Motor Controller

Contents

Chapter 1

Motor controller

A **motor controller** is a device or group of devices that serves to govern in some predetermined manner the performance of an electric motor.[1] A motor controller might include a manual or automatic means for starting and stopping the motor, selecting forward or reverse rotation, selecting and regulating the speed, regulating or limiting the torque, and protecting against overloads and faults.[2]

1.1 Applications

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

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

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

1.2 Types of motor CONTROLLER

Motor controllers can be manually, remotely or automatically operated. They may include only the means for starting and stopping the motor or they may include other functions.[2][3][4]

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

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

1.2.1 Motor starters

See also: Motor soft starter

A small motor can be started by simply plugging it into an electrical receptacle or by using a switch or circuit breaker. A larger motor requires a specialized switching unit called a motor starter or motor contactor. When energized, a direct on line (DOL) starter immediately connects the motor terminals directly to the power supply. Reduced-voltage, star-delta or soft starters connect the motor to the power supply through a voltage reduction device and increases the applied voltage gradually or in steps.[2][3][4] In smaller sizes a motor starter is a manually operated switch; larger motors, or those requiring remote or automatic control, use magnetic contactors. Very large motors running on medium voltage power supplies (thousands of volts) may use power circuit breakers as switching elements.

A *direct on line* (DOL) or *across the line* starter applies the full line voltage to the motor terminals, the starters or cubicle locations, can usually be found on an ELO drawing. This is the simplest type of motor starter. A DOL motor starter also contains protection devices, and in some cases, condition monitoring. Smaller sizes of direct online starters are manually operated; larger sizes use an electromechanical contactor (relay) to switch the motor circuit. Solid-state direct on line starters also exist.

A direct on line starter can be used if the high inrush current of the motor does not cause excessive voltage drop in the supply circuit. The maximum size of a motor allowed on a direct on line starter may be limited by the supply utility for this reason. For example, a utility may require rural customers to use reduced-voltage starters for motors larger than 10 kW.[5]

DOL starting is sometimes used to start small water pumps, compressors, fans and conveyor belts. In the case of an asynchronous motor, such as the 3-phase squirrel-cage motor, the motor will draw a high starting current until it has run up to full speed. This starting current is typically 6-7 times greater than the full load current. To reduce the inrush current, larger motors will have reduced-voltage starters or variable speed drives in order to minimise voltage dips to the power supply.

A reversing starter can connect the motor for rotation in either direction. Such a starter contains two DOL circuits—one for clockwise operation and the other for counter-clockwise operation, with mechanical and electrical interlocks to prevent simultaneous closure.[5] For three phase motors, this is achieved by swapping the wires connecting any two phases. Single phase AC motors and direct-current motors require additional devices for reversing rotation.

1.2.2 Reduced voltage starters

Two or more contactors may be used to provide reduced voltage starting of a motor. By using an autotransformer or a series inductance, a lower voltage is present at the motor terminals, reducing starting torque and inrush current. Once the motor has come up to some fraction of its full-load speed, the starter switches to full voltage at the motor terminals. Since the autotransformer or series reactor only carries the heavy motor starting current for a few seconds, the devices can be much smaller compared to continuously rated equipment. The transition between reduced and full voltage may be based on elapsed time, or triggered when a current sensor shows the motor current has begun to reduce. An autotransformer starter was patented in 1908.

1.2.3 Adjustable-speed drives

Main article: Adjustable-speed drive

An *adjustable-speed drive* (ASD) or *variable-speed drive* (VSD) is an interconnected combination of equipment that provides a means of driving and adjusting the operating speed of a mechanical load. An electrical adjustable-speed drive consists of an electric motor and a speed controller or power converter plus auxiliary devices and equipment. In common usage, the term “drive” is often applied to just the controller.[3][4] Most modern ASDs and VSDs can also implement soft motor starting. [6]

1.2.4 Intelligent controllers

An *Intelligent Motor Controller* (IMC) uses a microprocessor to control power electronic devices used for motor control. IMCs monitor the load on a motor and accordingly match motor torque to motor load. This is accomplished by reducing the voltage to the AC terminals and at the same time lowering current and kvar. This can provide a measure of energy efficiency improvement for motors that run under light load for a large part of the time, resulting in less heat, noise, and vibrations generated by the motor.

1.3 Overload relays

A starter will contain protective devices for the motor. At a minimum this would include a thermal overload relay. The thermal overload is designed to open the starting circuit and thus cut the power to the motor in the event of the motor drawing too much current from the supply for an extended time. The overload relay has a normally closed contact which opens due to heat generated by excessive current flowing through the circuit. Thermal overloads have a small heating device that increases in temperature as the motor running current increases.

There are two types of thermal overload relay. In one type, a bi-metallic strip located close to a heater deflects as the heater temperature rises until it mechanically causes the device to trip and open the circuit, cutting power to the motor should it become overloaded. A thermal overload will accommodate the brief high starting current of a motor while accurately protecting it from a running current overload. The heater coil and the action of the bi-metallic strip introduce a time delay that affords the motor time to start and settle into normal running current without the thermal overload tripping. Thermal overloads can be manually or automatically resettable depending on their application and have an adjuster that allows them to be accurately set to the motor run current.

A second type of thermal overload relay uses a eutectic alloy, like a solder, to retain a spring-loaded contact. When too much current passes through the heating element for too long a time, the alloy melts and the spring releases the contact, opening the control circuit and shutting down the motor. Since eutectic alloy elements are not adjustable, they are resistant to casual tampering but require changing the heater coil element to match the motor rated current.[5]

Electronic digital overload relays containing a microprocessor may also be used, especially for high-value motors. These devices model the heating of the motor windings by monitoring the motor current.

They can also include metering and communication functions.

1.4 Loss of voltage protection

Starters using magnetic contactors usually derive the power supply for the contactor coil from the same source as the motor supply. An auxiliary contact from the contactor is used to maintain the contactor coil energized after the start command for the motor has been released. If a momentary loss of supply voltage occurs, the contactor will open and not close again until a new start command is given. this prevents restarting of the motor after a power failure. This connection also provides a small degree of protection against low power supply voltage and loss of a phase. However since contactor coils will hold the circuit closed with as little as 80% of normal voltage applied to the coil, this is not a primary means of protecting motors from low voltage operation.[5]

1.5 Servo controllers

Main article: Servo drive
Main article: Servomechanism

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

- precise closed loop position control
- fast acceleration rates
- precise speed control Servo motors may be made from several motor types, the most common being:
    - brushed DC motor
    - brushless DC motors
    - AC servo motors

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

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

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

1.6 Stepper motor controllers

Main article: stepping motor

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

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

1.7 World record

In 2008 a new world record was set. Researchers at the ETH Zurich in collaboration with the German companies ATE GmbH (motor manufacturer) and myonic GmbH (ball bearing manufacturer) developed a new electrical drive system with 1 million revolutions per minute. This is the highest rotational speed achieved by an electrical drive system so far. Today, the applied technologies are further developed and distributed by the Swiss high-tech company Celeroton AG.[7][8]

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1.9 See also

- Motor control center (MCC)

Chapter 2

Contactor

AC contactor for pump application.

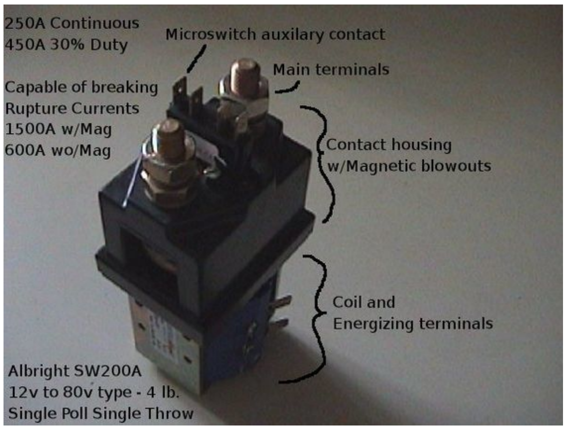
> *In **semiconductor testing**, **contactor** can also refer to the specialised socket that connects the device under test.*
>
> *In process industries a **contactor** is a vessel where two streams interact, for example, air and liquid. See Gas-liquid contactor.*

A **contactor** is an electrically controlled switch used for switching a power circuit, similar to a relay except with higher current ratings.[1] A contactor is controlled by a circuit which has a much lower power level than the switched circuit.

Contactors come in many forms with varying capacities and features. Unlike a circuit breaker, a contactor is not intended to interrupt a short circuit current. Contactors range from those having a breaking current of several amperes to thousands of amperes and 24 V DC to many kilovolts. The physical size of contactors ranges from a device small enough to pick up with one hand, to large devices approximately a meter (yard) on a side.

Contactors are used to control electric motors, lighting, heating, capacitor banks, thermal evaporators, and other electrical loads.

2.1 Construction



Albright SPST DC contactor,
sometimes used in Electric vehicle (EV) conversions

Powerful DC contactor with electro-pneumatic drive

A contactor has three components. The *contacts* are the current carrying part of the contactor. This includes power contacts, auxiliary contacts, and contact springs. The *electromagnet* (or "*coil*") provides the driving force to close the contacts. The *enclosure* is a frame housing the contact and the electromagnet. Enclosures are made of insulating materials like Bakelite, Nylon 6, and thermosetting plastics to protect and insulate the contacts and to provide some measure of protection against personnel touching the contacts. Open-frame contactors may have a further enclosure to protect against dust, oil, explosion hazards and weather.

Magnetic blowouts use blowout coils to lengthen and move the electric arc. These are especially useful in DC power circuits. AC arcs have periods of low current, during which the arc can be extinguished with relative ease, but DC arcs have continuous high current, so blowing them out requires the arc to be stretched further than an AC arc of the same current. The magnetic blowouts in the pictured Albright contactor (which is designed for DC currents) more than double the current it can break, increasing it from 600 A to 1,500 A.

Sometimes an economizer circuit is also installed to reduce the power required to keep a contactor closed; an auxiliary contact reduces coil current after the contactor closes. A somewhat greater amount of power is required to initially close a contactor than is required to keep it closed. Such a circuit can save a substantial amount of power and allow the energized coil to stay cooler. Economizer circuits are nearly always applied on direct-current contactor coils and on large alternating current contactor coils.

A basic contactor will have a coil input (which may be driven by either an AC or DC supply depending on the contactor design). The coil may be energized at the same voltage as a motor the contactor is controlling, or may be separately controlled with a lower coil voltage better suited to control by programmable controllers and lower-voltage pilot devices. Certain contactors have series coils connected in the motor circuit; these are used, for example, for automatic acceleration control, where the next stage of resistance is not cut out until the motor current has dropped.[2]

2.2 Operating principle

Unlike general-purpose relays, contactors are designed to be directly connected to high-current load devices. Relays tend to be of lower capacity and are usually designed for both *normally closed* and *normally open* applications. Devices switching more than 15 amperes or in circuits rated more than a few kilowatts are usually called contactors. Apart from optional auxiliary low current contacts, contactors are almost exclusively fitted with normally open (“form A”) contacts. Unlike relays, contactors are designed with features to control and suppress the arc produced when interrupting heavy motor currents.

When current passes through the electromagnet, a magnetic field is produced, which attracts the moving core of the contactor. The electromagnet coil draws more current initially, until its inductance increases when the metal core enters the coil. The moving contact is propelled by the moving core; the force developed by the electromagnet holds the moving and fixed contacts together. When the contactor coil is de-energized, gravity or a spring returns the electromagnet core to its initial position and opens the contacts.

For contactors energized with alternating current, a small part of the core is surrounded with a shading coil, which slightly delays the magnetic flux in the core. The effect is to average out the alternating pull of the magnetic field and so prevent the core from buzzing at twice line frequency.

Because arcing and consequent damage occurs just as the contacts are opening or closing, contactors are designed to open and close very rapidly; there is often an internal tipping point mechanism to ensure rapid action.

Rapid closing can, however, lead to increase contact bounce which causes additional unwanted open-close cycles. One solution is to have bifurcated contacts to minimize contact bounce; two contacts designed to close simultaneously, but bounce at different times so the circuit will not be briefly disconnected and cause an arc.

A slight variant has multiple contacts designed to engage in rapid succession. The first to make contact and last to break will experience the greatest contact wear and will form a high-resistance connection that would cause excessive heating inside the contactor. However, in doing so, it will protect the primary contact from arcing, so a low contact resistance will be established a millisecond later.

Another technique for improving the life of contactors is contact wipe; the contacts move past each other after initial contact on order to wipe off any contamination.

2.3 Arc suppression

Main article: Arc suppression

Without adequate contact protection, the occurrence of electric current arcing causes significant degradation of the contacts, which suffer significant damage. An electrical arc occurs between the two contact points (electrodes) when they transition from a closed to an open (break arc) or from an open to a closed (make arc). The break arc is typically more energetic and thus more destructive.[3]

The heat developed by the resulting electrical arc is very high, ultimately causing the metal on the contact to migrate with the current. The extremely high temperature of the arc (tens of thousands of degrees Celsius) cracks the surrounding gas molecules creating ozone, carbon monoxide, and other compounds. The arc energy slowly destroys the contact metal, causing some material to escape into the air as fine particulate matter. This activity causes the material in the contacts to degrade over time, ultimately resulting in device failure. For example, a properly applied contactor will have a life span of 10,000 to 100,000 operations when run under power; which is significantly less than the mechanical (non-powered) life of the same device which can be in excess of 20 million operations.[4]

Most motor control contactors at low voltages (600 volts and less) are air break contactors; air at atmospheric pressure surrounds the contacts and extinguishes the arc when interrupting the circuit. Modern medium-voltage AC motor controllers use vacuum contactors. High voltage AC contactors (greater than 1000 volts) may use vacuum or an inert gas around the contacts. High Voltage DC contactors (greater than 600V) still rely on air within specially designed arc-chutes to break the arc energy. High-voltage electric locomotives may be isolated from their overhead supply by roof-mounted circuit breakers actuated by compressed air; the same air supply may be used to “blow out” any arc that forms.[5][6]

2.4 Ratings

Contactors are rated by designed load current per contact (pole),[7] maximum fault withstand current, duty cycle, design life expectancy, voltage, and coil voltage. A general purpose motor control contactor may be suitable for heavy starting duty on large motors; so-called “definite purpose” contactors are carefully adapted to such applications as air-conditioning compressor motor starting. North American and European ratings for contactors follow different philosophies, with North American general purpose machine tool contactors generally emphasizing simplicity of application while definite purpose and European rating philosophy emphasizes design for the intended life cycle of the application.

2.4.1 IEC utilization categories

The current rating of the contactor depends on utilization category. Example IEC categories in standard 60947 are described as:

- **AC-1** - Non-inductive or slightly inductive loads, resistance furnaces
- **AC-2** - Starting of slip-ring motors: starting, switching-off
- **AC-3** - Starting of squirrel-cage motors and switching-off only after the motor is up to speed. (Make Locked Rotor Amps (LRA), Break Full Load Amps (FLA))
- **AC-4** - Starting of squirrel-cage motors with inching and plugging duty. Rapid Start/Stop. (Make and Break LRA)

Relays and auxiliary contact blocks are rated according to IEC 60947-5-1.

- **AC-15** - Control of electromagnetic loads (>72 VA)
- **DC-13** - Control of electromagnets

2.4.2 NEMA

NEMA contactors for low-voltage motors (less than 1000 volts) are rated according to NEMA size, which gives a maximum continuous current rating and a rating by horsepower for attached induction motors. NEMA standard contactor sizes are designated 00,0,1,2,3,4,5,6,7,8,9.

The horsepower ratings are based on voltage and on typical induction motor characteristics and duty cycle as stated in NEMA standard ICS2. Exceptional duty cycles or specialized motor types may require a different NEMA starter size than the nominal rating. Manufacturer’s literature is used to guide selection for non-motor loads, for example, incandescent lighting or power factor correction capacitors. Contactors for medium-voltage motors (greater than 1000 volts) are rated by voltage and current capacity.

Auxiliary contacts of contactors are used in control circuits and are rated with NEMA contact ratings for the pilot circuit duty required. Normally these contacts are not used in motor circuits. The nomenclature is a letter followed by a three digit number, the letter designates the current rating of the contacts and the current type (i.e., AC or DC) and the number designates the maximum voltage design values.[8]

2.5 Applications

2.5.1 Lighting control

Contactors are often used to provide central control of large lighting installations, such as an office building or retail building. To reduce power consumption in the contactor coils, latching contactors are used, which have two operating coils. One coil, momentarily energized, closes the power circuit contacts, which are then mechanically held closed; the second coil opens the contacts.

2.5.2 Magnetic starter

Main article: Magnetic starter

A **magnetic starter** is a device designed to provide power to electric motors. It includes a contactor as an essential component, while also providing power-cutoff, under-voltage, and overload protection.

2.5.3 Vacuum contactor

Vacuum contactors utilize vacuum bottle encapsulated contacts to suppress the arc. This arc suppression allows the contacts to be much smaller and use less space than air break contacts at higher currents. As the contacts are encapsulated, vacuum contactors are used fairly extensively in dirty applications, such as mining.

Vacuum contactors are only applicable for use in AC systems. The AC arc generated upon opening of the contacts will self-extinguish at the zero-crossing of the current waveform, with the vacuum preventing a re-strike of the arc across the open contacts. Vacuum contactors are therefore very efficient at disrupting the energy of an electric arc and are used when relatively fast switching is required, as the maximum break time is determined by the periodicity of the AC waveform.

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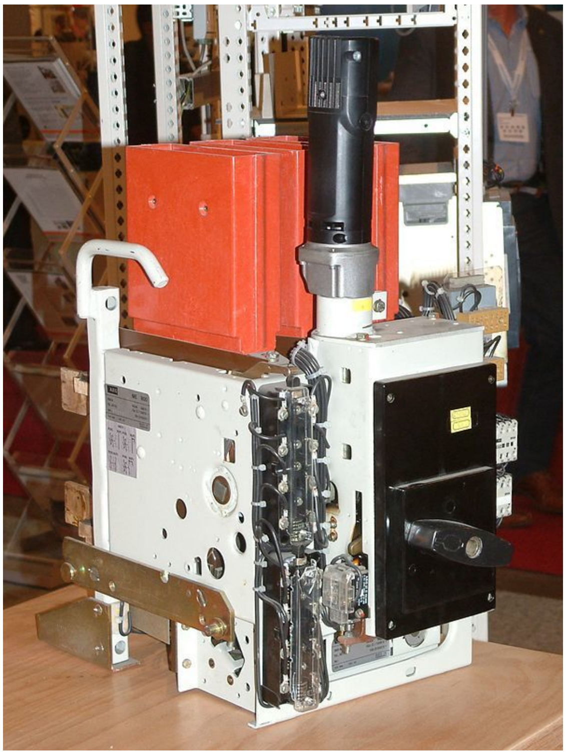
Chapter 3

Circuit breaker

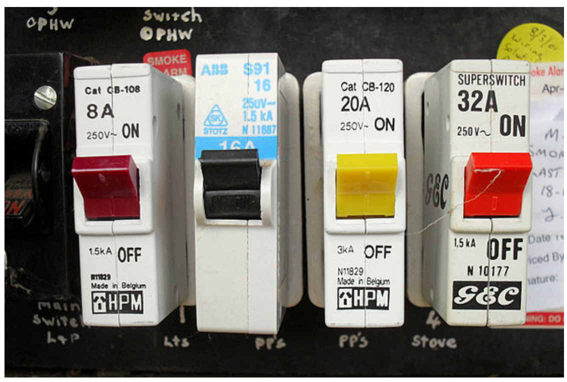
For other uses, see Circuit breaker (disambiguation).

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 interrupt current flow. Unlike a fuse, which operates once and then must 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.



An air circuit breaker for low-voltage (less than 1,000 volt) power distribution switchgear

A two-pole miniature circuit breaker



Four one-pole miniature circuit breakers

3.1 Origins

An early form of circuit breaker was described by Thomas Edison in an 1879 patent application, although his commercial power distribution system used fuses.[1]

Molded-case circuit breaker

Its purpose was to protect lighting circuit wiring from accidental short-circuits and overloads. A modern miniature circuit breaker similar to the ones now in use was patented by Brown, Boveri & Cie in 1924. Hugo Stotz, an engineer who had sold his company to BBC, was credited as the inventor on DRP (*Deutsches Reichspatent*) 458392.<ref http://www.abb.de/cawp/deabb201/061462650496e146c12570880035eede.aspx>"1920-1929 Stotz miniature circuit breaker and domestic appliances", ABB, 2006-01-09, accessed 4 July 2011</ref> Stotz's invention was the forerunner of the modern thermal-magnetic breaker commonly used in household load centers to this day. Interconnection of multiple generator sources into an electrical grid required development of circuit breakers with increasing voltage ratings and increased ability to safely interrupt the increasing short circuit currents produced by networks. Simple air-break manual switches produced hazardous arcs when interrupting high currents; these gave way to oil-enclosed contacts, and various forms using directed flow of pressurized air, or of pressurized oil, to cool and interrupt the arc. By 1935, the specially constructed circuit breakers used at the Boulder Dam project use eight series breaks and pressurized oil flow to interrupt faults of up to 2,500 MVA, in three cycles of the AC power frequency.[2]

3.2 Operation

All circuit breaker systems 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 protective relay pilot devices to sense a fault condition 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, protective 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 (opening) the circuit. Contacts are made of copper or copper alloys, silver alloys and other highly conductive materials. Service life of the contacts is limited by the erosion of contact material due to arcing while interrupting the current. Miniature and molded-case circuit breakers are usually discarded when the contacts have 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 the arc forms in. Different techniques are used to extinguish the arc including:

- Lengthening / deflection 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 50 Hz and 120 times per second for 60 Hz 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.

3.3 Arc interruption

Low-voltage MCB (Miniature Circuit Breaker) uses air alone to extinguish the arc. Larger ratings have metal plates or non-metallic arc chutes to divide and cool the arc. Magnetic blowout coils or permanent magnets 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.[3]

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 (less than 2–3 mm (0.079–0.118 in)). Vacuum circuit breakers are frequently used in modern medium-voltage switchgear to 38,000 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.

3.4 Short-circuit current

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

Under short-circuit conditions, the calculated maximum prospective short circuit current may be many times the normal, rated current of the circuit. 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 gases 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 sulfur 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.

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

3.5 Standard current ratings

Circuit breakers are manufactured in standard sizes, using a system of preferred numbers to cover a range of ratings. Miniature circuit breakers have a fixed trip setting; changing the operating current value requires changing the whole circuit breaker. Larger circuit breakers can have adjustable trip settings, allowing standardized elements to be applied but with a setting intended to improve protection. For example, a circuit breaker with a 400 ampere "frame size" might have its overcurrent detection set to operate at only 300 amperes, to protect a feeder cable.

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 maximum 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, 100 A,[4] and 125 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", which 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:

Circuit breakers are also rated by the maximum fault current that they can interrupt; this allows use of more economical devices on systems unlikely to develop the high short-circuit current found on, for example, a large commercial building distribution system.

In the United States, Underwriters Laboratories (UL) certifies equipment ratings, called Series Ratings (or "integrated equipment ratings") for circuit breaker equipment used for buildings. Power circuit breakers and medium- and high-voltage circuit breakers used for industrial or electric power systems are designed and tested to ANSI/IEEE standards in the C37 series.

3.6 Types of circuit breakers

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.

3.6.1 Low-voltage circuit breakers

Low-voltage (less than 1,000 VAC) 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.

There are three main types of MCBs: 1. Type B - trips between 3 and 5 times full load current; 2. Type C - trips between 5 and 10 times full load current; 3. Type D - trips between 10 and 20 times full load current. In the UK all MCBs *must* be selected in accordance with BS 7671.

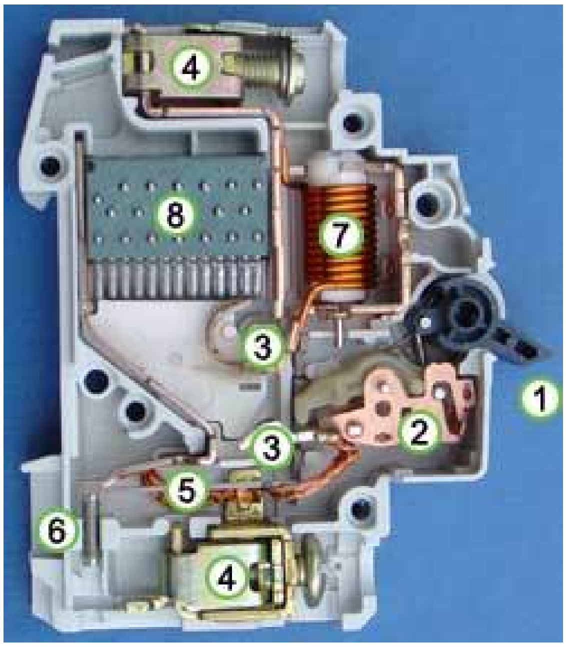
- MCCB (Molded Case Circuit Breaker)—rated current up to 2,500 A. Thermal or thermal-magnetic operation. Trip current may be adjustable in larger ratings.

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

The characteristics of low-voltage 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 electric motor operators so they can open and close 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, such as DC for subway lines. Direct current requires special breakers because the arc is continuous—unlike an AC arc, which tends to go out on each half cycle. A direct current circuit breaker has blow-out coils that generate a magnetic field that rapidly stretches the arc. Small circuit breakers are either installed directly in equipment, or are arranged in a breaker panel.



Inside of a circuit breaker

The 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 - separates contacts in response to smaller, longer-term overcurrents
6. Calibration screw - allows the manufacturer to precisely adjust the trip current of the device after assembly.
7. Solenoid - separates contacts rapidly in response to high overcurrents
8. Arc divider/extinguisher

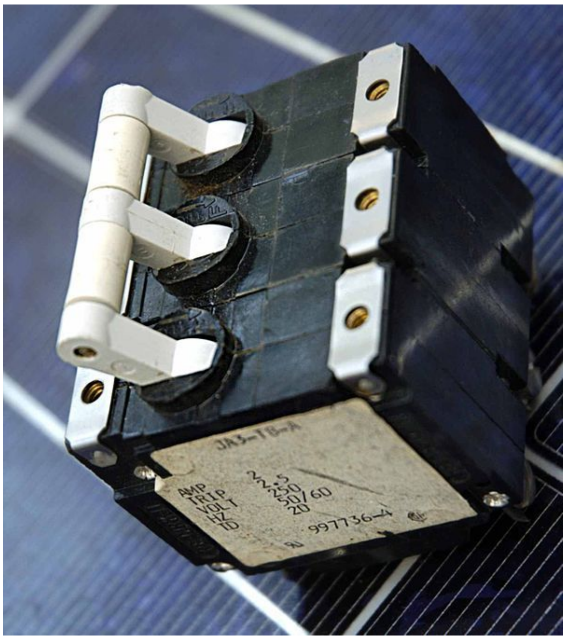
3.6.2 Magnetic circuit breakers

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 lets the contacts open by spring action. Some magnetic breakers incorporate a hydraulic time delay feature using a viscous fluid. A spring restrains the core 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

3.6.3 Thermal magnetic circuit breakers

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 overcurrent conditions. The thermal portion of the circuit breaker provides an "inverse time" response feature, which trips the circuit breaker sooner for larger overcurrents but allows smaller overloads to persist for a longer time. On very large over-currents during a short-circuit, the magnetic element trips the circuit breaker with no intentional additional delay.[5]

3.6.4 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 multiple phase AC, or to disconnect the neutral wire to ensure that no current flows through the neutral wire from other loads connected to the same network when workers may touch the wires during maintenance. Separate circuit breakers must never be used for live and neutral, because if the neutral is disconnected while the live conductor stays connected, a dangerous condition arises: the circuit appears de-energized (appliances don't work), but wires remain live and some RCDs may not trip if someone touches the live wire (because some RCDs need power to trip). This is why only common trip breakers must be used when neutral wire switching is needed.

3.6.5 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 40.5 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 breakers—With rated current up to 6,300 A, and higher for generator circuit breakers. These breakers interrupt the current by creating and extinguishing the arc in a vacuum container - aka “bottle”. Long life bellows are designed to travel the 6-10 mm the contacts must part. These are generally applied for voltages up to about 40,500 V,[6] 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 breakers—Rated current up to 6,300 A and higher for generator circuit breakers. 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.

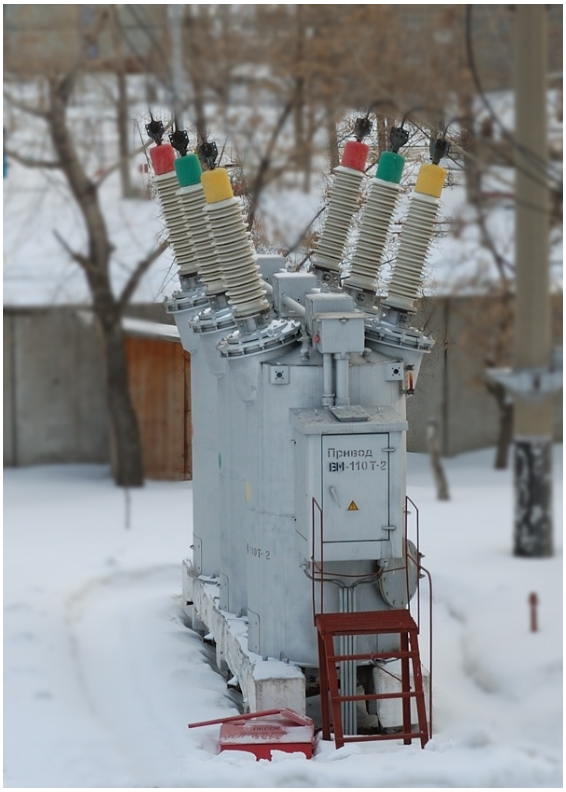
- SF_6 circuit breakers extinguish the arc in a chamber filled with sulfur hexafluoride gas.

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 breaker removal without disturbing power circuit connections, using a motor-operated or hand-cranked mechanism to separate the breaker from its enclosure. Some important manufacturer of VCB from 3.3 kV to 38 kV are ABB, Eaton, Siemens, HHI(Hyundai Heavy Industry), S&C Electric Company, Jyoti and BHEL.

3.6.6 High-voltage circuit breakers

Main article: High-voltage switchgear

Electrical power transmission networks are protected



Three single phase Russian 110 kV oil circuit breakers

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
- CO_2

400 kV SF_6 live tank circuit breakers

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. 1,200 kV breakers were launched by Siemens in November 2011,[7] followed by ABB in April the following year.[8]

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.

High-voltage direct current circuit breakers are still a field of research as of 2015. Such breakers would be useful to interconnect HVDC transmission systems. [9]

3.6.7 Sulfur hexafluoride (SF_6) high-voltage circuit breakers

Main article: Sulfur hexafluoride circuit breaker

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-

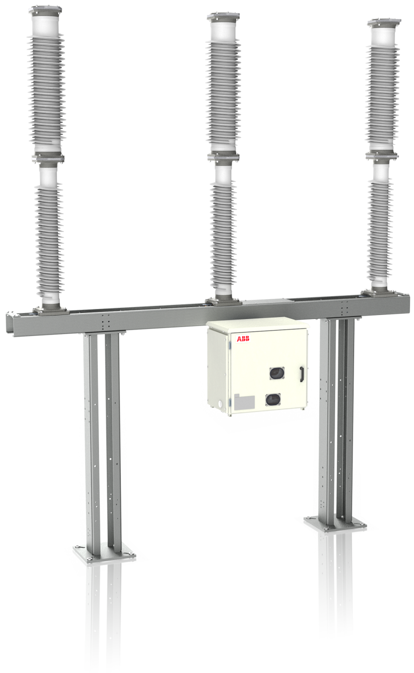
72.5 kV Hybrid Switchgear Module

rating of the circuit breakers may be required due to liquefaction of the SF6 gas.

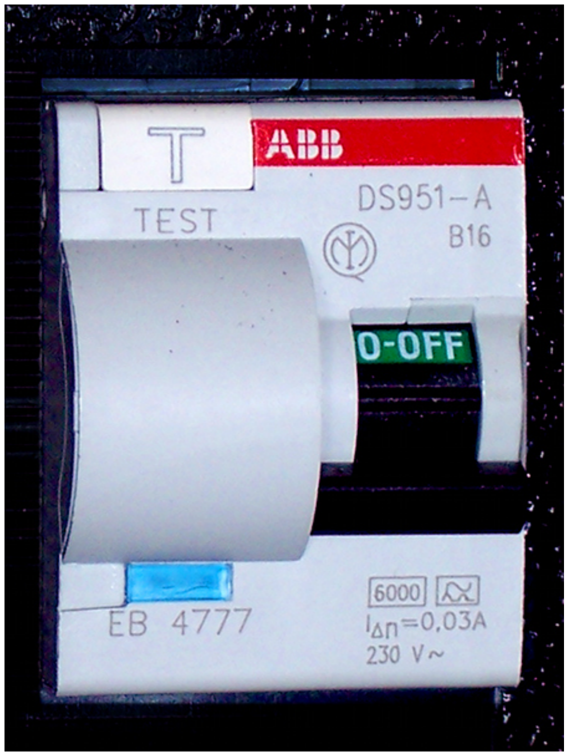
3.6.8 Disconnecting circuit breaker (DCB)

The disconnecting circuit breaker (DCB) was introduced in 2000[10] and is a high-voltage circuit breaker modeled after the SF_6-breaker. It presents a technical solution where the disconnecting function is integrated in the breaking chamber, eliminating the need for separate disconnectors. This increases the availability, since open-air disconnecting switch main contacts need maintenance every 2–6 years, while modern circuit breakers have maintenance intervals of 15 years. Implementing a DCB solution also reduces the space requirements within the substation, and increases the reliability, due to the lack of separate disconnectors.[11][12]

In order to further reduce the required space of substation, as well as simplifying the design and engineering of the substation, a fiber optic current sensor (FOCS) can be integrated with the DCB. A 420 kV DCB with integrated FOCS can reduce a substation's footprint with over 50 % compared to a conventional solution of live tank breakers



72.5 kV carbon dioxide high-voltage circuit breaker



Residual current circuit breaker with overload protection

with disconnectors and current transformers, due to reduced material and no additional insulation medium.[13]

3.6.9 Carbon dioxide (CO_2) high-voltage circuit breakers

In 2012 ABB presented a 75 kV high-voltage breaker that uses carbon dioxide as the medium to extinguish the arc. The carbon dioxide breaker works on the same principles as an SF_6 breaker and can also be produced as a disconnecting circuit breaker. By switching from SF_6 to CO_2 it is possible to reduce the CO_2 emissions by 10 tons during the product's life cycle.[14]

3.7 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 Interrupter (GFI) breakers; a wall mounted outlet device or separately enclosed plug-in device providing ground fault detection and interruption only (no overload protection) is called a Ground Fault Circuit Interrupter (GFCI).
  - 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.
- Recloser—A type of circuit breaker that closes automatically after a delay. These are used on overhead electric 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.

3.8 See also

- Arc-fault circuit interrupter
- Circuit breaker panel
- Circuit Total Limitation (CTL)
- Earthing system

- Hybrid switchgear modules
- Insulation monitoring device
- Network protector
- Power system protection
- Remote racking system
- Sulfur hexafluoride circuit breaker
- Motor control center (MCC)
- Power distribution center (PDC)

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- BS EN 60898-1. Electrical accessories — Circuit breakers for over-current protection for household and similar installations. British Standards Institution, 2003.

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- L. W. Brittian: *Electrical Circuit Breakers*
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Chapter 4

Motor soft starter

Examples of motor soft starters

A **motor soft starter** is a device used with AC electrical motors to temporarily reduce the load and torque in the power train and electrical current surge of the motor during start-up. This reduces the mechanical stress on the motor and shaft, as well as the electrodynamic stresses on the attached power cables and electrical distribution network, extending the lifespan of the system.[1]

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

Across-the line starting of induction motors is accompanied by inrush currents up to 7 times higher than running current, and starting torque up to 3 times higher than running torque. The increased torque results in sudden mechanical stress on the machine which leads to a reduced service life. Moreover, the high inrush current stresses the power supply, which may lead to voltage dips. As a result, the operability of sensitive consumers may be impaired.[1]

A *soft start-up* eliminates the undesired side effects. Several types based on control of the supply voltage or mechanical devices such as slip clutches were developed. The list provides an overview of the various electric start-up types. The current and torque characteristic curves show the behavior of the respective starter solution. Torque surges entail high mechanical stress on the machine, which results in higher service costs and increased wear. High currents and current peaks lead to high fixed costs charged by the power supply companies (peak current calculation) and to increased mains and generator loads.

A soft starter continuously controls the three-phase motor's voltage supply during the start-up phase. This way, the motor is adjusted to the machine's load behavior. Mechanical operating equipment is accelerated smoothly. Service life, operating behavior and work flows are positively influenced. Electrical soft starters can use solid state devices to control the current flow and therefore the voltage applied to the motor. They can be connected in series with the line voltage applied to the motor, or can be connected inside the delta (Δ) loop of a delta-connected motor, controlling the voltage applied to each winding. Solid state soft starters can control one or more phases of the voltage applied to the induction motor with the best results achieved by three-phase control. Typically, the voltage is controlled by reverse-parallel-connected silicon-controlled rectifiers (thyristors), but in some circumstances with three-phase control, the control elements can be a reverse-parallel-connected SCR and diode.[2]

Another way to limit motor starting current is a series reactor. If an air core is used for the series reactor then a very efficient and reliable soft starter can be designed which is suitable for all types of 3 phase induction motor [synchronous / asynchronous] ranging from 25 kW 415 V to 30 MW 11 kV. Using an air core series reactor soft starter is very common practice for applications like pump, compressor, fan etc. Usually high starting torque applications do not use this method.

4.1 Applications

Soft starters can be set up to the requirements of the individual application. In pump applications, a soft start can avoid pressure surges. Conveyor belt systems can be smoothly started, avoiding jerk and stress on drive components. Fans or other systems with belt drives can be started slowly to avoid belt slipping. In all systems, a soft start limits the inrush current and so improves stability of the power supply and reduces transient voltage drops that may affect other loads. [3][4][5]

Non-Applications As described above, soft starters can be an excellent method for providing “gentle” startup of pumps and motors. However, they should not be used in applications that require full torque at startup.

4.2 See also

- Adjustable-speed drive
- Braking chopper
- DC motor starter section of Electric motor
- Electronic speed control
- Korndorfer starter
- Motor controller
- Space Vector Modulation
- Thyristor drive
- Variable-frequency drive
- Variable speed air compressor
- Vector control (motor)

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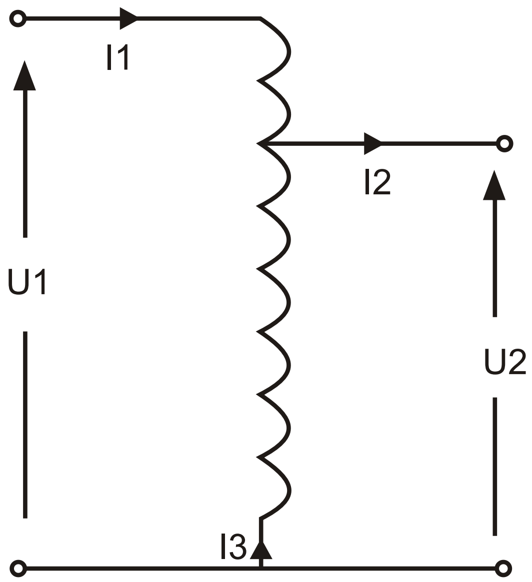
Chapter 5

Autotransformer



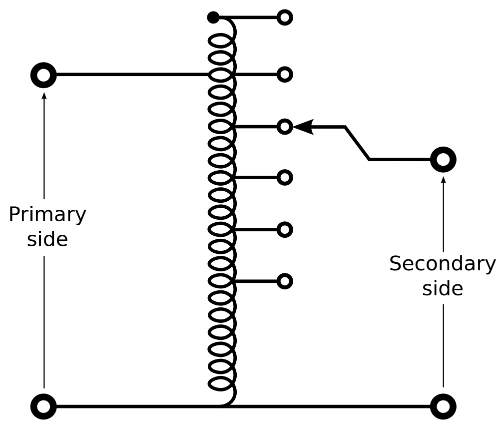
autotransformer

An **autotransformer** (sometimes called ***autostep down transformer***)[1] is an electrical transformer with only one winding. The "auto" (Greek for “self”) prefix refers to the single coil acting on itself and not to any kind of automatic mechanism. In an autotransformer, portions of the same winding act as both the primary and secondary sides of the transformer. In contrast, an ordinary transformer has separate primary and secondary windings which are not connected.

The winding has at least three taps where electrical connections are made. Since part of the winding does “double duty”, autotransformers have the advantages of often being smaller, lighter, and cheaper than typical dual-winding transformers, but the disadvantage of not providing electrical isolation. Other advantages of autotransformers include lower leakage reactance, lower losses, lower excitation current, and increased KVA rating for a given size and mass.[2]

Autotransformers are often used to step up or step down voltages in the 110-115-120 V range and voltages in the 220-230-240 V range - for example, providing 110 V or 120 V (with taps) from 230 V input, allowing equipment designed for 100 or 120 V to be used with a 230 V supply. This allows US electrical equipment to be fed from the higher European voltage. Autotransformers can also be used to supply European 230 V appliances from a 100 or 120 V supply in countries outside Europe. In all cases the supply and the autotransformer must be correctly rated to supply the required power.

5.1 Operation



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

An autotransformer has a single winding with two end terminals, and one or more terminals at intermediate tap points, or a transformer in which the primary and secondary coils have part or all of their turns in common. The primary voltage is applied across two of the terminals, and the secondary voltage taken from two terminals, almost always having one terminal in common with the primary voltage. The primary and secondary circuits therefore have a number of windings turns in common.[3] Since the volts-per-turn is the same in both windings, each develops a voltage in proportion to its number of turns. In an autotransformer part of the current flows directly from the input to the output, and only part is transferred inductively, allowing a smaller, lighter, cheaper core to be used as well as requiring only a single winding.[4] However the voltage and current ratio of autotransformers can be formulated the same as other two-winding transformers:[2]

$\frac{V_1}{V_2} = \frac{N_1}{N_2} = a$

(0<V<sub>2<V<sub>1)

The ampere-turns provided by the upper half:

$F_U = (N_1 - N_2)I_1 = (1 - \frac{1}{a})N_1 I_1$

The ampere-turns provided by the lower half:

$F_L = N_2(I_2 - I_1) = \frac{N_1}{a}(I_2 - I_1)$

For ampere-turn balance, FU=FL:

$(1 - \frac{1}{a})N_1 I_1 = \frac{N_1}{a}(I_2 - I_1)$

Therefore:

$\frac{I_1}{I_2} = \frac{1}{a}$

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

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

If one of the center-taps is used for the ground, then the autotransformer can be used as a balun to convert a balanced line (connected to the two end taps) to an unbalanced line (the side with the ground).

5.2 Limitations

An autotransformer does not provide electrical isolation between its windings as an ordinary transformer does; if the neutral side of the input is not at ground voltage, the neutral side of the output will not be either. A failure of the isolation of the windings of an autotransformer can result in full input voltage applied to the output. Also, a break in the part of the winding that is used as both primary and secondary will result in the transformer acting as an inductor in series with the load (which under light load conditions may result in near full input voltage being applied to the output). These are important safety considerations when deciding to use an autotransformer in a given application.

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

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

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

Like multiple-winding transformers, autotransformers use time-varying magnetic fields to transfer power. They require alternating currents to operate properly and will not function on direct current.

5.3 Applications

5.3.1 Power transmission and distribution

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

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

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

5.3.2 Audio system

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

5.3.3 Railways

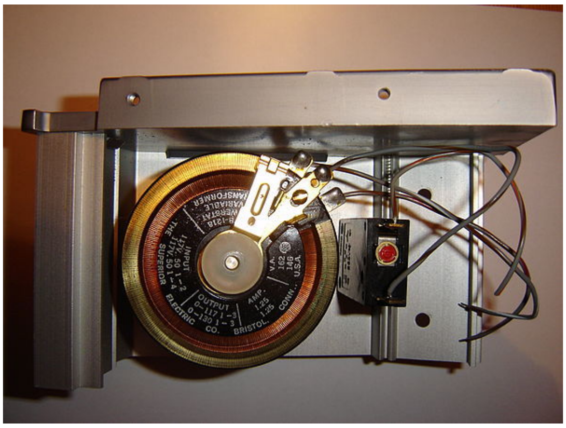
Main article: 25 kV AC railway electrification

In UK railway applications, it is common to power the trains at 25 kV AC. To increase the distance between electricity supply Grid feeder points they can be arranged to supply a 25-0-25 kV supply with the third wire (opposite phase) out of reach of the train's overhead collector pantograph. The 0 V point of the supply is connected to the rail while one 25 kV point is connected to the overhead contact wire. At frequent (about 10 km) intervals, an autotransformer links the contact wire to rail and to the second (antiphase) supply conductor. This system increases usable transmission distance, reduces induced interference into external equipment and reduces cost. A variant is occasionally seen where the supply conductor is at a different voltage to the contact wire with the autotransformer ratio modified to suit.[5]

5.4 Variable autotransformers

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

As with two-winding transformers, autotransformers may be equipped with many taps and automatic switchgear to allow them to act as automatic voltage regulators, to



Variable Transformer - part of Tektronix 576 Curve Tracer

maintain a steady voltage at the customers' service during a wide range of load conditions. They can also be used to simulate low line conditions for testing. Another application is a lighting dimmer that doesn't produce the EMI typical of most thyristor dimmers.

By exposing part of the winding coils and making the secondary connection through a sliding brush, a continuously variable turns ratio can be obtained, allowing for very smooth control of voltage. Applicable only for relatively low voltage designs, this device is known as a variable AC transformer (often referred to by the trademark name Variac). The output voltage is not limited to the discrete voltages represented by actual number of turns. The voltage can be smoothly varied between turns as the brush has a relatively high resistance (compared with a metal contact) and the actual output voltage is a function of the relative area of brush in contact with adjacent windings.[6] The relatively high resistance of the brush also prevents it from acting as a short circuited turn when it contacts two adjacent turns. Typically the primary connection connects to only a part of the winding allowing the output voltage to be varied smoothly from zero to above the input voltage and thus allowing the device to be used for testing electrical equipment at the limits of its specified voltage range.

5.4.1 Variac Trademark

From 1934 to 2002, **Variac** was a U.S. trademark of General Radio for a variable autotransformer intended to conveniently vary the output voltage for a steady AC input voltage. In 2004, Instrument Service Equipment applied for and obtained the *Variac* trademark for the same type of product.[7] This word has become generic for hand-variable autotransformers in general.

5.5 See also

- balun

- Electromagnetism
- Faraday's law of induction
- Ignition coil
- Inductor
- Magnetic field

5.6 Notes

[1] Paul Horowitz and Winfield Hill, *The Art of Electronics Second Edition*, Cambridge University Press, Cambridge MA, 1989, ISBN 0-521-37095-7, page 58

[2] Sen 1997, p. 64.

[3] Pansini. *Electrical Transformers and Power Equipment*. pp. 89–91.

[4] Commercial site explaining why autotransformers are smaller

[5] "*Fahrleitungen electrischer Bahnen*" BG Teubner-Verlag, Stuttgart, page 672. An English edition "Contact Lines for Electric Railways" appears to be out of print. This industry standard text describes the various European electrification principles. See the website of the UIC in Paris for the relevant international rail standards, in English. No comparable publications seem to exist for American railways, probably due to the paucity of electrified installations there.

[6] Bakshi, M. V. and Bakshi, U. A. *Electrical Machines - I*. p. 330. ISBN 81-8431-009-9.

[7] http://tsdr.uspto.gov/#caseNumber=76573123&caseType=SERIAL_NO&searchType=documentSearch

- Sen, P. C. (1997). *Principles of electric machines and power electronics*. John Wiley & Sons. ISBN 0471022950.

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