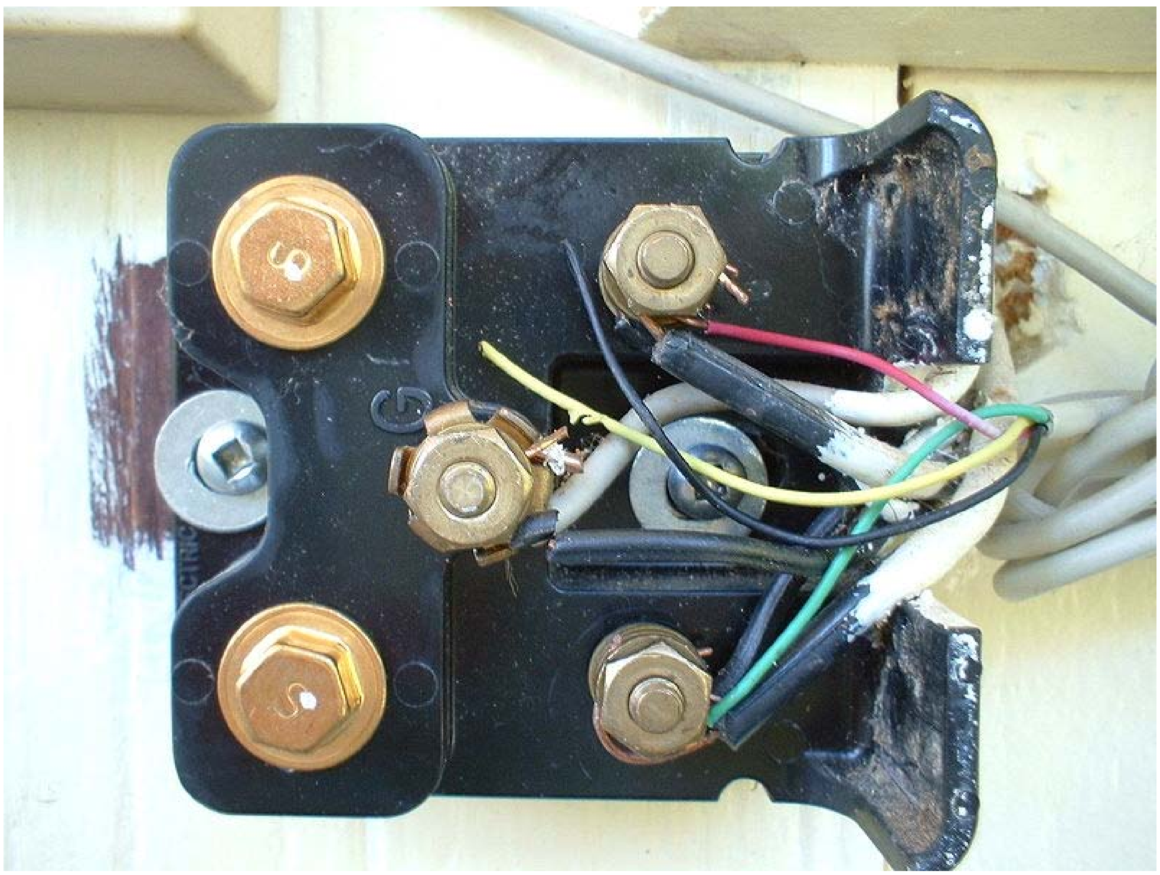
GDTs create an effective short circuit when triggered, so that if any electrical energy (spike, signal, or power) is present, the GDT will short this, and will continue conducting (called **follow-on current**) until all electric current sufficiently diminishes. Unlike other shunt protector devices, a GDT once triggered will continue to conduct at a voltage less than the high voltage that initially ionized the gas; this behavior is called negative resistance. Additional auxiliary circuitry may be needed in DC applications to suppress follow-on current, to prevent it from destroying the GDT after the initiating spike has dissipated. Some GDTs are designed to deliberately short out to a grounded terminal when overheated, thereby triggering an external fuse or circuit breaker.

Due to their exceptionally low capacitance, GDTs are commonly used on high frequency lines, such as are used in telecommunications equipment. Because of their high current handling capability, GDTs can also be used to protect power lines, but the follow-on current problem must be controlled.

Selenium voltage suppressor

A "overvoltage clamping" bulk semiconductor similar to a MOV, though it does not clamp as well. However, it usually has a longer life than a MOV. It is used mostly in high-energy DC circuits, like the exciter field of an alternator. It can dissipate power continuously, and it retains its clamping characteristics throughout the surge event, if properly sized.

Carbon block spark gap overvoltage suppressor



A telephone network connection point with spark-gap overvoltage suppressors. The two brass hex-head objects on the left cover the suppressors, which act to short overvoltage on the tip or ring lines to ground.

A spark gap is one of the oldest protective electrical technologies still found in telephone circuits, having been developed in the nineteenth century. A carbon rod electrode is held with an insulator a specific distance from a second electrode. The gap dimension determines the voltage at which a spark will jump between the two parts and short to ground. The typical spacing for telephone applications in North America is 0.076 mm (0.003"). Carbon block suppressors are similar to gas arrestors (GDTs) but with the two electrodes exposed to the air, so their behavior is affected by the surrounding atmosphere, especially the humidity. Since their operation produces an open spark, these devices should *never* be installed where an explosive atmosphere may develop.

Quarter-wave coaxial surge arrestor

Used in RF signal transmission paths, this technology features a tuned quarter-wavelength short-circuit stub that allows it to pass a bandwidth of frequencies, but presents a short to any other signals, especially down towards DC. The passbands can be narrowband (about ±5% to ±10% bandwidth) or wideband (above ±25% to ±50% bandwidth). Quarter-wave coax surge arrestors have coaxial terminals, compatible with common coax cable connectors (especially N or 7-16 types). They provide the most rugged available protection for RF signals above 400 MHz; at these frequencies they can perform much better than the gas discharge cells typically used in the universal/broadband coax surge arrestors. Quarter-wave arrestors are useful for telecommunications applications, such as Wi-Fi at 2.4 or 5 GHz but less useful for TV/CATV frequencies. Since a quarter-wave arrestor shorts out the line for low frequencies, it is not compatible with systems which send DC power for a LNB up the coaxial downlink.

Series Mode (SM) surge suppressors

These devices are not rated in joules because they operate differently than the earlier suppressors, and they do not depend on materials that inherently wear out during repeated surges. SM suppressors are primarily used to control transient voltage spikes on electrical power feeds to protected devices. They are essentially heavy-duty low-pass filters connected so that they allow 60 Hz line voltages through to the load, while blocking and diverting higher frequencies. This type of suppressor differs from others by using banks of inductors, capacitors and resistors that shunt voltage spikes to the neutral wire, whereas other designs shunt to the ground wire. Since electrical code requires bonding of ground to neutral at the service entrance, the resulting surge ultimately flows into ground at that connection, but by first dumping into neutral, nearby ground contamination is avoided. Since the inductor in series with the circuit path slows the current spike, the peak surge energy is spread out in the time domain and harmlessly diverted into the capacitor bank.

Experimental results show most surge energies occur at under 100 Joules, so exceeding the SM design parameters is unlikely, but it provides no contingency should rare events induce energies that exceed it. SM suppressors do present a theoretical fire risk should the absorbed energy exceed design limits of the dielectric material of the components. In practice, surge energy is also limited via arc-over to ground during lightning strikes, leaving a surge remnant that often does not exceed a theoretical maximum (such as 6000 V at 3000 A with a modeled shape of 8 x 20 microsecond waveform specified by IEEE/ANSI C62.41).

SM suppression focuses its protective philosophy on a *power supply input*, but offers nothing to protect against surges appearing between the input of an SM device and *data lines*, such as antennae, telephone or LAN connections, or multiple such devices cascaded and linked to the primary devices. In this design philosophy, such events are already protected against by the SM device before the power supply. The limitation of such filter approaches has been examined. SM low-pass filters are generally not suitable for data communications circuits, because they would also block high-speed data signals from getting through.

In comparison to devices relying on components that operate only briefly and do not normally conduct electricity (such as MOVs or GDTs), SM devices tend to be bulkier and heavier than those simpler spike shunting components. The initial costs of SM filters are higher, typically 130 USD and up, but a long service life can be expected if they are are used properly. In-field installation costs can be higher, since SM devices are installed in *series* with the power feed, requiring the feed to be cut and reconnected.