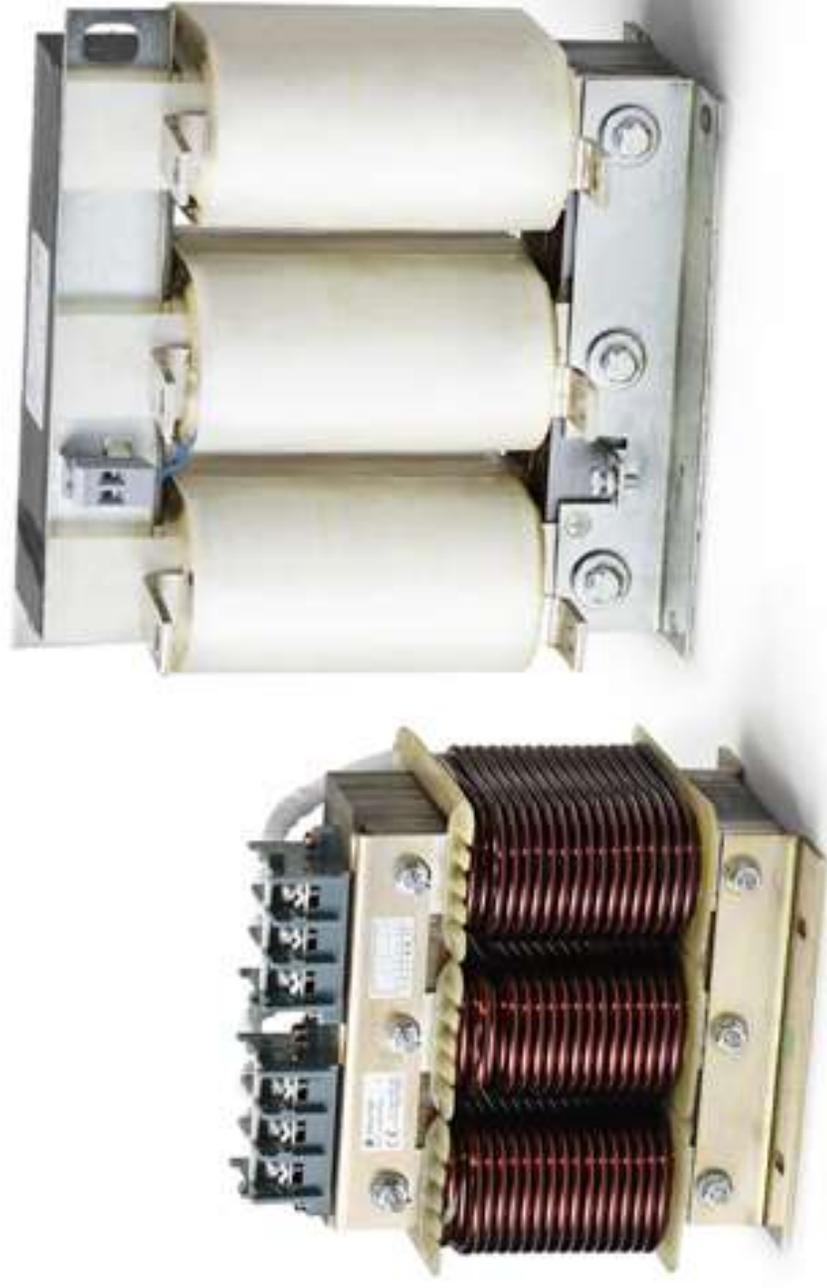


Handbook of Electrical Power Cables & Capacitors



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First Edition, 2012

ISBN 978-81-323-1350-2

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Published by:

College Publishing House
4735/22 Prakashdeep Bldg,
Ansari Road, Darya Ganj,
Delhi - 110002
Email: info@wtbooks.com

WORLD TECHNOLOGIES

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Chapter 1

Power Cable

A **power cable** is an assembly of two or more electrical conductors, usually held together with an overall sheath. The assembly is used for transmission of electrical power. Power cables may be installed as permanent wiring within buildings, buried in the ground, run overhead, or exposed.

Flexible power cables are used for portable devices, mobile tools and machinery.

History

Early telegraph systems used the first forms of electrical cabling, transmitting tiny amounts of power. Gutta-percha insulation used on the first submarine cables was, however, unsuitable for building wiring use since it deteriorated rapidly when exposed to air.

The first power distribution system developed by Thomas Edison in 1882 in New York City used copper rods, wrapped in jute and placed in rigid pipes filled with a bituminous compound. Although vulcanized rubber had been patented by Charles Goodyear in 1844, it was not applied to cable insulation until the 1880s, when it was used for lighting circuits. Rubber-insulated cable was used for 11,000 volt circuits in 1897 installed for the Niagara Falls power project.

Mass-impregnated paper-insulated medium voltage cables were commercially practical by 1895. During World War II several varieties of synthetic rubber and polyethylene insulation were applied to cables.

Construction

Modern power cables come in a variety of sizes, materials, and types, each particularly adapted to its uses. Large single insulated conductors are also sometimes called power cables in the industry.

Cables consist of three major components: conductors, insulation, protective jacket. The makeup of individual cables varies according to application. The construction and material are determined by three main factors:

- Working voltage, determining the thickness of the insulation;
- Current-carrying capacity, determining the cross-sectional size of the conductor(s);
- Environmental conditions such as temperature, water, chemical or sunlight exposure, and mechanical impact, determining the form and composition of the outer cable jacket.

Cables for direct burial or for exposed installations may also include metal armor in the form of wires spiralled around the cable, or a corrugated tape wrapped around it. The armor may be made of steel or aluminum, and although connected to earth ground is not intended to carry current during normal operation.

Power cables use stranded copper or aluminum conductors, although small power cables may use solid conductors. The cable may include uninsulated conductors used for the circuit neutral or for ground (earth) connection.

The overall assembly may be round or flat. Non-conducting filler strands may be added to the assembly to maintain its shape. Special purpose power cables for overhead or vertical use may have additional elements such as steel or Kevlar structural supports.

Some power cables for outdoor overhead use may have no overall sheath. Other cables may have a plastic or metal sheath enclosing all the conductors. The materials for the sheath will be selected for resistance to water, oil, sunlight, underground conditions, chemical vapors, impact, or high temperatures. In nuclear industry applications the cable may have special requirements for ionizing radiation resistance. Cable materials may be specified not to produce large amounts of smoke if burned. Cables intended for underground use or direct burial in earth will have heavy plastic or metal, most often lead sheaths, or may require special direct-buried construction. When cables must run where exposed to mechanical impact damage, they may be protected with flexible steel tape or wire armor, which may also be covered by a water resistant jacket.

Higher voltages

For circuits operating at or above 2,000 volts between conductors, a conductive shield may surround each insulated conductor. This equalizes electrical stress on the cable insulation. This technique was patented by Martin Hochstadter in 1916; the shield is sometimes called a Hochstadter shield. The individual conductor shields of a cable are connected to earth ground at the ends of the cable, and at locations along the length if voltage rise during faults would be dangerous.

Cables for power distribution of 10kV or higher may be insulated with oil and paper, and are run in a rigid steel pipe, semi-rigid aluminum or lead sheath. For higher voltages the oil may be kept under pressure to prevent formation of voids that would allow partial discharges within the cable insulation.



A high voltage cable designed for 400 kv. Large center conductor carries the current, smaller conductors on the outside act as a shield to equalize the voltage stress in the thick polyethylene insulation layer.

Modern high voltage cables use polymers or polyethylene, including (XLPE) for insulation. They require special techniques for jointing and terminating.

Many multiconductor cables have a bare or insulated *grounding* or *bonding* wire which is for connection to earth ground. The grounding conductor connects equipment enclosures to ground for protection from electric shock.

Electrical power cables are often installed in raceways, including electrical conduit and cable trays, which may contain one or more conductors.

A hybrid cable can include conductors for control signals or may also include optical fibers for data.

Flexible cables

All electrical cables are somewhat flexible, allowing them to be shipped to installation sites wound on reels or drums. Where applications require a cable to be moved repeatedly, such as for portable equipment, more flexible cables called "cords" or "flex" are used. Flexible cords contain fine stranded conductors, not solid core conductors, and have insulation and sheaths to withstand the forces of repeated flexing and abrasion. Heavy duty flexible power cords such as those feeding a mine face cutting machine are carefully engineered — their life is measured in weeks. Very flexible power cables are used in automated machinery, robotics, and machine tools.

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Chapter 2

Power Cord and Extension Cord

Power cord

A **power cord**, **line cord**, or **mains cable** is a cord or cable that temporarily connects an electrical appliance to the distribution circuits of an electrical power source via a wall socket or extension cord.

The terms are generally used for cables using a power plug to connect to a single-phase alternating current power source at the local line voltage—(generally 100 to 240 volts, depending on the location). The terms **power cable**, **mains lead** or **flex** are also used. A **lamp cord** is a light weight ungrounded two wire cord used for small loads such as a table or floor lamp. The term **cord set** is also used to distinguish those cords that include connectors molded to the cord at each end.

Power cables may be either fixed or detachable from the appliance. In the case of detachable leads, the appliance end of the power cord has a socket rather than a plug to link it to the appliance, to avoid the dangers from having a live protruding pin. Cords may also have twist-locking features, or other attachments to prevent accidental disconnection at one or both ends. A cord set may include accessories such as fuses for overcurrent protection, a pilot lamp to indicate voltage is present, or a leakage current detector. Power cords for sensitive instruments, or audio/video equipment may also include a shield over the power conductors to minimize electromagnetic interference.

Connectors

Common types of detachable power cables have appliance-side connectors such as the *IEC 60320 C13*, "kettle lead", "jug plug" or "IBM plug" (commonly used for higher current appliances where an earth or ground connection is required) and *IEC 60320 C7* commonly used for low-current applications such as an power supply inlet for use with a laptop computer. The IEC C7 is also known as a "figure-of-eight lead", the connector has a figure-of-eight cross section). The polarised *IEC 60320 C5* connector is now commonly used on the AC side of laptop computer power supplies. The IEC C5 is commonly known as "cloverleaf plug" or "Mickey Mouse plug" because of the shape of its cross section.

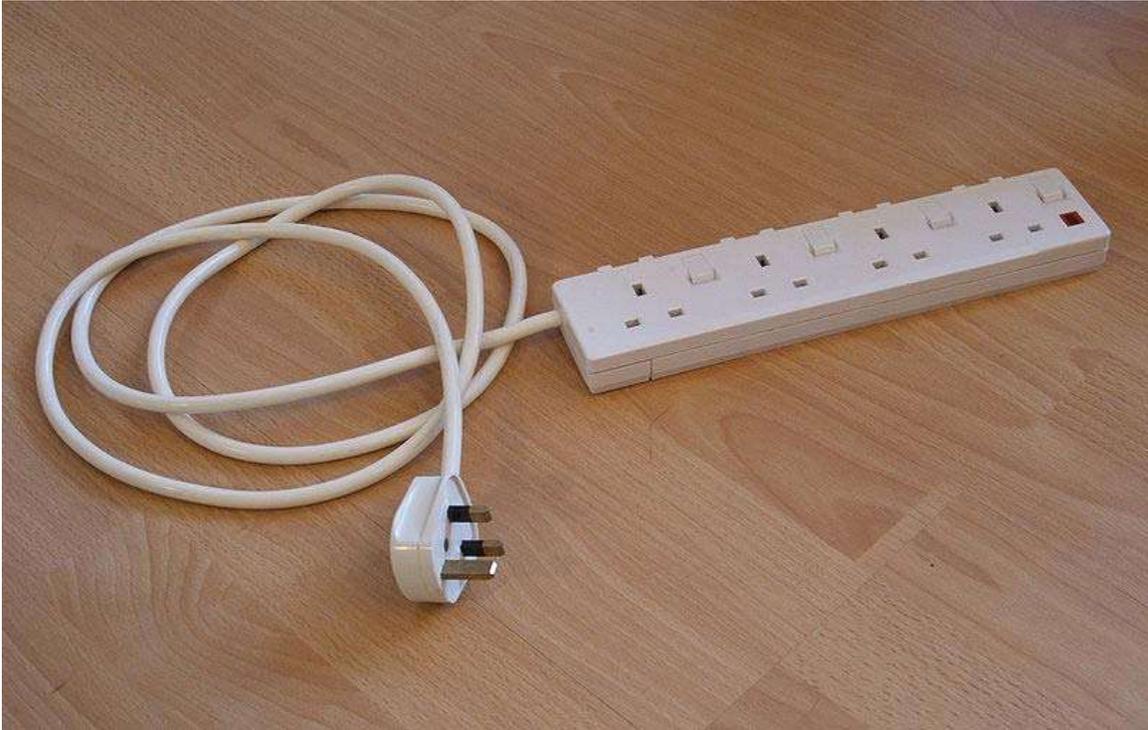
IEC power cables come in high-temperature and low-temperature variants, as well as various current capacities. The connectors have slightly different shapes to ensure that it is not possible to substitute a cable with a lower temperature or current rating, but that it *is* possible to use an over-rated cable. Cords also have different types of exterior jackets available to accommodate environmental variables such as moisture, temperature, oils, sunlight, flexibility, and heavy wear. For example, a heating appliance may come with a cord designed to withstand accidental contact with heated surfaces.

Worldwide, more than a dozen different types of connectors are used for fixed building wiring. Products sold in many different markets can use a standardized IEC connector and then use a detachable power cord to match the local electrical outlets. This simplifies safety approvals, factory testing, and production since the power cord is a low-cost item available as a commodity. Note that the same types of appliance-side connectors are used with both 110 V and 230 V power cables, so care must be used when moving appliances between countries with different voltage standards — substituting a power cord that matches local power outlets will result in an incorrect voltage being applied to the appliance or equipment. Some devices have a slide-switch to adapt to different voltages, or wide-ranging power supplies. Unless explicitly labelled as capable of handling local voltages, this is very likely to damage or destroy the appliance.

Power supplies

Cord sets must be distinguished from plug-in wall mounted power supplies, where the connector also contains a transformer, and possibly rectifiers, filters and regulators. Unwary substitution of a standard mains-voltage connector for the power supply would result in application of full line voltage to the connected device, resulting in its destruction and possible fire or personal injury.

Extension cord



A British extension cord or power strip with a power indicator and switches for each individual socket.

An **extension cord**, **power extender**, or **extension lead** is a length of flexible electrical power cable (flex) with a plug on one end and one or more sockets on the other end (usually of the same type as the plug). The term usually refers to mains (household AC) extensions but is also used to refer to extensions for other types of cabling. If the plug and receptacle are of different types, the term "adapter cord" may be used. **Extension cable** is also used, but that has a distinct meaning from **extension cord** for many people.

Overview

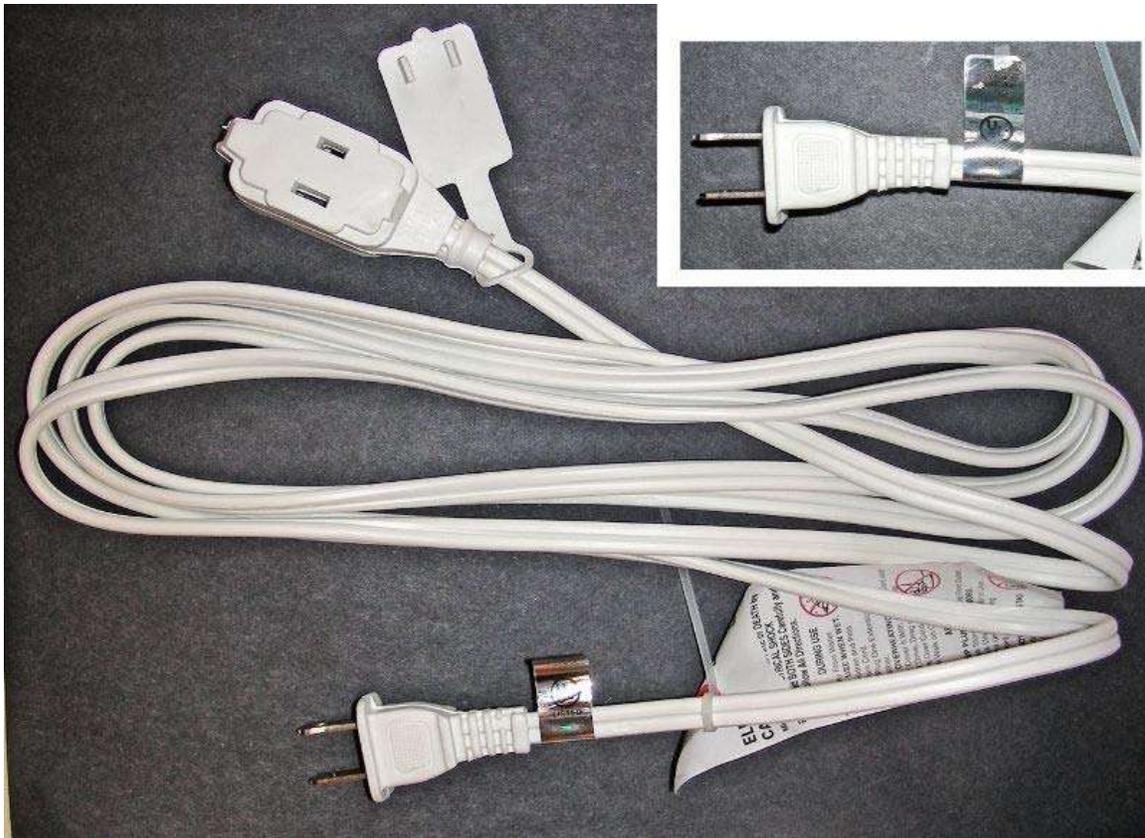
Some extension cords also incorporate safety features, such as a polarized plug and receptacle, grounded terminals, a 'power-on' indicator, a fusible link, or even a residual-current device (also known as a ground-fault circuit interrupter or GFCI).

Extension cords come in various lengths and thicknesses, and service duties. In general, the more power needed by the appliance, the thicker the cord should be (that is, larger wires inside). Cords to be used outdoors, in wet areas, around oils, or exposed to sunlight for long periods should be selected for such specific service.



Yellow NEMA 5-15 Extension Cord

In the USA where the domestic voltage is 120 V, the National Electrical Code (NEC) prohibits the use of extension cords in a 20 A circuit unless they are of 16 AWG or larger (for example, 14 AWG or 12 AWG). As with other flexible cords, the NEC also prohibits their use where attached to building surfaces, or concealed inside walls, floors, or ceilings, above suspended ceilings, or where run through holes or other openings (windows, doors) in structures (with limited exceptions). Cords run across the floor should be covered with a suitable device to protect them from physical damage.



Counterfeit extension cord (and labels) from China. Undersize wiring is a fire hazard.

Other countries also regulate the use of extension cables but the specific conditions and the nature of the regulation varies. In Europe and elsewhere where the normal domestic voltage is around 230 V, there is less risk of causing fire through overheating of cables for any given power due to the lower current. However most European extension reel cables now include an automatic current cut-out to avoid misuse of the cable. This requires manual re-setting if excess current is drawn through the cable. (American multiplug cords also include such a device but single- or triple-outlet cords do not.)

An extension reel is an extension lead that rolls up, usually into the socket end, which in some cases has more than one socket on it (often 2 or 4). Another type of extension reel hangs near the plug end and permits the user to draw the cord out by grasping the socket end. Such cables can only be used to carry full rated current when fully extended since the portion on the reel constitutes a concentration of the loss power (the result of its series resistance) which is not suitably dissipated unless most of the cable is unreeled to expose it to ambient air.

A power cord is similar but the socket end is designed to mate with a panel plug (usually IEC or figure 8 style) and is usually much shorter. With IEC connectors cables are frequently seen with a line plug and socket. These may be considered either as powercords (if IEC outlets are in use) or as extensions (if used to extend a powercord.)

A power strip is a block on the end of a power cable with a number of sockets (usually 3 or more), often arranged in a line. This term is also used to refer to the whole unit of a short extension cord terminating in a power strip.

The term "extension cord" has been in use since at least 1946.

Below is the Coleman Cable Inc specifications as given to consider run footage for US cords:

Gauge:	Max Current (Amps):
16/2	13A 0'-50' 10A 50'-100'
16/3	13A 0'-50' 10A 50'-100'
14/3	15A 0'-50' 13A 50'-100'
12/3	15A 0'-100'
10/3	15A 0'-100'

Colors are assigned to cords, but they can be found across the gauges. 12 or 10 gauge used for heavy duty equipment.

Length

To avoid the need to roll-up any excess length, and to avoid the need for the user to cut the cord to size, extension cords are sometimes sold in prefabricated lengths 1 to 10 yards (Also measured by the foot). The longer the length of the cord the larger the wire should be to minimise voltage drop.

Signal



USB Extension Cord



Retractable Mouse Cord

Extension cords may sometimes refer to cables that transmit data, electricity, or both (for example, USB extension cable). This type of cable comes in handy when certain USB plugs cannot fit into the hubs, such as a USB flash drive. But they are more likely to be called "extenders" or "extender cables" or "cable extenders".

A retractable cord is capable of being retracted. It is used in optical mini-mouses and elsewhere.

Safety

The majority of extension cords sold in the United States contain lead in the PVC housing. California Proposition 65 (1986) was passed to warn consumers when a product contains toxic chemicals such as lead which may cause cancer or reproductive harm. Many of these products carry warning labels, and advise to consumer to wash hands after handling the cable. There is currently no widespread movement in the USA to stop manufactured products containing lead in the first place. European countries developed RoHS to prevent products from containing harmful chemicals such as lead. However, some cables that fall under the Proposition 65 warning are RoHS compliant because of the amount of lead they contain, and for some applications RoHS doesn't apply.

Chapter 3

Ground (Electricity)

In electrical engineering, **ground** or **earth** may be the reference point in an electrical circuit from which other voltages are measured, or a common return path for electric current, or a direct physical connection to the Earth.



A typical earthing electrode (left) at a home in Australia. Fig. 1. Note the green and yellow marked earth wire.

Electrical circuits may be connected to ground (earth) for several reasons. In mains powered equipment, exposed metal parts are connected to ground to prevent contact with a dangerous voltage if electrical insulation fails. Connections to ground limit the build-up of static electricity when handling flammable products or when repairing electronic devices. In some telegraph and power transmission circuits, the earth itself can be used as one conductor of the circuit, saving the cost of installing a separate return conductor.

For measurement purposes, the Earth serves as a (reasonably) constant potential reference against which other potentials can be measured. An electrical ground system should have an appropriate current-carrying capability in order to serve as an adequate zero-voltage reference level. In electronic circuit theory, a "ground" is usually idealized as an infinite source or sink for charge, which can absorb an unlimited amount of current without changing its potential. Where a real ground connection has a significant resistance, the approximation of zero potential is no longer valid. Stray voltages or earth potential rise effects will occur, which may create noise in signals or if large enough will produce an electric shock hazard.

The use of the term ground (or earth) is so common in electrical and electronics applications that circuits in portable electronic devices such as cell phones and media players as well as circuits in vehicles such as ships, aircraft, and spacecraft may be spoken of as having a "ground" connection without any actual connection to the Earth. This is usually a large conductor attached to one side of the power supply (such as the "ground plane" on a printed circuit board) which serves as the common return path for current from many different components in the circuit.

Synonyms

The terms *ground* and *grounding* are used in US electrical practice. In the UK the equivalent terms are *earth* and *earthing*.

History

Long-distance electromagnetic telegraph systems from 1820 onwards used two or more wires to carry the signal and return currents. It was then discovered, probably by the German scientist Carl August Steinheil in 1836-1837, that the ground could be used as the return path to complete the circuit, making the return wire unnecessary. However, there were problems with this system, exemplified by the transcontinental telegraph line constructed in 1861 by the Western Union Company between Saint Joseph, Missouri, and Sacramento, California. During dry weather, the ground connection often developed a high resistance, requiring water to be poured on the ground rod to enable the telegraph to work or phones to ring.

Later, when telephony began to replace telegraphy, it was found that the currents in the earth induced by power systems, electrical railways, other telephone and telegraph circuits, and natural sources including lightning caused unacceptable interference to the audio signals, and the two-wire system was reintroduced.

Radio communications

An electrical connection to earth can be used as a reference potential for radio frequency signals for certain kinds of antennas. The part directly in contact with the earth (the "earth electrode") can be as simple as a metal rod or stake driven into the earth (Fig. 1), or a connection to buried metal water piping (though this carries the risk of the water pipe

being later replaced with plastic). Because high frequency signals can flow to earth through capacitance, capacitance to ground is an important factor in effectiveness of signal grounds. Because of this a complex system of buried rods and wires can be effective. An ideal signal ground maintains zero voltage regardless of how much electric current flows into ground or out of ground. The resistance at the signal frequency of the electrode-to-earth connection determines its quality, and that quality is improved by increasing the surface area of the electrode in contact with the earth, increasing the depth to which it is driven, using several connected ground rods, increasing the moisture of the soil, improving the conductive mineral content of the soil, and increasing the land area covered by the ground system.

Some types of transmitting antenna systems in the VLF, LF, MF and lower SW range depend on a good ground to operate efficiently. For example, a vertical monopole antenna requires a ground plane that often consists of an interconnected network of wires running radially away from the base of the antenna for a distance about equal to the height of the antenna. Sometimes such a ground plane is supported above ground to reduce losses.

AC power wiring installations

In a mains electricity (AC power) wiring installation, the term ground conductor typically refers to three different conductors or conductor systems as listed below.

Equipment earthing conductor. This provides an electrical connection between non-current-carrying metallic parts of equipment and the earth. The reason for doing this according to the U.S. National Electrical Code (NEC), is to limit the voltage imposed by lightning, line surges, and contact with higher voltage lines. Note that equipment earthing does not provide protection from equipment ground faults, unless it is a grounded system (see below) and the voltage is over one thousand volts (typically). This is because the earth is generally a very poor conductor—it takes a large voltage to push enough current through it back to the electrical system's source to operate a circuit breaker or fuse. The equipment earthing conductor is usually also used as the equipment bonding conductor (see below).

Equipment bonding conductor. The purpose of the equipment bonding conductor is to provide a low impedance path between non-current-carrying metallic parts of equipment and one of the conductors of that electrical system's source so that should these parts become energized for any reason, such as a frayed or damaged conductor, a short circuit will occur and thus cause an overcurrent protection device such as a circuit breaker or fuse to activate and disconnect the faulted circuit. Note that the earth itself has no role in this fault-clearing process since current must return to its source, not the earth as is sometimes believed. By bonding (interconnecting) all exposed non-current carrying metal objects together, they should remain near the same potential thus reducing the chance of a shock. This is especially important in bathrooms where one may be in contact with several different metallic systems such as supply and drain pipes and appliance frames.

The equipment bonding conductor is usually also used as the equipment earthing conductor (see above).

Grounding electrode conductor. is a conductor which connects one leg of an electrical system to one or more earth electrodes. This is called "system grounding" and most but not all systems are required to be grounded. The U.S. NEC and the UK's BS 7671 list systems that are required to be grounded. The grounding electrode conductor is usually but not always connected to the leg of the electrical system that is the "neutral wire". The grounding electrode conductor is also usually bonded to pipework and structural steel in larger structures. According to the NEC, the purpose of earthing an electrical system in this manner is to limit the voltage to earth imposed by lightning events and contact with higher voltage lines, and also to stabilize the voltage to earth during normal operation. In the past, water supply pipes were often used as ground electrodes, but this was banned in some countries when plastic pipe such as PVC became popular. This type of ground applies to radio antennas and to lightning protection systems.

Permanently installed electrical equipment usually also has permanently connected grounding conductors. Portable electrical devices with metal cases may have them connected to earth ground by a pin in the interconnecting plug. The size of power ground conductors is usually regulated by local or national wiring regulations.

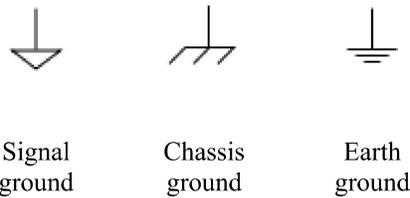
Power transmission

Some HVDC power transmission systems use the ground as second conductor. This is especially common in schemes with submarine cables as sea water is a good conductor. Buried grounding electrodes are used to make the connection to the earth. The site of these electrodes must be chosen very carefully in order to prevent electrochemical corrosion on underground structures.

In Single Wire Earth Return (SWER) AC electrical distribution systems, costs are saved by using just a single high voltage conductor for the power grid, while routing the AC return current through the earth. This system is mostly used in rural areas where large earth currents will not otherwise cause hazards.

A particular concern in design of electrical substations is earth potential rise. When very large fault currents are injected into the earth, the area around the point of injection may rise to a high potential with respect to distant points. This is due to the limited finite conductivity of the layers of soil in the earth. The gradient of the voltage (changing voltage within a distance) may be so high that two points on the ground may be at significantly different potentials, creating a hazard to anyone standing on the ground in the area. Pipes, rails, or communication wires entering a substation may see different ground potentials inside and outside the substation, creating a dangerous touch voltage.

Electronics



Ground symbols

Signal grounds serve as return paths for signals and power (at extra low voltages, i.e., less than about 50 V) within equipment, and on the signal interconnections between equipment. Many electronic designs feature a single return that acts as a reference for all signals. Power and signal grounds often get connected together, usually through the metal case of the equipment.

Circuit ground versus earth

Voltage is a differential quantity. To measure the voltage of a single point, a reference point must be selected to measure against. This common reference point is called "ground" and considered to have zero voltage. This signal ground may not actually be connected to a power ground. A system where the system ground is not actually connected to another circuit or to earth (though there may still be AC coupling) is often referred to as a floating ground.

Separating low signal ground from a noisy ground

In television stations, recording studios, and other installations where sound quality is critical, a special signal ground known as a "technical ground" (or "technical earth") is often installed, to prevent ground loops. This is basically the same thing as an AC power ground, but no appliance ground wires are allowed any connection to it, as they may carry electrical interference. In most cases, the studio's metal equipment racks are all joined together with heavy copper cables (or flattened copper tubing or busbars) and similar connections are made to the technical ground. Great care is taken that no AC-grounded appliances are placed on the racks, as a single AC ground connection to the technical ground will destroy its effectiveness. For particularly demanding applications, the main technical ground may consist of a heavy copper pipe, if necessary fitted by drilling through several concrete floors, such that all technical grounds may be connected by the shortest possible path to a grounding rod in the basement.

Lightning protection systems

Lightning protection systems are special grounding systems designed to safely conduct the extremely high voltage currents associated with lightning strikes.



Busbars are used for ground conductors in high-current circuits

Earthing system

In electricity supply systems, an earthing (grounding) system defines the electrical potential of the conductors relative to that of the Earth's conductive surface. The choice of earthing system has implications for the safety and electromagnetic compatibility of the power supply. Note that regulations for earthing systems vary considerably between different countries.

A functional earth connection serves a purpose other than providing protection against electrical shock. In contrast to a protective earth connection, a functional earth connection may carry a current during the normal operation of a device. Functional earth connections

may be required by devices such as surge suppression and electromagnetic-compatibility filters, some types of antennas and various measurement instruments. Generally the protective earth is also used as a functional earth, though this requires care in some situations.

Ground (Earth) mat

A ground (earth) mat or grounding (earthing) mat is a flat, flexible pad used for working on electrostatic sensitive devices. It is generally made of a conductive plastic or metal mesh covered substrate which is electrically attached to ground (earth). This helps discharge any static charge which a worker has built up, as well as any static charge on tools or exposed components laid on the mat. It is used most commonly in computer repair. Ground (earth) mats are also found on fuel trucks and tankers, which are otherwise insulated from ground (earth) as they make physical contact only with their tires and the air; obviously static discharge is undesirable during fuel-transfer operations. Similarly, in aircraft refueling, a ground (earth) cable connects the tanker (truck or airplane) to the fuel-seeking craft to eliminate charge differences before fuel is transferred.

In an electrical substation a ground (earth) mat is a mesh of conductive material installed at places where a person would stand to operate a switch or other apparatus; it is bonded to the local supporting metal structure and to the handle of the switchgear, so that the operator will not be exposed to a high differential voltage due to a fault in the substation.

Chapter 4

Ground and Neutral

Since the neutral point of an electrical supply system is often connected to earth ground, **ground and neutral** are closely related. Under certain conditions, a conductor used to connect to a system neutral is also used for grounding (earthing) of equipment and structures. Current carried on a grounding conductor can result in objectionable or dangerous voltages appearing on equipment enclosures, so the installation of grounding conductors and neutral conductors is carefully defined in electrical regulations. Where a neutral conductor is used also to connect equipment enclosures to earth, care must be taken that the neutral conductor never rises to a high voltage with respect to local ground.

Definitions

Ground or **earth** in a mains (AC power) electrical wiring system is a conductor that provides a low impedance path to the earth to prevent hazardous voltages from appearing on equipment (the terms "ground" (North American practice) and "earth" (most other English-speaking countries) are used synonymously here). Normally a grounding conductor does not carry current.

Neutral is a circuit conductor (that carries current in normal operation), which is connected to earth (or ground) generally at the service panel with the main disconnecting switch or breaker.

In a polyphase or three-wire (single-phase) AC system, the neutral conductor is intended to have similar voltages to each of the other circuit conductors. By this definition, a circuit must have at least three wires for one to serve as a neutral.

In the electrical trade, the conductor of a 2-wire circuit that is connected to the supply neutral point and earth ground is also referred to as the "neutral". This is formally described in the US and Canadian electrical codes as the "identified" circuit conductor.

The NEC and Canadian electrical code only define neutral as the first of these. In North American use, the second definition is used in less formal language but not in official specifications. In the UK the IET definition of a neutral conductor is one connected to the supply system neutral point, which includes both these uses.

All neutral wires of the same electrical system should have the same electrical potential, because they are all connected together through the system ground. Neutral conductors are usually insulated for the same voltage as the line conductors, with interesting exceptions.

Circuitry

Neutral wires are usually connected together at a neutral bus within panelboards or switchboards, and are "bonded" to earth ground at either the electrical service entrance, or at transformers within the system. For electrical installations with three-wire single phase service, the neutral point of the system is at the center-tap on the secondary side of the service transformer. For larger electrical installations, such as those with polyphase service, the neutral point is usually at the common connection on the secondary side of delta/bye connected transformers. Other arrangements of polyphase transformers may result in no neutral point, and no neutral conductors.

Wiring colours

CAUTION
This installation has wiring colours to two versions of BS7671

Great care should be taken before undertaking extension, alteration or repair that all conductors are correctly identified.

HARMONISED CORE COLOUR INTRODUCTION

Old Colour	Transition Period	New Colour	Label
Red	April 2004 - April 2006	Brown	(L1)
Yellow	April 2004 - April 2006	Black	(L2)
Blue	April 2004 - April 2006	Grey	(L3)
Black	April 2004 - April 2006	Blue	(N)

April 2004 April 2006

To be read in conjunction with BS7671 2004 Amendment No. 2

U.K. Electrical wiring colours notices.

The insulation of a neutral wire is coloured blue in the EU. This was the same in the UK until 2006, (although legacy cabling neutral wire is black in house wiring). In the USA white or grey is used. For large diameter wires or "mains" cables, the insulation of neutral conductors may be coloured black, as are also the phase or hot conductors, but they may be distinctively designated by applying the appropriate coloured tape—again blue in the EU (including the UK until recently), and white or grey in the USA and Canada. In the U.K. the phases of the incoming supply are designated L1, L2 and L3.

Earthing systems

The names for the following methods of earthing are those defined by IEC standards, which are used in Europe and many other regions. Different terminology is used in North America, but the basic principles should be the same everywhere.

Different systems are used to minimize the voltage difference between neutral and local earth ground. In some systems, the neutral and earth join together at the service intake (TN-C-S); in others, they run completely separately back to the transformer neutral terminal (TN-S), and in others they are kept completely separate with the house earth having its own rod and the neutral connected to earth within the distribution network (TT). In a few cases, they are combined in house wiring (TN-C), but the dangers of broken neutrals (see below) and the cost of the special cables needed to mitigate this mean that it is rarely done nowadays.

Combining neutral with earth

Stray voltages created in grounding (earthing) conductors by currents flowing in the supply utility neutral conductors can be troublesome. For example, special measures may be required in barns used for milking dairy cattle. Very small differential voltages, not usually perceptible to humans, may cause low milk yield, or even mastitis (inflammation of the udder). So-called "tingle voltage filters" may be required in the electrical distribution system for a milking parlour.

Connecting the neutral to the equipment case provides some protection against faults/shorts, but may produce a dangerous voltage on the case if the neutral connection is broken.

Combined neutral and ground conductors are commonly used in electricity supply companies' wiring and occasionally for fixed wiring in buildings and for some specialist applications where there is little choice like railways and trams. Since normal circuit currents in the neutral conductor can lead to objectionable or dangerous differences between local earth potential and the neutral, and to protect against neutral breakages, special precautions such as frequent rodding down to earth, use of cables where the combined neutral and earth completely surrounds the phase conductor(s), and thicker than normal equipotential bonding must be considered to ensure the system is safe.

Fixed appliances on three-wire circuits

In North America, the cases of some ovens and clothes dryers were grounded through their neutral wires as a measure to conserve copper during the Second World War. This practice was removed from the NEC in the 1996 edition, but existing installations may still allow the case of such appliances to be connected to the neutral conductor for grounding. Note that the NEC may be amended by local regulations in each state and city. This practice arose from the three wire system used to supply both 120 volt and 240 volt loads. Because ovens and dryers have components that use both 120 and 240 volts there is often some current on the neutral wire. This differs from the protective grounding wire, which only carries current under fault conditions. Using the neutral conductor for grounding the equipment enclosure was considered safe since the devices were permanently wired to the supply and so the neutral was unlikely to be broken without also breaking both supply conductors. Also, the unbalanced current due to lamps and small motors in the appliance was small compared to the rating of the conductors and therefore unlikely to cause a large voltage drop in the neutral conductor.

Portable appliances

In North American practice small portable equipment connected by a cord set may have only two conductors in the attachment plug. A polarised plug is used to maintain the identity of the neutral conductor into the appliance but it is never used as a chassis/case ground. The small cords to lamps, etc., often have one or more ridges or embedded strings to identify the neutral conductor, or may be identified by color. Portable appliances never rely on using the neutral conductor for case grounding.

In places where the design of the plug and socket cannot ensure that a system neutral conductor is connected to particular terminals of the device, portable appliances must be designed on the assumption that either pole of each circuit may reach full voltage with respect to ground.

Chapter 5

High Voltage Cable

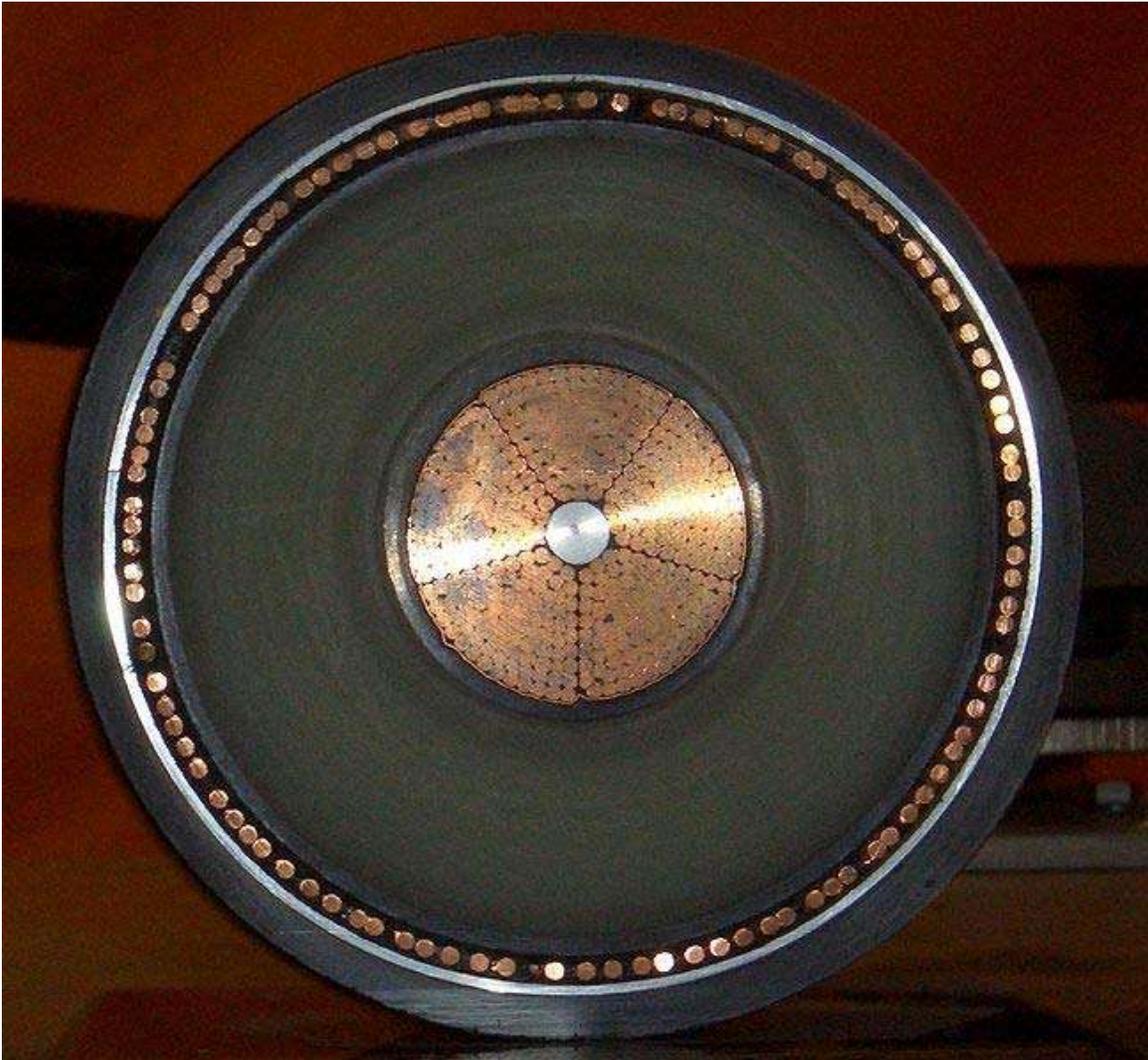
A **high voltage cable** - also called **HV cable** - is used for electric power transmission at high voltage. High voltage cables of differing types have a variety of applications in instruments, ignition systems, AC and DC power transmission. In all applications, the insulation of the cable must not deteriorate due to the high voltage stress, ozone produced by electric discharges in air, or tracking. The cable system must prevent contact of the high-voltage conductor with other objects or persons, and must contain and control leakage current. Cable joints and terminals must be designed to control the high-voltage stress to prevent breakdown of the insulation. Often a high-voltage cable will have a metallic shield layer over the insulation, connected to earth ground and designed to equalize the dielectric stress on the insulation layer, and to prevent shock.



Segments of high-voltage cables

High voltage cables may be any length, with relatively short cables used in apparatus, longer cables run within buildings or as buried cables in an industrial plant or for power distribution, and the longest cables are often run as submarine cables under the ocean for power transmission.

Construction



A cross-section through a 400 kV cable, showing the stranded segmented copper conductor in the center, semiconducting and insulating layers, copper shield conductors, aluminum sheath and plastic outer jacket.

Like other power cables, high voltage cables have the structural elements of one or more conductors, insulation, and a protective jacket. High voltage cables differ from lower-voltage cables in that they have additional internal layers in the insulation jacket to control the electric field around the conductor.

For circuits operating at or above 2,000 volts between conductors, a conductive shield may surround each insulated conductor. This equalizes electrical stress on the cable insulation. This technique was patented by Martin Hochstadter in 1916; the shield is sometimes called a Hochstadter shield. The individual conductor shields of a cable are connected to earth ground at the ends of the shield, and at splices. Stress relief cones are applied at the shield ends.

Cables for power distribution of 10kV or higher may be insulated with oil and paper, and are run in a rigid steel pipe, semi-rigid aluminum or lead sheath. For higher voltages the oil may be kept under pressure to prevent formation of voids that would allow partial discharges within the cable insulation.

Sebastian Ziani de Ferranti was the first to demonstrate in 1887 that carefully dried and prepared paper could form satisfactory cable insulation at 11,000 volts. Previously paper-insulated cable had only been applied for low-voltage telegraph and telephone circuits. An extruded lead sheath over the paper cable was required to ensure that the paper remained absolutely dry.

Vulcanized rubber was patented by Charles Goodyear in 1844, but it was not applied to cable insulation until the 1880s, when it was used for lighting circuits. Rubber-insulated cable was used for 11,000 volt circuits in 1897 installed for the Niagara Falls power project.

Mass-impregnated paper-insulated medium voltage cables were commercially practical by 1895. During World War II several varieties of synthetic rubber and polyethylene insulation were applied to cables. Modern high voltage cables use polymers or polyethylene, including (XLPE) for insulation.

AC power cable

High voltage is defined as any voltage over 1000 volts. Cables for 3000 and 6000 volts exist, but the majority of cables are used from 10 kV and upward. Those of 10 to 33 kV are usually called *medium voltage* cables, those over 50 kV *high voltage* cables.

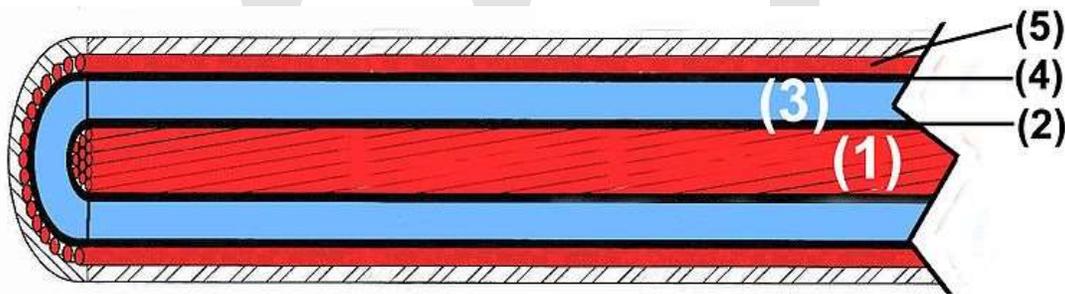


Figure 1, cross section of a high voltage cable, (1) conductor, (3) insulation.

Modern HV cables have a simple design consisting of few parts. A conductor of copper or aluminum wires transports the current, see (1) in figure 1. Conductor sections up to 2000 mm² may transport currents up to 2000 amperes. The individual strands are often preshaped to provide a smoother overall circumference. The insulation (3) may consist of cross-linked polyethylene, also called XLPE. It is reasonably flexible and tolerates operating temperatures up to 120 °C. EPDM is also an insulation.

At the inner (2) and outer (4) sides of this insulation, semi-conducting layers are fused to the insulation. The function of these layers is to prevent air-filled cavities between the metal conductors and the dielectric so that little electric discharges can arise and endanger the insulation material.

The outer conductor or sheath (5) serves as an earthed layer and will conduct leakage currents if needed.

Most high voltage cables for power transmission that are currently sold on the market are insulated by a sheath of cross-linked polyethylene (XLPE). Some cables may have a lead or aluminium jacket in conjunction with XLPE insulation to allow for fiber optics. Before 1960, underground power cables were insulated with oil and paper and ran in a rigid steel pipe, or a semi-rigid aluminium or lead jacket or sheath. The oil was kept under pressure to prevent formation of voids that would allow partial discharges within the cable insulation. There are still many of these oil-and-paper insulated cables in use worldwide. Between 1960 and 1990, polymers became more widely used at distribution voltages, mostly EPDM (ethylene propylene diene M-class); however, their relative unreliability, particularly early XLPE, resulted in a slow uptake at transmission voltages. While cables of 330 kV are commonly constructed using XLPE, this has occurred only in recent decades.

Quality

During the development of the HV insulation, which has taken about half a century, two characteristics proved to be paramount. First, the introduction of the semiconducting layers. These layers must be absolutely smooth, without even protrusions as small as some microns. Further the fusion between the insulation and these layers must be absolute; any fission, air-pocket or other defect - of the same micro-dimensions as above - is detrimental for the breakdown characteristics of the cable.

Secondly, the insulation must be free of inclusions, cavities or other defects of the same sort of size. Any defect of these types shortens the voltage life of the cable which is supposed to be in the order of 30 years or more.

Cooperation between cable-makers and manufacturers of materials has resulted in grades of XLPE with tight specifications about the number and size of foreign particles per pound or per kilogram. Packing the raw material and unloading it within a cleanroom environment in the cable-making machines is required. The development of extruders for plastics extrusion and cross-linking has resulted in cable-making installations for making defect-free and pure insulations.

HVDC cable

A high voltage cable for HVDC transmission has the same construction as the AC cable shown in figure 1. The physics and the test-requirements are different. In this case the smoothness of the semiconducting layers (2) and (4) is of utmost importance. Cleanliness of the insulation remains imperative.

Many HVDC cables are used for DC submarine connections, because at distances over 30 km AC can no longer be used. The longest submarine cable today is the NorNed cable between Norway and Holland that is almost 600 km long and transports 700 megawatts, a capacity equal to two large power stations.

Most of these long deep-sea cables are made in an older construction, using oil-impregnated paper as an insulator.

Cable terminals

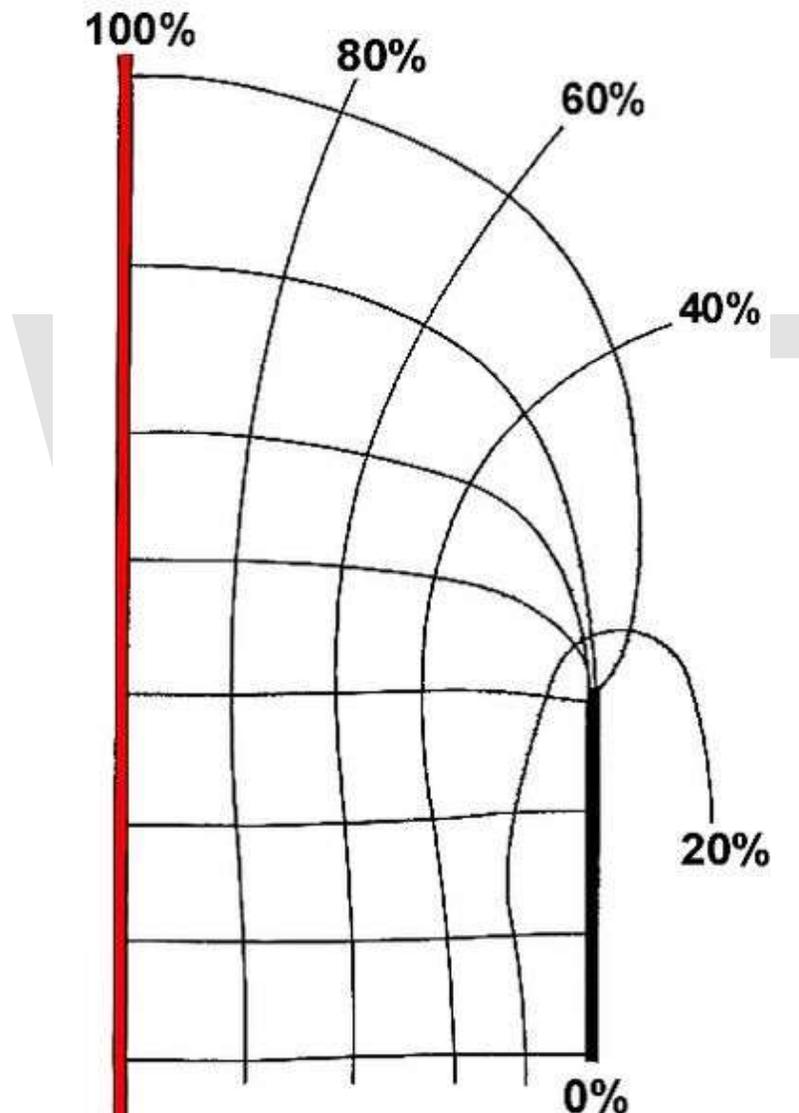


Figure 2, the earth shield of a cable (0%) is cut off, the equipotential lines (from 20% to 80%) concentrate at the edge of the earth electrode, causing danger of breakdown.

Terminals of high voltage cables must manage the electric fields at the ends. Without such a construction the electric field will concentrate at the end of the earth-conductor as shown in figure 2.

Equipotential lines are shown here which can be compared with the contour lines on a map of a mountainous region: the nearer these lines are to each other, the steeper the slope and the greater the danger, in this case the danger of an electric breakdown. The equipotential lines can also be compared with the isobars on a weather map: the denser the lines, the more wind and the greater the danger of damage.

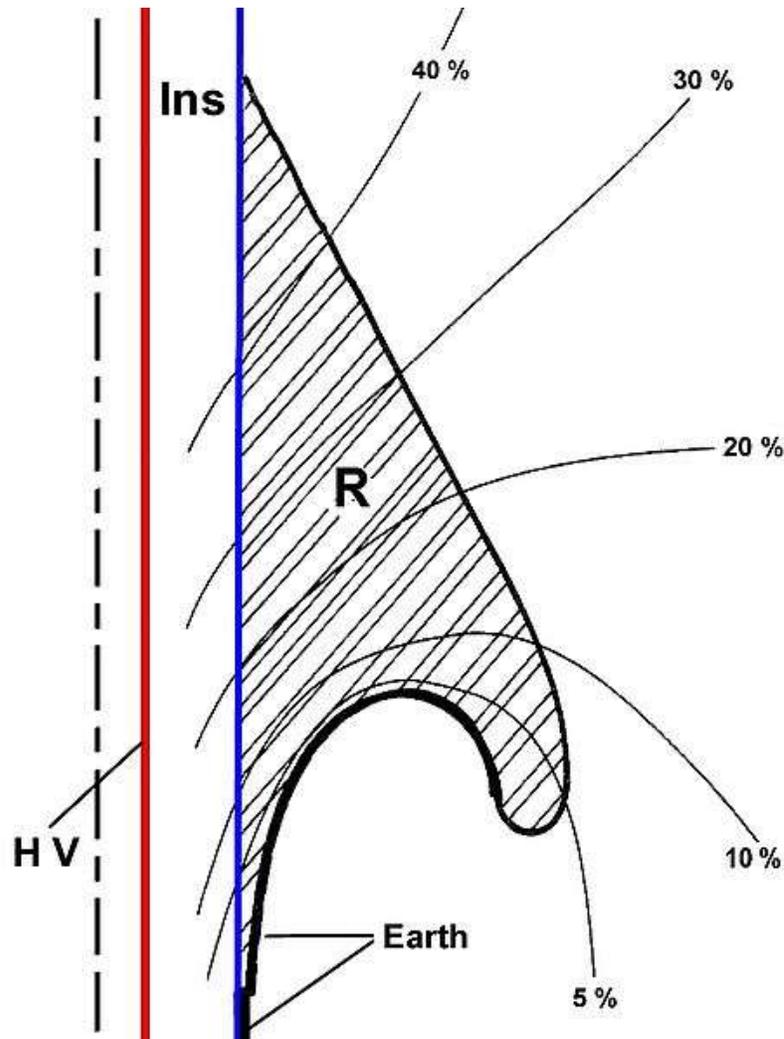


Figure 3, a rubber or elastomer body **R** is pushed over the insulation (blue) of the cable. The equipotential lines between **HV** (high voltage) and **earth** are evenly spread out by the shape of the earth electrode. Field concentrations are prevented in this way.

In order to control the equipotential lines (that is to control the electric field) a device is used that is called a **stress-cone**, see figure 3. The crux of stress relief is to flare the shield end along a logarithmic curve. Before 1960, the stress cones were hand made using tape—after the cable was installed. These were protected by potheads, so named because a potting compound/ dielectric was poured around the tape inside a metal/ porcelain body insulators. About 1960, preformed terminations were developed. Such consists of a rubber or elastomer body that is stretched over the cable end. On this rubber-like body **R**

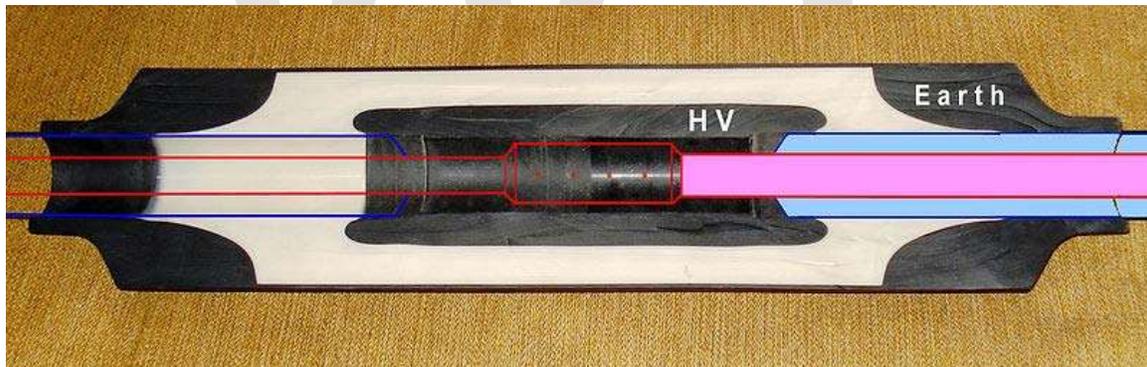
an **earth**electrode is applied that spreads the equipotential lines. These lines pass the surface of the body after they have sufficiently been spread out to guarantee a low electric field.

The crux of this device, invented by NKF in Delft in 1964, is the fact that the bore of the elastic body R is narrower than the diameter of the cable. In this way the (blue) interface between cable and stress-cone is brought under mechanical pressure so that no cavities or air-pockets can be formed between cable and cone. Electric breakdown in this region is prevented in this way.

This construction can further be surrounded by a porcelain or silicone insulator for outdoor use, or by contraptions to enter the cable into a power transformer under oil, or switchgear under gas-pressure.

Cable joints

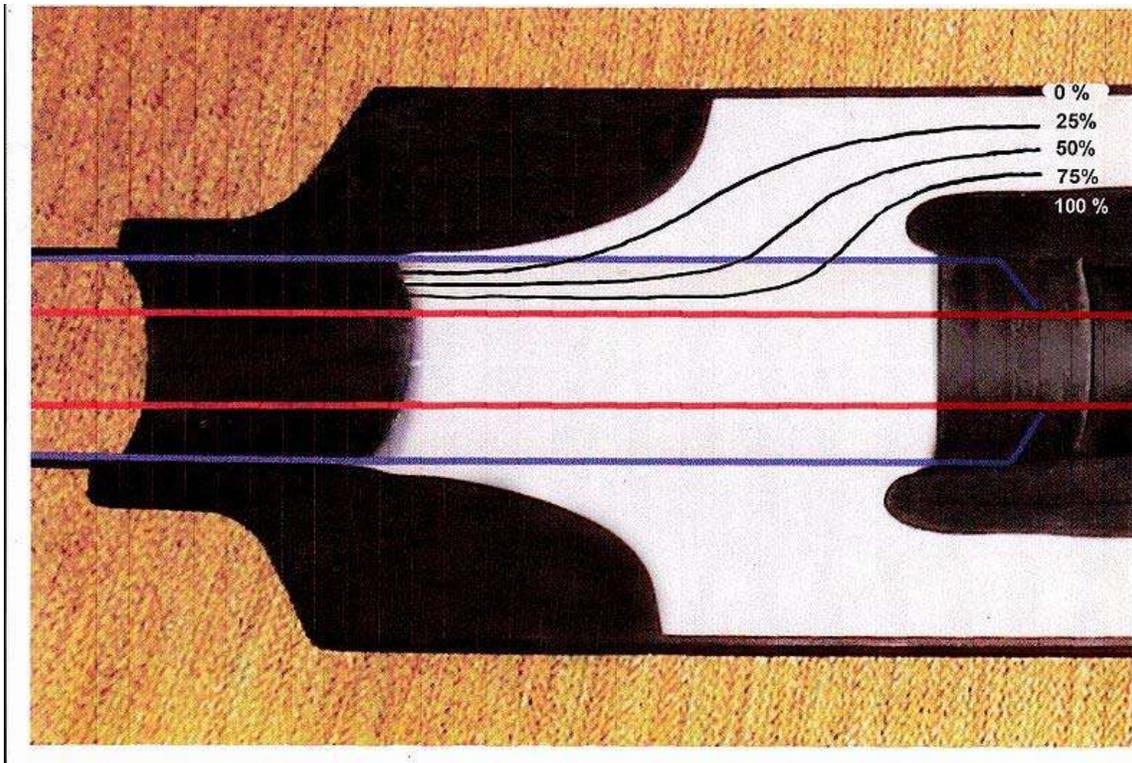
Connecting two high-voltage cables with one another poses two main problems. First, the outer conducting layers in both cables shall be terminated without causing a field concentration, similar as with the making of a cable terminal. Secondly, a field free space shall be created where the cut-down cable insulation and the connector of the two conductors safely can be accommodated. These problems have been solved by NKF in Delft in 1965 by introducing a device called **bi-manchet**.



Photograph of a section of a high-voltage joint, **bi-manchet**, with a high voltage cable mounted at the right hand side of the device.

Figure 4 shows a photograph of the cross-section of such a device. At one side of this photograph the contours of a high voltage cable are drawn. Here **red** represents the conductor of that cable and **blue** the insulation of the cable. The black parts in this picture are semi-conducting rubber parts. The outer one is at earth potential and spreads the electric field in a similar way as in a cable terminal. The inner one is at high-voltage and shields the connector of the conductors from the electric field.

The field itself is diverted as shown in figure 5, where the equipotential lines are smoothly directed from the inside of the cable to the outer part of the bi-manchet (and vice versa at the other side of the device).



Field distribution in a **bi-manchet** or HV joint

The crux of the matter is here, like in the cable terminal, that the inner bore of this bi-manchet is chosen smaller than the diameter over the cable-insulation. In this way a permanent pressure is created between the bi-manchet and the cable surface and cavities or electrical weak points are avoided.

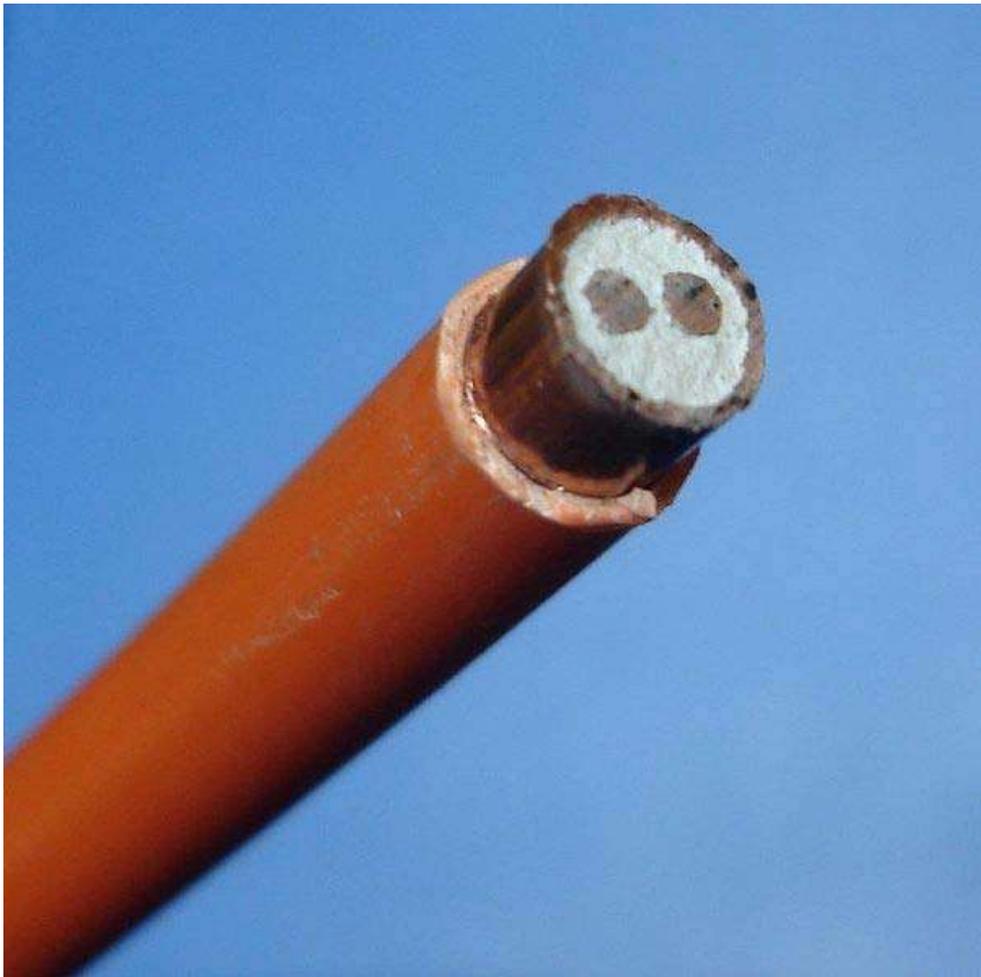
Installing a terminal or bi-manchet is skilled work. Removing the outer semiconducting layer at the end of the cables, placing the field-controlling bodies, connecting the conductors, etc., require skill, cleanness and precision.

X-ray cable

X-ray cables are used in lengths of some meters to connect the HV source with an X-ray tube or any other HV device in scientific equipment. They transmit small currents, in the order of milliamperes at DC voltages of 30 to 200 kV, or sometimes higher. The cables are flexible, with rubber or other elastomer insulation, stranded conductors, and an outer sheath of braided copper-wire. The construction has the same elements as other HV power cables.

Chapter 6

Mineral-Insulated Copper-Clad Cable



PVC-sheathed MICC cable. Conductor cross section area is 1.5 mm^2 ; overall diameter is 7.2 mm



Mineral insulated cables at a panel board

Mineral-insulated copper-clad cable is a variety of electrical cable made from copper conductors inside a copper sheath, insulated by inorganic magnesium oxide powder. The name is often abbreviated to MICC or MI cable, and colloquially known as **pyro** (because the original manufacturer and vendor for this product in the UK is a company called Pyrotenax). A similar product sheathed with metals other than copper is called *mineral insulated metal sheathed* (MIMS) cable.

MI cable is made by placing copper rods inside a circular copper tube and filling the intervening spaces with dry magnesium oxide powder. The overall assembly is then pressed between rollers to reduce its diameter (and increase its length). Up to seven conductors are often found in an MI cable, with up to 19 available from some manufacturers.

Since MI cables use no organic material as insulation (except at the ends), they are more resistant to fires than plastic-insulated cables. MI cables are used in critical fire protection applications such as alarm circuits, fire pumps, and smoke control systems. In process industries handling flammable fluids MI cable is used where small fires would otherwise cause damage to control or power cables. MI cable is also highly resistant to ionising radiation and so finds applications in instrumentation for nuclear reactors and nuclear physics apparatus.

The metal tube surrounding the conductors effectively shields circuits in MI cable from electromagnetic interference. The metal sheath provides protection against accidental contact with energised circuit conductors.

MI cables may be covered with a plastic sheath, coloured for identification purposes. The plastic sheath also provides additional corrosion protection for the copper sheath.

History

The first patent for MI cable was issued to the Swiss inventor Arnold Francois Borel in 1896. Initially the insulating mineral was described in the patent application as pulverized glass, silicious stones, or asbestos, in powdered form. Much development ensued by the French company Societe Alsacienne de Construction Mechaniques. Commercial production began in 1932 and much mineral-insulated cable was used on ships such as the Normandie and oil tankers, and in such critical applications as the Louvre museum. In 1937 a British company *Pyrotenax*, having purchased patent rights to the product from the French company, began production. During the Second World War much of the company's product was used in military equipment.

About 1947 the British Cable Maker's Association investigated the option of manufacturing a mineral-insulated cable that would compete with the Pyrotenax product. The manufacturers of the products "Bicalmin" and "Glomin" eventually merged with the Pyrotenax company.

The Pyrotenax company introduced an aluminum sheathed version of its product in 1964. MI cable is now manufactured in several countries. Pyrotenax is now a wholly owned subsidiary of Tyco Corporation.

Purpose and use

MI cables are used for power and control circuits of critical equipment, such as the following examples:

- Nuclear reactors
- Air pressurisation systems for stairwells to enable building egress during a fire
- Hospital operating rooms
- Fire alarm systems
- Emergency power systems
- Emergency lighting systems
- Temperature measurement devices; RTD's and Thermocouples.
- Critical process valves in the petrochemical industry
- Public buildings such as theatres, cinemas, hotels
- Transport hubs (railway stations, airports etc)
- Tunnels and mines
- Electrical equipment in hazardous areas where flammable gases may be present e.g. oil refineries, petrol stations

- Areas where corrosive chemicals may be present e.g. factories
- Building plant rooms
- Hot areas e.g. power stations, foundries, and close to or even inside industrial furnaces, kilns and ovens

MI cable fulfills the passive fire protection called circuit integrity, which is intended to provide operability of critical electrical circuits during a fire. It is subject to strict listing and approval use and compliance

Heating cable

A similar appearing product is mineral-insulated trace heating cable, in which the conductors are made of a high-resistance alloy. A heating cable is used to protect pipes from freezing, or to maintain temperature of process piping and vessels. An MI resistance heating cable may not be repairable if damaged. Most electric stove and oven heating elements are constructed in a similar manner.

Typical specifications

maximum voltage	600 or 1000 volts
current rating	18 - 450 amperes
conductor area	1.0 - 240 mm ²
copper sheath area	5 - 70 mm ² effective
number of cores	1,2,3,4,7,12,19
overall diameter	5 - 26 mm
minimum bend radius	6 x diameter (3 x diameter if bent once only)
weight	100 - 3300 kg/km
twists per metre	0, 20; In many applications NO twist is preferred.
finish	bare copper, standard PVC sheath, low smoke and fume (LSF) polymer sheath, various Stainless Steels, Inconel, Titanium, and some super alloys.
colour	natural (Bare Stainless),(bare copper), white, black, red, orange

maximum operating temperature	continuous - exposed to touch	70 °C
	continuous - not exposed to touch; PVC- sheathed	90 °C
	continuous - not exposed to touch; not PVC- sheathed	250 °C
	intermittent	>1000 °C
(melting point of copper is 1083 °C)		

Advantages

The metal sheath and solid filling of MI cable makes it mechanically robust and resistant to impact; an MI cable may be struck repeatedly with a hammer and still provide adequate insulation resistance for a circuit . Copper sheathing is waterproof and resistant to ultraviolet light and many corrosive elements. MI cable is approved by electrical codes for use in areas with hazardous concentrations of flammable gas in air; an MI cable will not allow propagation of an explosion inside the copper tube, and the cable is unlikely to initiate an explosion even during circuit fault conditions. Metal sheathing will not contribute fuel or hazardous combustion products to a fire, and cannot propagate a fire along a cable tray or within a building. The cable is inherently fire-rated without additional coatings, and will survive designated fire tests representative of actual fire conditions longer than the enclosing structure.

When used within a tenanted area, carrying electricity supplied and billed to the landlord, for example for a communal extract system or antenna booster, it provides a supply cable that cannot easily be 'tapped' into to obtain free energy.

Although made from solid copper elements, the finished cable assembly is still pliable due to the malleability of copper. The cable can be bent to follow shapes of buildings or bent around obstacles, allowing for a neat appearance when exposed.

Since the inorganic insulation does not degrade with (moderate) heating, the finished cable assembly can be allowed to rise to higher temperatures than plastic-insulated cables; the limits to temperature rise may be only due to possible contact of the sheath with people or structures. This may also allow a smaller cross-section cable to be used in particular applications.

Due to oxidation, the copper cladding darkens with age and MICC is therefore often used in historic buildings such as castles where it blends in with stonework.

Disadvantages

- *The termination points:* While the length of the MI cable is very tough, at some point, each run of cabling terminates at a splice or within electrical equipment. These terminations are vulnerable to fire, moisture, or mechanical impact.
- *Vibration:* MICC is not suitable for use where it will be subject to vibration or flexing, for example connection to heavy or movable machinery. Vibration will crack the cladding and cores, leading to failure.
- *Labour Cost:* During installation MI cable must not be bent repeatedly as this will cause work hardening and cracks in the cladding and cores. A minimum bend radius must be observed and the cable must be supported at regular intervals. The magnesium oxide insulation is hygroscopic so MICC cable must be protected from moisture until it has been terminated. Termination requires stripping back the copper cladding and attaching a compression gland fitting. Individual conductors are insulated with plastic sleeves. A sealing tape, insulating putty or an epoxy resin is then poured into the compression gland fitting to provide a watertight seal. If a termination is faulty due to workmanship or damage then the magnesium oxide will absorb moisture and lose its insulating properties. Depending on the size and number of conductors, a single termination can take between 1 to 2 hours of labour. Installation of a 3-conductor MI cable (size No. 10 AWG (about 5 square mm)) takes about 65% more time than installation of a PVC-sheathed armored cable of the same conductor size. Installation of MICC is therefore a costly task. Certain PTFE, silicone or other polymer-insulated cables have been substituted in applications which require similar properties in terms of flame spread, which use less labour to terminate. MICC is still used in applications which are particularly suited to its combination of properties.
- *Voltage rating:* MI cable is only manufactured with ratings up to 1000 volts.
- *Moisture absorption:* The magnesium oxide insulation has a high affinity for moisture. Moisture introduced into the cable can cause electrical leakage from the internal conductors to the metal sheath. Moisture absorbed at a cut end of the cable may be driven off by heating the cable.
- *Corrosion:* The copper sheath material is resistant to most chemicals but can be severely damaged by ammonia-bearing compounds and urine. A pinhole in the copper sheathing will allow moisture into the insulation, and eventual failure of the circuit. A PVC over jacket or sheaths of other metals may be required where such chemical damage is expected. When MI cable is embedded in concrete as snow melting cable it is subject to physical damage by concrete workers working the concrete into the pour. If the 3-5mil coating is damaged pin holes in the copper jacket develop causing premature failure of the snow melting system.

- *Repair:* If the MI cable jacket has been damaged the magnesium oxide will wick moisture into the cable and it will lose its insulating properties causing high resistance shorts to the grounding jacket (Copper Jacket). It is often necessary to remove 2' to 10' of the MI Cable and splice in a new section to accomplish the repair. Depending on the size and number of conductors, a single termination can take between 1 to 2 hours of labor.

Alternatives

Circuit integrity for conventional plastic-insulated cables requires additional measures to obtain a fire-resistance rating or to lower the flammability and smoke contributions to a minimum degree acceptable for certain types of construction. Sprayed-on coatings or flexible wraps cover the plastic insulation to protect it from flame and reduce its flame spreading ability. However, since these coatings reduce the heat dissipation of the cables, often they must be rated for less current after application of fire-resistant coatings. This is called ampacity derating. It can be tested through the use of IEEE 848 Standard Procedure for the Determination of the Ampacity Derating of Fire-Protected Cables. The following materials have been used on their own and/or in combination with one another for fireproofing electrical circuits:

- Calcium silicate
- Vermiculite boards
- Ceramic fibre boards and blankets
- Rockwool boards and blankets
- Intumescent coatings and boards
- Endothermic coatings and boards

So far as building code and fire code compliance are concerned, what matters is Listing and approval use and compliance in order to be able to demonstrate empirically, that the field-installed configuration is capable of achieving a fire-resistance rating. Whether one uses MI Cable or ordinary cables that have been externally fireproofed is a matter of choice, which is largely dictated by economics.

Chapter 7

Overhead Power Line



Transmission lines in Lund, Sweden



High and medium voltage power lines in Łomża, Poland



Overhead lines in Japan

An **overhead power line** is an electric power transmission line suspended by towers or utility poles. Since most of the insulation is provided by air, overhead power lines are generally the lowest-cost method of transmission for large quantities of electric energy. Towers for support of the lines are made of wood (as-grown or laminated), steel (either lattice structures or tubular poles), concrete, aluminium, and occasionally reinforced plastics. The bare wire conductors on the line are generally made of aluminium (either plain or reinforced with steel or sometimes composite materials), though some copper wires are used in medium-voltage distribution and low-voltage connections to customer premises. A major goal of overhead power line design is to maintain adequate clearance between energized conductors and the ground so as to prevent dangerous contact with the line.

The invention of the strain insulator was a critical factor in allowing higher voltages to be used. At the end of the 19th century, the limited electrical strength of telegraph-style pin insulators limited the voltage to no more than 69,000 volts. Today overhead lines are routinely operated at voltages exceeding 765,000 volts between conductors, with even higher voltages possible in some cases.

Overhead power transmission lines are classified in the electrical power industry by the range of voltages:

- Low voltage – less than 1000 volts, used for connection between a residential or small commercial customer and the utility.

- Medium Voltage (Distribution) – between 1000 volts (1 kV) and to about 33 kV, used for distribution in urban and rural areas.
- High Voltage (subtransmission less than 100 kV; subtransmission or transmission at voltage such as 115 kV and 138 kV), used for sub-transmission and transmission of bulk quantities of electric power and connection to very large consumers.
- Extra High Voltage (transmission) – over 230 kV, up to about 800 kV, used for long distance, very high power transmission.
- Ultra High Voltage – higher than 800 kV.

Structures

Structures for overhead lines take a variety of shapes depending on the type of line. Structures may be as simple as wood poles directly set in the earth, carrying one or more cross-arm beams to support conductors, or "armless" construction with conductors supported on insulators attached to the side of the pole. Tubular steel poles are typically used in urban areas. High-voltage lines are often carried on lattice-type steel towers or pylons. For remote areas, aluminium towers may be placed by helicopters. Concrete poles have also been used. Poles made of reinforced plastics are also available, but their high cost restricts application.

Each structure must be designed for the loads imposed on it by the conductors. A large transmission line project may have several types of towers, with "tangent" ("suspension" or "line" towers, UK) towers intended for most positions and more heavily constructed towers used for turning the line through an angle, dead-ending (terminating) a line, or for important river or road crossings. Depending on the design criteria for a particular line, semi-flexible type structures may rely on the weight of the conductors to be balanced on both sides of each tower. More rigid structures may be intended to remain standing even if one or more conductors is broken. Such structures may be installed at intervals in power lines to limit the scale of cascading tower failures.

Foundations for tower structures may be large and costly, particularly if the ground conditions are poor, such as in wetlands. Each structure may be stabilized considerably by the use of guy wires to counteract some of the forces applied by the conductors.

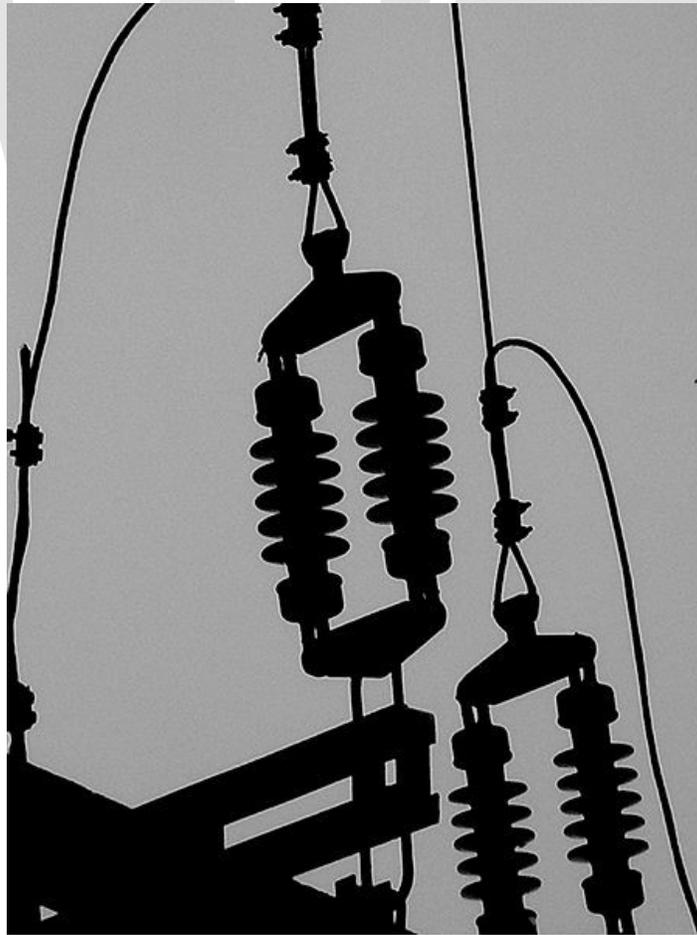
Power lines and supporting structures can be a form of visual pollution. In some cases the lines are buried to avoid this, but this "undergrounding" is more expensive and therefore not common.

For a single wood utility pole structure, a pole is placed in the ground, then three crossarms extend from this, either staggered or all to one side. The insulators are attached to the crossarms. For an "H"-type wood pole structure, two poles are placed in the ground, then a crossbar is placed on top of these, extending to both sides. The insulators are attached at the ends and in the middle. Lattice tower structures have two common forms. One has a pyramidal base, then a vertical section, where three crossarms extend out, typically staggered. The strain insulators are attached to the crossarms. Another has a

pyramidal base, which extends to four support points. On top of this a horizontal truss-like structure is placed. The insulators are attached to this.

Insulators

Insulators must support the conductors and withstand both the normal operating voltage and surges due to switching and lightning. Insulators are broadly classified as either pin-type, which support the conductor above the structure, or suspension type, where the conductor hangs below the structure. Up to about 33 kV (69 kV in North America) both types are commonly used. At higher voltages only suspension-type insulators are common for overhead conductors. Insulators are usually made of wet-process porcelain or toughened glass, with increasing use of glass-reinforced polymer insulators. However, with rising voltage levels and changing climatic conditions, polymer insulators (silicone rubber based) are seeing increasing usage. China has already developed polymer insulators having a highest system voltage of 1100kV and India is currently developing a 1200kV (highest system voltage) line which will initially be charged with 400kV to be upgraded to a 1200kV line.



Ceramic insulators

Suspension insulators are made of multiple units, with the number of unit insulator disks increasing at higher voltages. The number of disks is chosen based on line voltage, lightning withstand requirement, altitude, and environmental factors such as fog, pollution, or salt spray. Longer insulators, with longer creepage distance for leakage current, are required in these cases. Strain insulators must be strong enough mechanically to support the full weight of the span of conductor, as well as loads due to ice accumulation, and wind.

Porcelain insulators may have a semi-conductive glaze finish, so that a small current (a few milliamperes) passes through the insulator. This warms the surface slightly and reduces the effect of fog and dirt accumulation. The semiconducting glaze also ensures a more even distribution of voltage along the length of the chain of insulator units.

Polymer insulators by nature have hydrophobic characteristics providing for improved wet performance. Also, studies have shown that the specific creepage distance required in polymer insulators is much lower than that required in porcelain or glass. Additionally, the mass of polymer insulators (especially in higher voltages) is approximately 50% to 30% less than that of a comparative porcelain or glass string. Better pollution and wet performance is leading to the increased use of such insulators.

Insulators for very high voltages, exceeding 200 kV, may have grading rings installed at their terminals. This improves the electric field distribution around the insulator and makes it more resistant to flash-over during voltage surges.

Conductors

Aluminium conductors reinforced with steel (known as ACSR) are primarily used for medium and high voltage lines and may also be used for overhead services to individual customers. Aluminium conductors are used as it has the advantage of better resistivity/weight than copper, as well as being cheaper. Some copper cable is still used, especially at lower voltages and for grounding.

While larger conductors may lose less energy due to lower electrical resistance, they are more costly than smaller conductors. An optimization rule called *Kelvin's Law* states that the optimum size of conductor for a line is found when the cost of the energy wasted in the conductor is equal to the annual interest paid on that portion of the line construction cost due to the size of the conductors. The optimization problem is made more complex due to additional factors such as varying annual load, varying cost of installation, and by the fact that only definite discrete sizes of cable are commonly made.

Since a conductor is a flexible object with uniform weight per unit length, the geometric shape of a conductor strung on towers approximates that of a catenary. The sag of the conductor (vertical distance between the highest and lowest point of the curve) varies depending on the temperature. A minimum overhead clearance must be maintained for safety. Since the temperature of the conductor increases with increasing heat produced by the current through it, it is sometimes possible to increase the power handling capacity

(update) by changing the conductors for a type with a lower coefficient of thermal expansion or a higher allowable operating temperature.

Bundle conductors

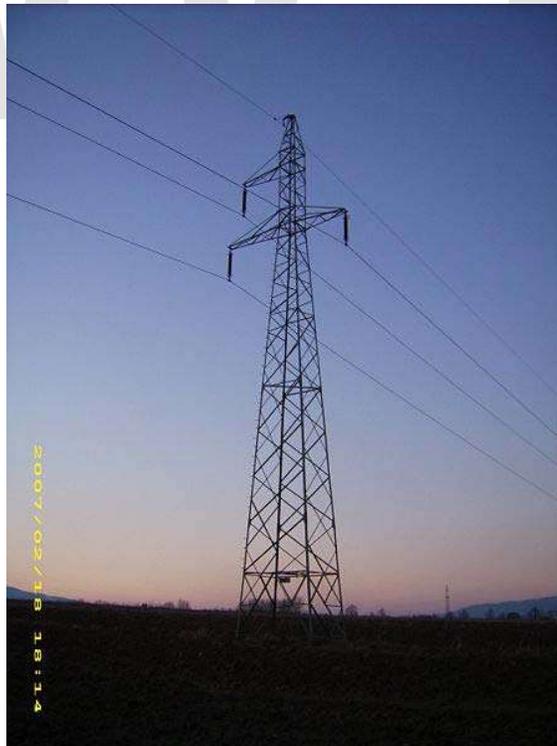
Bundle conductors are used to reduce corona losses and audible noise. Bundle conductors consist of several conductor cables connected by non-conducting spacers. For 220 kV lines, two-conductor bundles are usually used, for 380 kV lines usually three or even four. American Electric Power is building 765 kV lines using six conductors per phase in a bundle. Spacers must resist the forces due to wind, and magnetic forces during a short-circuit.

Bundle conductors are used to increase the amount of current that may be carried in a line. Due to the skin effect, ampacity of conductors is not proportional to cross section, for the larger sizes. Therefore, bundle conductors may carry more current for a given weight.

A bundle conductor results in lower reactance, compared to a single conductor. It reduces corona discharge loss at EHV (extra high voltage) and interference with communication systems. It also reduces voltage gradient in that range of voltage.

As a disadvantage, the bundle conductors have higher wind loading.

Circuits



Single 3-phase circuit carried by electricity pylon, with ground wire

A *single-circuit transmission line* carries conductors for only one circuit. For a three-phase system, this implies that each tower supports three conductors.



Typical double-circuit line

A *double-circuit transmission line* has two circuits. For three-phase systems, each tower supports and insulates six conductors. Single phase AC-powerlines as used for traction current have four conductors for two circuits. Usually both circuits operate at the same voltage.

In HVDC systems typically two conductors are carried per line, but rarely only one pole of the system is carried on a set of towers.

In some countries like Germany most powerlines with voltages above 100 kV are implemented as double, quadruple or in rare cases even hexuple powerline as rights of

way are rare. Sometimes all conductors are installed with the erection of the pylons; often some circuits are installed later. A disadvantage of double circuit transmission lines is that maintenance works can be more difficult, as either work in close proximity of high voltage or switch-off of 2 circuits is required. In case of failure, both systems can be affected.

The largest double-circuit transmission line is the Kita-Iwaki Powerline.

Ground wires

Overhead power lines are often equipped with a ground conductor (shield wire or overhead earth wire). A ground conductor is a conductor that is usually grounded (earthed) at the top of the supporting structure to minimise the likelihood of direct lightning strikes to the phase conductors. The ground wire is also a parallel path with the earth for fault currents in earthed neutral circuits. Very high-voltage transmission lines may have two ground conductors. These are either at the outermost ends of the highest cross beam, at two V-shaped mast points, or at a separate cross arm. Older lines may use surge arrestors every few spans in place of a shield wire; this configuration is typically found in the more rural areas of the United States. By protecting the line from lightning, the design of apparatus in substations is simplified due to lower stress on insulation. Shield wires on transmission lines may include optical fibers (OPGW), used for communication and control of the power system.

Medium-voltage distribution lines may have the grounded conductor strung below the phase conductors to provide some measure of protection against tall vehicles or equipment touching the energized line, as well as to provide a neutral line in Wye wired systems.

Insulated conductors

While overhead lines are usually bare conductors, rarely overhead insulated cables are used, usually for short distances (less than a kilometer). Insulated cables can be directly fastened to structures without insulating supports. An overhead line with bare conductors insulated by air is typically less costly than a cable with insulated conductors.

A more common approach is "covered" line wire. It is treated as bare cable, but often is safer for wildlife, as the insulation on the cables increases the likelihood of a large wing-span raptor to survive a brush with the lines, and reduces the overall danger of the lines slightly. These types of lines are often seen in the eastern United States and in heavily wooded areas, where tree-line contact is likely. The only pitfall is cost, as insulated wire is often costlier than its bare counterpart. Many utility companies implement covered line wire as jumper material where the wires are often closer to each other on the pole, such as an underground riser/Pothead, and on reclosers, cutouts and the like.

Low voltage



Aerial bundled cable in Old Coulsdon, Surrey

Low voltage overhead lines may use either bare conductors carried on glass or ceramic insulators or an aerial bundled cable system. The number of conductors may be anywhere between four (three phase plus a combined earth/neutral conductor - a TN-C earthing system) up to as many as six (three phase conductors, separate neutral and earth plus street lighting supplied by a common switch).

Train power

Overhead lines or overhead wires are used to transmit electrical energy to trams, trolleybuses or trains. Overhead line is designed on the principle of one or more overhead wires situated over rail tracks. Feeder stations at regular intervals along the overhead line supply power from the high voltage grid. For some cases low-frequency AC is used, and distributed by a special traction current network.

Further applications

Overhead lines are also occasionally used to supply transmitting antennas, especially for efficient transmission of long, medium and short waves. For this purpose a staggered array line is often used. Along a staggered array line the conductor cables for the supply of the earth net of the transmitting antenna are attached on the exterior of a ring, while the conductor inside the ring, is fastened to insulators leading to the high voltage standing feeder of the antenna.

Usage of area under overhead power lines

Use of the area below an overhead line is restricted because objects must not come too close to the energized conductors. Overhead lines and structures may shed ice, creating a hazard. Radio reception can be impaired under a power line, due both to shielding of a receiver antenna by the overhead conductors, and by partial discharge at insulators and sharp points of the conductors which creates radio noise.

In the area surrounding overhead lines it is dangerous to risk interference; e.g. flying kites or balloons, using ladders or operating machinery.

Overhead distribution and transmission lines near airfields are often marked on maps, and the lines themselves marked with conspicuous plastic reflectors, to warn pilots of the presence of conductors.

Construction of overhead power lines, especially in wilderness areas, may have significant environmental effects. Environmental studies for such projects may consider the effect of brush clearing, changed migration routes for migratory animals, possible access by predators and humans along transmission corridors, disturbances of fish habitat at stream crossings, and other effects.

History

The first transmission of electrical impulses over an extended distance was demonstrated on July 14, 1729 by the physicist Stephen Gray, in order to show that one can transfer electricity by that method. The demonstration used damp hemp cords suspended by silk threads (the low resistance of metallic conductors not being appreciated at the time).

However the first practical use of overhead lines was in the context of telegraphy. By 1837 experimental commercial telegraph systems ran as far as 13 miles (20 km). Electric power transmission was accomplished in 1882 with the first high voltage transmission between Munich and Miesbach. 1891 saw the construction of the first three-phase alternating current overhead line on the occasion of the International Electricity Exhibition in Frankfurt, between Lauffen and Frankfurt.

In 1912 the first 110 kV-overhead power line entered service followed by the first 220 kV-overhead power line in 1923. In the 1920s RWE AG built the first overhead line for this voltage and in 1926 built a Rhine crossing with the pylons of Voerde, two masts 138 meters high.

In Germany in 1957 the first 380 kV overhead power line was commissioned (between the transformer station and Rommerskirchen). In the same year the overhead line traversing of the Strait of Messina went into service in Italy, whose pylons served the Elbe crossing 1. This was used as the model for the building of the Elbe crossing 2 in the second half of the 1970s which saw the construction of the highest overhead line pylons of the world. Starting from 1967 in Russia, and also in the USA and Canada, overhead lines for voltage of 765 kV were built. In 1982 overhead power lines were built in Russia between Elektrostal and the power station at Ekibastuz, this was a three-phase alternating current line at 1150 kV (Powerline Ekibastuz-Kokshetau). In 1999, in Japan the first powerline designed for 1000 kV with 2 circuits were built, the Kita-Iwaki Powerline. In 2003 the building of the highest overhead line commenced in China, the Yangtze River Crossing.

Similar constructions

- Aerial cable
- Antenna (Some antennas for lower frequencies are similar to overhead power lines)
- Electric fence
- Overhead cable
- Overhead line
- Radio masts and towers
- Third rail

Chapter 8

Electrical Wiring

Electrical wiring in general refers to insulated conductors used to carry electricity, and associated devices. Here we, describes general aspects of electrical wiring as used to provide power in buildings and structures, commonly referred to as **building wiring**.

Wiring safety codes

Wiring safety codes are intended to protect people and buildings from electrical shock and fire hazards. Regulations may be established by city, county, provincial/state or national legislation, sometimes by adopting in amended form a model code produced by a technical standards-setting organization, or by a national standard electrical code.

Electrical codes arose in the 1880s with the commercial introduction of electrical power. Many conflicting standards existed for the selection of wire sizes and other design rules for electrical installations.

The first electrical codes in the United States originated in New York in 1881 to regulate installations of electric lighting. Since 1897 the U.S. National Fire Protection Association, a private nonprofit association formed by insurance companies, has published the National Electrical Code (NEC). States, counties or cities often include the NEC in their local building codes by reference along with local differences. The NEC is modified every three years. It is a consensus code considering suggestions from interested parties. The proposals are studied by committees of engineers, tradesmen, manufacturer representatives, fire fighters, and other invitees.

Since 1927, the Canadian Standards Association (CSA) has produced the Canadian *Safety Standard for Electrical Installations*, which is the basis for provincial electrical codes. The CSA also produces the Canadian Electrical Code, the 2006 edition of which references IEC 60364 (*Electrical Installations for Buildings*) and states that the code addresses the fundamental principles of electrical protection in Section 131. The Canadian code reprints Chapter 13 of IEC 60364, and it is interesting to note that there are no numerical criteria listed in that chapter whereby the adequacy of any electrical installation can be assessed.

Although the U.S. and Canadian national standards deal with the same physical phenomena and broadly similar objectives, they differ occasionally in technical detail. As

part of the North American Free Trade Agreement (NAFTA) program, U.S. and Canadian standards are slowly converging toward each other, in a process known as harmonization.

In European countries, an attempt has been made to harmonize national wiring standards in an IEC standard, IEC 60364 *Electrical Installations for Buildings*. Hence national standards follow an identical system of sections and chapters. However, this standard is not written in such language that it can readily be adapted as a national wiring code. Neither is it designed for field use by electrical tradesmen and inspectors for testing compliance with national wiring standards. National codes, such as the NEC or CSA C22.1, exemplify the common objectives of IEC 60364, and provide rules in a form that allows for guidance of those installing and inspecting electrical systems.

DKE - the German Commission for Electrical, Electronic and Information Technologies of DIN and VDE - is the German organisation responsible for the promulgation of electrical standards and safety specifications. DIN VDE 0100 is the German wiring regulations document harmonised with IEC 60364.

In the United Kingdom wiring installations are regulated by the Institution of Engineering and Technology *Requirements for Electrical Installations: IEE Wiring Regulations, BS 7671: 2008*, which are harmonised with IEC 60364. The previous edition (16th) was replaced by the current 17th Edition in January 2008. The 17th edition includes new sections for microgeneration and solar photovoltaic systems. The first edition was published in 1882.

AS/NZS 3000 is an Australian/New Zealand standard, commonly known as the "wiring rules," that specifies the requirements for the selection and installation of electrical equipment and the design and testing of such installations. The standard is a mandatory standard in both New Zealand and Australia; therefore, all electrical work covered by the standard must comply.

The international standard wire sizes are given in the IEC 60228 standard of the International Electrotechnical Commission. In North America, the American Wire Gauge is used.

Colour code

To enable wires to be easily and safely identified, all common wiring safety codes mandate a colour scheme for the insulation on power conductors. Many local rules and exceptions exist. Older installations vary in colour codes, and colours may shift with heat and age of insulation.

**Standard wire colours for FLEXIBLE cable
(e.g. Extension cords, power (line) cords and lamp cords)**

Region or Country	Phases	Neutral	Protective earth/ground
European Union (EU), Australia, South Africa (IEC 60446)	brown	blue	green/yellow
Australia, New Zealand (AS/NZS 3000:2007 3.8.1)	brown	light blue	green/yellow
United States, Canada	black (<i>brass</i>)	white (<i>silver</i>)	green (<i>green</i>)

**Standard wire colours for FIXED cable
(e.g. In-, On-, or Behind-the-wall wiring cables)**

Region or Country	Phases	Neutral	Protective earth/ground
European Union (EU) (IEC 60446) including UK from 31 March 2004	brown, black, grey	blue	green/yellow
UK prior to 31 March 2004	red, yellow, blue	black	green/yellow green (formerly) bare conductor, sleeved at terminations (formerly)
Australia	red	black	green/yellow (since about 1980) green (since about 1980) bare conductor, sleeved at terminations (formerly)
South Africa	red	black	green/yellow bare conductor, sleeved at

terminations

United States	black, red, blue (120/208/240V) <i>(brass)</i> brown, orange, yellow (277/480V)	white (120/208/240V) <i>(silver)</i> grey(277/480V)	green <i>(green)</i> bare conductor green/yellow (isolated ground)
Canada	red, black (120/208/240V) red, black, blue (600/347V)	white (120/208/240V) white (600/347V)	green <i>(green)</i> bare conductor green (isolated ground)

Notes:

Parenthesized colours in *italics* are used on metallic terminals.

"Green/yellow" means green with yellow stripe.

The colours in this table represent the most common and preferred standard colours for wiring; however others may be in use, especially in older installations.

The Canadian and American wiring standards are very similar with small differences, and have different operating voltages in ICI applications.

Wiring methods



Installing electrical wiring by cutting into the bricks of the building

Materials for wiring interior electrical systems in buildings vary depending on:

- Intended use and amount of power demand on the circuit
- Type of occupancy and size of the building
- National and local regulations
- Environment in which the wiring must operate.

Wiring systems in a single family home or duplex, for example, are simple, with relatively low power requirements, infrequent changes to the building structure and layout, usually with dry, moderate temperature, and noncorrosive environmental conditions. In a light commercial environment, more frequent wiring changes can be expected, large apparatus may be installed, and special conditions of heat or moisture may apply. Heavy industries have more demanding wiring requirements, such as very

large currents and higher voltages, frequent changes of equipment layout, corrosive, or wet or explosive atmospheres. In facilities that handle flammable gases or liquids, special rules may govern the installation and wiring of electrical equipment in hazardous areas.

Wires and cables are rated by the circuit voltage, temperature rating, and environmental conditions (moisture, sunlight, oil, chemicals) in which they can be used. A wire or cable has a voltage (to neutral) rating, and a maximum conductor surface temperature rating. The amount of current a cable or wire can safely carry depends on the installation conditions.

Early wiring methods

The very first interior power wiring systems used conductors that were bare or covered with cloth, which were secured by staples to the framing of the building or on running boards. Where conductors went through walls, they were protected with cloth tape. Splices were done similarly to telegraph connections, and soldered for security. Underground conductors were insulated with wrappings of cloth tape soaked in pitch, and laid in wooden troughs which were then buried. Such wiring systems were unsatisfactory because of the danger of electrocution and fire and the high labour cost for such installations.

Knob and tube



Knob-and-Tube wiring

The earliest standardized method of wiring in buildings, in common use in North America from about 1880 to the 1930s, was *knob and tube* (K&T) wiring: single conductors were run through cavities between the structural members in walls and ceilings, with ceramic tubes forming protective channels through joists and ceramic knobs attached to the structural members to provide air between the wire and the lumber and to support the wires. Since air was free to circulate over the wires, smaller conductors could be used than required in cables. By arranging wires on opposite sides of building structural members, some protection was afforded against short-circuits that can be caused by driving a nail into both conductors simultaneously. By the 1940s, the labour cost of installing two conductors rather than one cable resulted in a decline in new knob-and-tube installations.

Metal-sheathed wires

In the United Kingdom, an early form of insulated cable, introduced in 1896, consisted of two impregnated-paper-insulated conductors in an overall lead sheath. Joints were soldered, and special fittings were used for lamp holders and switches. These cables were similar to underground telegraph and telephone cables of the time. Paper-insulated cables proved unsuitable for interior wiring installations because very careful workmanship was required on the lead sheaths to ensure moisture did not affect the insulation.

A system later invented in the UK in 1908 employed vulcanized-rubber insulated wire enclosed in a strip metal sheath. The metal sheath was bonded to each metal wiring device to ensure continuity.

A system developed in Germany called *Kuhlo wire* used one, two, or three rubber-insulated wires in a brass or lead-coated iron sheet tube, with a crimped seam. The enclosure could also be used as a return conductor. Kuhlo wire could be run exposed on surfaces and painted, or embedded in plaster. Special outlet and junction boxes were made for lamps and switches, made either of porcelain or sheet steel. The crimped seam was not considered as watertight as the *Stannos* wire used in England, which had a soldered sheath.

A somewhat similar system called "concentric wiring" was introduced in the United States around 1905. In this system, an insulated copper wire was wrapped with copper tape which was then soldered, forming the grounded (return) conductor of the wiring system. The bare metal sheath, at earth potential, was considered safe to touch. While companies such as General Electric manufactured fittings for the system, and a few buildings were wired with it, it was never adopted into the US National Electrical Code. Drawbacks of the system were that special fittings were required, and that any defect in the connection of the sheath would result in the sheath becoming energized.

Other historical wiring methods

Other methods of securing wiring that are now obsolete include:

- Re-use of existing gas pipes for electric lighting. Insulated conductors were pulled into the pipes feeding gas lamps.
- Wood mouldings with grooves cut for single conductor wires, covered by a wooden cap strip. These were prohibited in North American electrical codes by 1928. Wooden moulding was also used to some degree in England, but was never permitted by German and Austrian rules.
- A system of flexible twin cords supported by glass or porcelain buttons was used near the turn of the 20th century in Europe, but was soon replaced by other methods.
- During the first years of the 20th century various patented forms of wiring system such as Bergman and Peschel tubing were used to protect wiring; these used very thin fibre tubes or metal tubes which were also used as return conductors.
- In Austria, wires were concealed by embedding a rubber tube in a groove in the wall, plastering over it and then removing the tube and pulling in wires in the cavity.

Metal moulding systems, with a flattened oval section consisting of a base strip and a snap-on cap channel, were more costly than open wiring or wooden moulding, but could be easily run on wall surfaces. Similar systems are still available today.

Cables



Wiring in extremely-wet conditions

Armoured cables with two rubber-insulated conductors in a flexible metal sheath were used as early as 1906, and were considered at the time a better method than open knob-and-tube wiring, although much more expensive.

The first polymer-insulated cables for building wiring were introduced in 1922. These were two or more solid copper wires, with rubber insulation, woven cotton cloth over each conductor for protection of the insulation, with an overall woven jacket, usually impregnated with tar as a protection from moisture. Waxed paper was used as a filler and separator.

Rubber-insulated cables become brittle over time because of exposure to oxygen, so they must be handled with care, and should be replaced during renovations. When switches, outlets or light fixtures are replaced, the mere act of tightening connections may cause insulation to flake off the conductors. Rubber was hard to separate from bare copper, so copper was tinned, causing slightly more resistance.



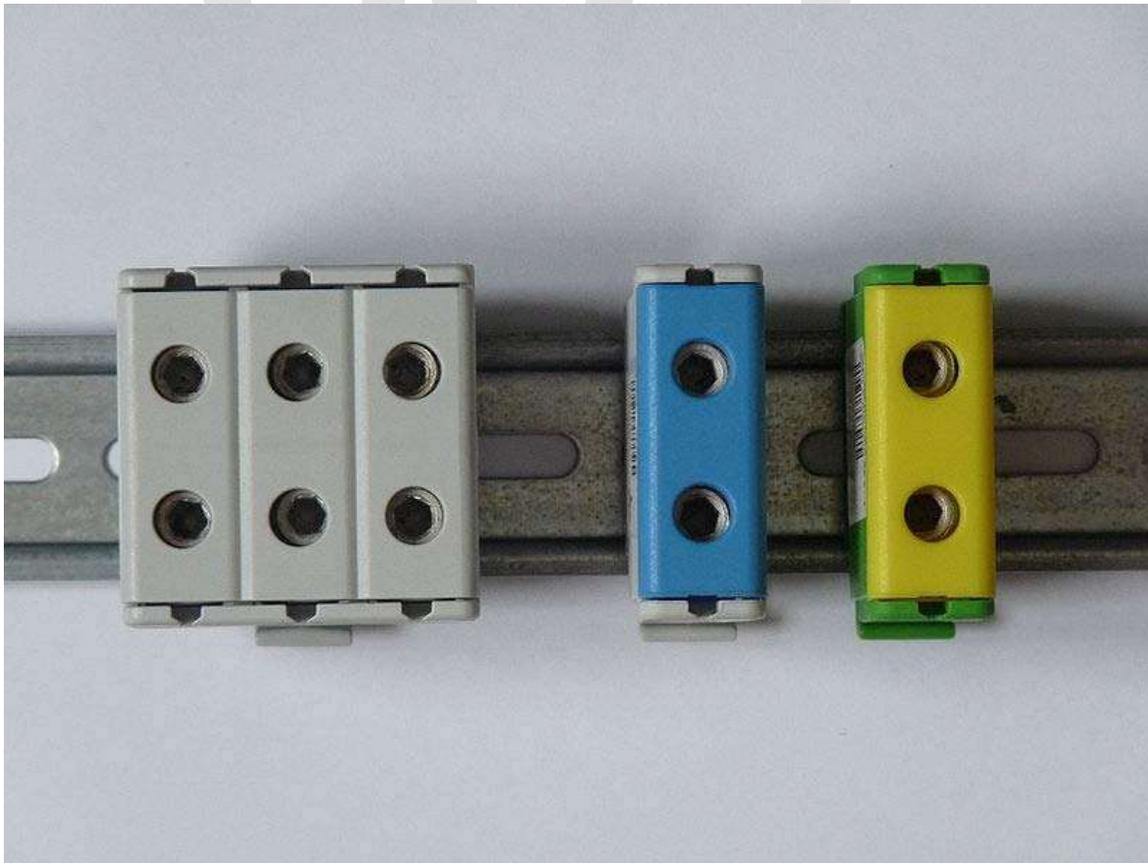
Three-phase copper cable TN-S 16mm² (5AWG) with PVC insulation

About 1950, PVC insulation and jackets were introduced, especially for residential wiring. About the same time, single conductors with a thinner PVC insulation and a thin nylon jacket became common.

The simplest form of cable has two insulated conductors twisted together to form a unit; such unjacketed cables with two or three conductors are used for low-voltage signal and control applications such as doorbell wiring. In North American practice, an overhead cable from a transformer on a power pole to a residential electrical service consists of three twisted (triplexed) wires, often with one being a bare copper wire (protective earth/ground) and the other two being insulated for the line voltage (hot/live wire and neutral wire).

Aluminium conductors

Aluminium wire was common in North American residential wiring from the late 1960s to mid 1970s due to the rising cost of copper. Because of its greater resistivity, aluminium wiring requires larger conductors than copper. For instance, instead of 14 AWG (American wire gauge) for most lighting circuits, aluminium wiring would be 12 AWG on a typical 15 ampere circuit, though local building codes may vary.



Terminal blocks for joining aluminium and copper conductors. The terminal blocks may be mounted on a DIN rail.

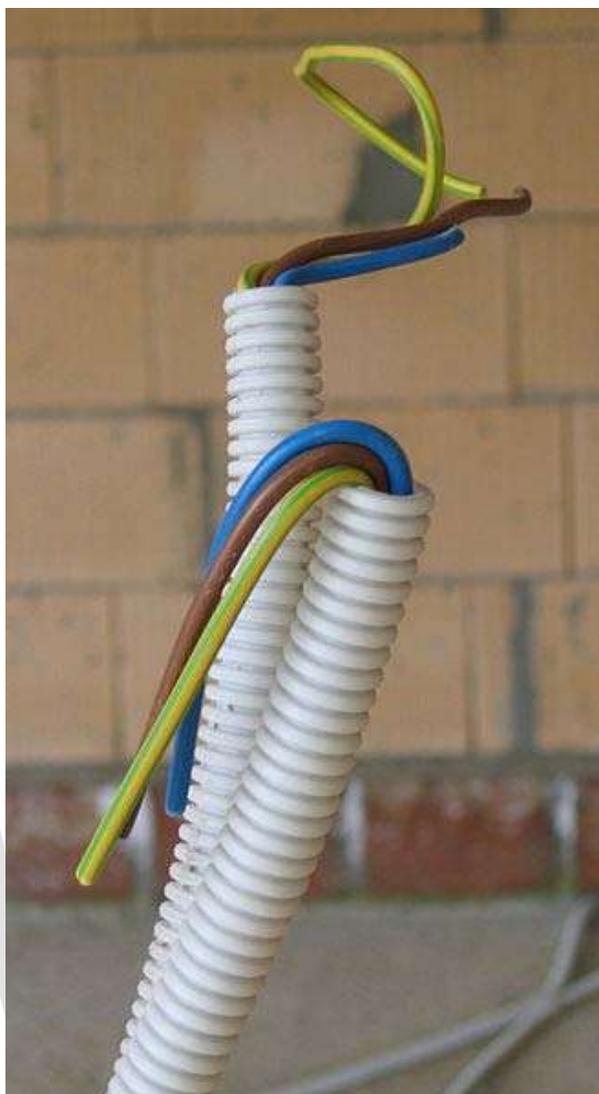
Aluminium conductors were originally used with wiring devices intended for copper wires. This can cause defective connections unless the aluminium was one of a special alloy, or all devices — breakers, switches, receptacles, splice connectors, i.e., wire nuts, etc. — were designed to address problems with junctions between dissimilar metals, oxidation on metal surfaces and mechanical effects that occur as different metals expand at different rates with increases in temperature. Unlike copper, aluminium has a tendency to cold-flow under pressure, so screw clamped connections may get loose over time. This can be mitigated by using spring-loaded connectors that apply constant pressure, applying high pressure cold joints in splices and termination fittings, and torquing the bolted connection. Unlike copper, aluminium forms an insulating oxide layer on the surface. This is sometimes addressed by coating aluminium wires with an antioxidant paste at joints, or applying a mechanical termination designed to break through the oxide layer during installation.

Because of improper design and installation, some junctions to wiring devices overheated under heavy current load and caused fires. Revised standards for wiring devices (such as the CO/ALR "copper-aluminium-revised" designation) were developed to reduce these problems. Nonetheless, aluminium wiring for residential use has acquired a poor reputation and has fallen out of favour.

Aluminium conductors are still used for power distribution and large feeder circuits, because they cost less than copper wiring, and weigh less, especially in the large sizes needed for heavy current loads. Aluminium conductors must be installed with compatible connectors.

Modern wiring materials

Modern nonmetallic sheathed cables (NMC), like (U.S. and Canadian) Type NM, consist of two to four wires covered with thermoplastic insulation and a bare wire for grounding (bonding) surrounded by a flexible plastic jacket. Some versions wrap the individual conductors in paper before the plastic jacket is applied. It is often called **Romex™** cable, since the first of its type was manufactured by Rome Cable Division of Cyprus Mines, Rome, New York. The trade name has been owned by Southwire since it purchased the electrical building wire assets of General Cable in 2001.



An electrical "3G" power cable found commonly in modern European houses. The cable consists of 3 wires (2 wires + 1 grounding in case if cable has "3G" name) and is double-insulated.

Rubber-like synthetic polymer insulation is used in industrial cables and power cables installed underground because of its superior moisture resistance.

Insulated cables are rated by their allowable operating voltage and their maximum operating temperature at the conductor surface. A cable may carry multiple usage ratings for applications, for example, one rating for dry installations and another when exposed to moisture or oil.

Generally, single conductor building wire in small sizes is solid wire, since the wiring is not required to be very flexible. Building wire conductors larger than 10 AWG (or about 6 mm²) are stranded for flexibility during installation, but not stranded enough to be flexible enough to use as appliance cord.

Cables for industrial, commercial, and apartment buildings may contain many insulated conductors in an overall jacket, with helical tape steel or aluminium armour, or steel wire armour, and perhaps as well an overall PVC or lead jacket for protection from moisture and physical damage. Cables intended for very flexible service or in marine applications may be protected by woven bronze wires. Power or communications cables (e.g., computer networking) that are routed in or through air-handling spaces (plenums) of office buildings are required under the model code to be either encased in metal conduit or rated for low flame and smoke production.

For some industrial uses in steel mills and similar hot environments, no organic material gives satisfactory service. Cables insulated with compressed mica flakes are sometimes used. Another form of high-temperature cable is a mineral insulated cable, with individual conductors placed within a copper tube, and the space filled with magnesium oxide powder. The whole assembly is drawn down to smaller sizes, thereby compressing the powder. Such cables have a certified fire resistance rating, are more costly than non-fire rated cable, and have little flexibility and are effectively rigid to the user of the cable.



Mineral insulated cables at a panel board

Because multiple conductors bundled in a cable cannot dissipate heat as easily as single insulated conductors, those circuits are always rated at a lower "ampacity". Tables in electrical safety codes give the maximum allowable current for a particular size of conductor, for the voltage and temperature rating at the surface of the conductor for a given physical environment, including the insulation type and thickness. The allowable

current will be different for wet or dry, for hot (attic) or cool (underground) locations. In a run of cable through several areas, the most severe area will determine the appropriate rating of the overall run.

Cables usually are secured by special fittings where they enter electrical apparatus; this may be a simple screw clamp for jacketed cables in a dry location, or a polymer-gasketed cable connector that mechanically engages the armour of an armoured cable and provides a water-resistant connection. Special cable fittings may be applied to prevent explosive gases from flowing in the interior of jacketed cables, where the cable passes through areas where inflammable gases are present. To prevent loosening of the connections of individual conductors of a cable, cables must be supported near their entrance to devices and at regular intervals through their length. In tall buildings special designs are required to support the conductors of vertical runs of cable. Usually, only one cable per fitting is allowed unless the fitting is otherwise rated.

Special cable constructions and termination techniques are required for cables installed in ocean-going vessels; in addition to electrical safety and fire safety, such cables may also be required to be pressure-resistant where they penetrate bulkheads of a ship.

Raceways



Electrical Conduit risers, seen inside fire-resistance rated shaft, as seen entering bottom of a firestop. The firestop is made of firestop mortar on top, rockwool on the bottom. Raceways are used to protect cables from damage.

Insulated wires may be run in one of several forms of a raceway between electrical devices. This may be a pipe, called a conduit, or in one of several varieties of metal (rigid steel or aluminum) or non-metallic (PVC or HDPE) tubing. Rectangular cross-section metal or PVC wire troughs (North America) or trunking (UK) may be used if many circuits are required. Wires run underground may be run in plastic tubing encased in concrete, but metal elbows may be used in severe pulls. Wiring in exposed areas, for example factory floors, may be run in cable trays or rectangular raceways having lids.

Where wiring, or raceways that hold the wiring, must traverse fire-resistance rated walls and floors, the openings are required by local building codes to be firestopped. In cases where the wiring has to be kept operational during an accidental fire, fireproofing must be applied to maintain circuit integrity in a manner to comply with a product's certification listing. The nature and thickness of any passive fire protection materials used in conjunction with wiring and raceways has a quantifiable impact upon the ampacity derating.



A cable tray can be used in stores and dwellings

Cable trays are used in industrial areas where many insulated cables are run together. Individual cables can exit the tray at any point, simplifying the wiring installation and

reducing the labour cost for installing new cables. Power cables may have fittings in the tray to maintain clearance between the conductors, but small control wiring is often installed without any intentional spacing between cables.

Since wires run in conduits or underground cannot dissipate heat as easily as in open air, and adjacent circuits contribute induced currents, wiring regulations give rules to establish the current capacity (ampacity).

Special fittings are used for wiring in potentially explosive atmospheres.

Bus bars, bus duct, cable bus

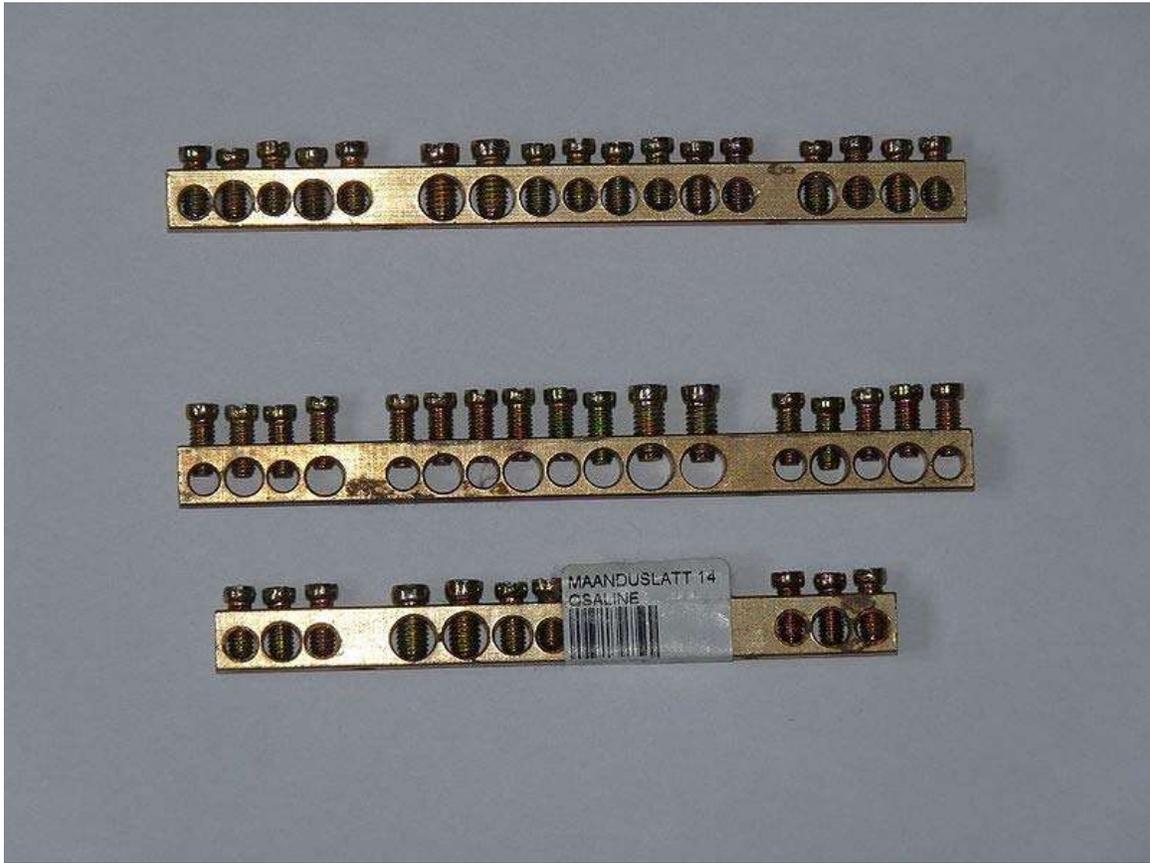


Topside of firestop with penetrants consisting of electrical conduit on the left and a bus duct on the right. The firestop consists of firestop mortar on top and rockwool on the bottom, for a 2 hour fire-resistance rating.

For very heavy currents in electrical apparatus, and for heavy currents distributed through a building, bus bars can be used. Each live conductor of such a system is a rigid piece of copper or aluminium, usually in flat bars (but sometimes as tubing or other shapes). Open bus bars are never used in publicly accessible areas, although they are used in manufacturing plants and power company switch yards to gain the benefit of air cooling. A variation is to use heavy cables, especially where it is desirable to transpose or "roll" phases.

In industrial applications, conductor bars are assembled with insulators in grounded enclosures. This assembly, known as bus duct or busway, can be used for connections to large switchgear or for bringing the main power feed into a building. A form of bus duct known as plug-in bus is used to distribute power down the length of a building; it is constructed to allow tap-off switches or motor controllers to be installed at definite places

along the bus. The big advantage of this scheme is the ability to remove or add a branch circuit without removing voltage from the whole duct.



Busbars for distributing PE (ground)

Bus ducts may have all phase conductors in the same enclosure (non-isolated bus), or may have each conductor separated by a grounded barrier from the adjacent phases (segregated bus). For conducting large currents between devices, a cable bus is used. For very large currents in generating stations or substations, where it is difficult to provide circuit protection, an isolated-phase bus is used. Each phase of the circuit is run in a separate grounded metal enclosure. The only fault possible is a phase-to-ground fault, since the enclosures are separated. This type of bus can be rated up to 50,000 amperes and up to hundreds of kilovolts (during normal service, not just for faults), but is not used for building wiring in the conventional sense.

Electrical panels



Electrical panels in an electrical service room at St. Mary's Pulp and Paper, Sault Ste. Marie, Ontario, Canada, April 1996

Electrical panels, cables and firestops in an electrical service room at St. Mary's Pulp and Paper, a paper mill in Sault Ste. Marie, Ontario, Canada.

Electrical panels are easily accessible junction boxes used to reroute and switch electrical services.

Chapter 9

Submarine Power Cable

Submarine power cables are major transmission cables for carrying electric power below the surface of the water. These are called "submarine" because they usually carry electric power beneath salt water (arms of the ocean, seas, straits, etc.) but it is also possible to use submarine power cables beneath fresh water (large lakes and rivers). Examples of the latter exist that connect the mainland with large islands in the St. Lawrence River.

Design technologies

The majority of submarine power cables use high-voltage direct current (HVDC) electric power transmission. This is a form of power transmission that was favored by Thomas Edison long ago, but mostly rejected in the late 19th century in favor of alternating-current (AC) transmission. This is the kind of electricity that is now used to power almost everything that is significant. However, high-voltage alternating-current (HVAC) power lines are sometimes difficult to use, because the electromagnetic interactions between the current and the metal casing of the cable can drive up voltages to unusable peaks - damaging insulation and causing many other problems.) However, there are several significant engineering advantages in using HVDC to transmit large amounts of electric power underwater. (what are the advantages?)

Direct-current transmission has also undergone a modest revival over dry land, over long distances, because in this case its power losses (due to waste heat) are smaller, and its current flows are easier to control.

A DC power-transmission system can use the earth (including seafloor) and seawater as the return path for current. However, this method cannot always be used because of deleterious ecological effects of electrochemical reactions below ground and where the electrical conductors are connected to the ground.

The overall length of AC submarine cables is restricted by the capacitance between their active electric conductors and their surrounding metallic shields. If the cable were to be made long enough, the reactive power produced by an AC cable would take up the entire current carrying capacity of the conductor, so no usable power would be transmitted. Therefore, for transmission of large amounts of electric power via long submarine cables,

DC transmission is nearly-always preferable over AC transmission, because DC cables have no such effect as mentioned above.

Operational submarine power cables

Alternating current cables

Alternating-current (AC) submarine cable systems for transmitting lower amounts of three phase electric power can be constructed with three-core cables in which all three insulated conductors are placed into a single underwater cable. Most offshore-to-shore wind-farm cables are constructed this way.

For larger amounts of transmitted power, the AC systems are composed of three separate single-core underwater cables, each containing just one insulated conductor and carrying one phase of the three-phase electric current. A fourth identical cable is often added in parallel with the other three, simply as a spare in case one of the three primary cables is damaged and needs to be replaced. This damage can happen, for example, from a ship's anchor carelessly dropped onto it. The fourth cable can substitute for any one of the other three, given the proper (and complicated) electrical switching system.

- Mainland British Columbia to Nelson Island to Texada Island to Vancouver Island, the destination of the power. This is a high-capacity 500 kilovolt (kV) three-phase system.
- Mainland Sweden to Bornholm Island, Denmark (110 kilovolts, but some sources state 72 kV).
- Under the Strait of Messina, connecting southern tip of the mainland of Italy with the large island of Sicily (380 kV). This submarine cable replaced an earlier, and very long overhead line crossing (the "Pylons of Messina")
- Negros Island to Panay Island, in the Philippines (138 kV)

Direct current cables

- Baltic-Cable - between Germany and Sweden beneath the Baltic Sea
- Basslink - between the mainland State of Victoria and the island of Tasmania, Australia, 500 kilovolts (kV), with a length of 290 kilometers beneath the Bass Strait
- BritNed - between the Netherlands and Great Britain beneath the North Sea
- Cross Sound Cable - between Long Island, New York, and the State of Connecticut beneath Long Island Sound
- Estlink - between northern Estonia and southern Finland beneath the Gulf of Finland
- Fenno-Skan - between Sweden and Finland beneath the Baltic Sea
- HVDC Cross-Channel - very high power cable between the French mainland and the island of Great Britain beneath the English Channel

- HVDC Gotland - the first HVDC submarine power cable (non-experimental) - between the Swedish mainland and the Swedish island of Gotland beneath the Baltic Sea
- HVDC Inter-Island - between the power-rich South Island (much hydroelectric power) of New Zealand and the more-populous North Island beneath the Cook Strait
- HVDC Italy-Corsica-Sardinia (SACOI) - between the Italian mainland, the Italian island of Sardinia, and its neighboring French island of Corsica beneath the Mediterranean Sea
- HVDC Italy-Greece - between Italy and Greece beneath the Adriatic Sea
- HVDC Leyte - Luzon - between Leyte Island and Luzon in the Philippines, beneath the Pacific Ocean
- HVDC Moyle - connecting Scotland with Northern Ireland within the United Kingdom, and thence to the Republic of Ireland, beneath the Irish Sea
- HVDC Vancouver Island - between Vancouver Island and the mainland of the Province of British Columbia, beneath the Strait of Juan de Fuca
- Japanese Home Islands
- Kontek - between Germany and Denmark beneath the Baltic Sea
- Konti-Skan - between Sweden and Denmark beneath the Baltic Sea
- Neptune Cable - between the State of New Jersey and Long Island, New York - 64 miles beneath the Atlantic Ocean
- Swepol - between Poland and Sweden beneath the Baltic Sea

Longest

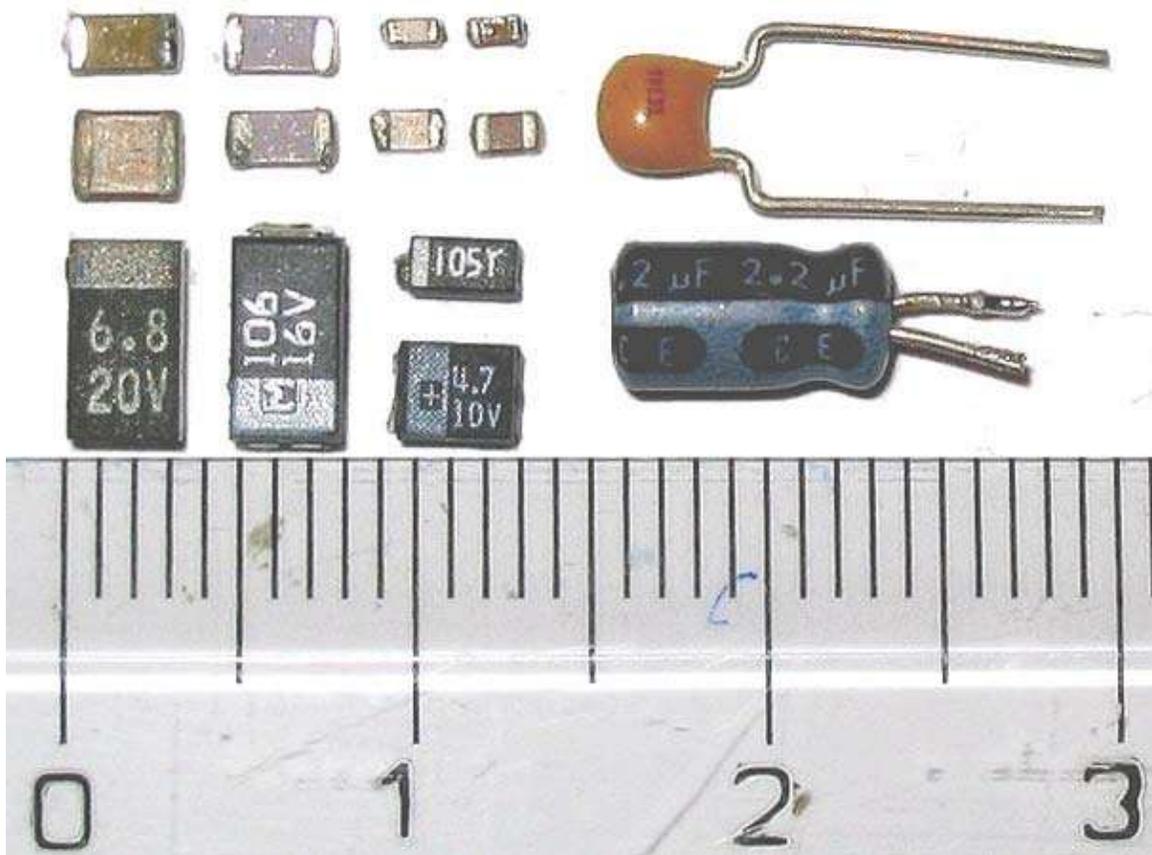
- NorNed (between Eemshaven, Netherlands and Fedaa, Norway), HVDC, 700 MW, 580 km (360 mi)

Proposed submarine power cables

- Champlain Hudson Power Express, 335-mile line. The Transmission Developers Company of Toronto, Ontario, is proposing "to use the [Hudson River] for the most ambitious underwater transmission project yet. Beginning south of Montreal, a 335-mile line would run along the bottom of Lake Champlain, [and then] down the bed of the Hudson all the way to New York City."
- Power Bridge, Hawaii
- Power Bridge, State of Maine
- Puerto Rico to the Virgin Islands
- 400 kV HVDC India to Sri Lanka
- Atlantic Wind Connection between Delaware and New Jersey, potentially between Virginia and New York
- 100 megawatts 165 km Canadian province of Newfoundland and Labrador and province of Nova Scotia
- 200 megawatts 95 km Magħtab (Malta) and Marina the Ragusa (Sicily)

Chapter 10

Capacitor



Modern capacitors, by a cm rule



A typical electrolytic capacitor

A **capacitor** (formerly known as **condenser**) is a passive electronic component consisting of a pair of conductors separated by a dielectric (insulator). When there is a potential difference (voltage) across the conductors, a static electric field develops in the dielectric that stores energy and produces a mechanical force between the conductors. An ideal capacitor is characterized by a single constant value, capacitance, measured in farads. This is the ratio of the electric charge on each conductor to the potential difference between them.

Capacitors are widely used in electronic circuits for blocking direct current while allowing alternating current to pass, in filter networks, for smoothing the output of power supplies, in the resonant circuits that tune radios to particular frequencies and for many other purposes.

The effect is greatest when there is a narrow separation between large areas of conductor, hence capacitor conductors are often called "plates", referring to an early means of construction. In practice the dielectric between the plates passes a small amount of leakage current and also has an electric field strength limit, resulting in a breakdown voltage, while the conductors and leads introduce an undesired inductance and resistance.

History



Battery of four Leyden jars in Museum Boerhaave, Leiden, the Netherlands

In October 1745, Ewald Georg von Kleist of Pomerania in Germany found that charge could be stored by connecting a high voltage electrostatic generator by a wire to a volume of water in a hand-held glass jar. Von Kleist's hand and the water acted as conductors and the jar as a dielectric (although details of the mechanism were incorrectly identified at the time). Von Kleist found, after removing the generator, that touching the wire resulted in a painful spark. In a letter describing the experiment, he said "I would not take a second shock for the kingdom of France." The following year, the Dutch physicist Pieter van Musschenbroek invented a similar capacitor, which was named the Leyden jar, after the University of Leiden where he worked.

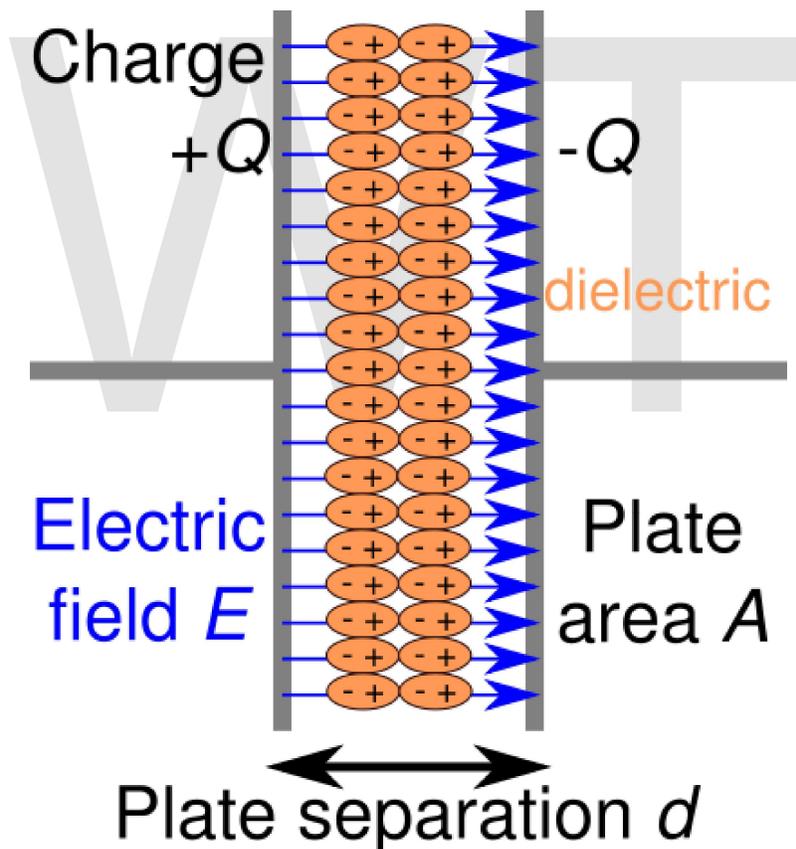
Daniel Galvani was the first to combine several jars in parallel into a "battery" to increase the charge storage capacity. Benjamin Franklin investigated the Leyden jar and "proved" that the charge was stored on the glass, not in the water as others had assumed. He also adopted the term "battery", (denoting the increasing of power with a row of similar units as in a battery of cannon), subsequently applied to clusters of electrochemical cells. Leyden jars were later made by coating the inside and outside of jars with metal foil,

leaving a space at the mouth to prevent arcing between the foils. The earliest unit of capacitance was the 'jar', equivalent to about 1 nanofarad.

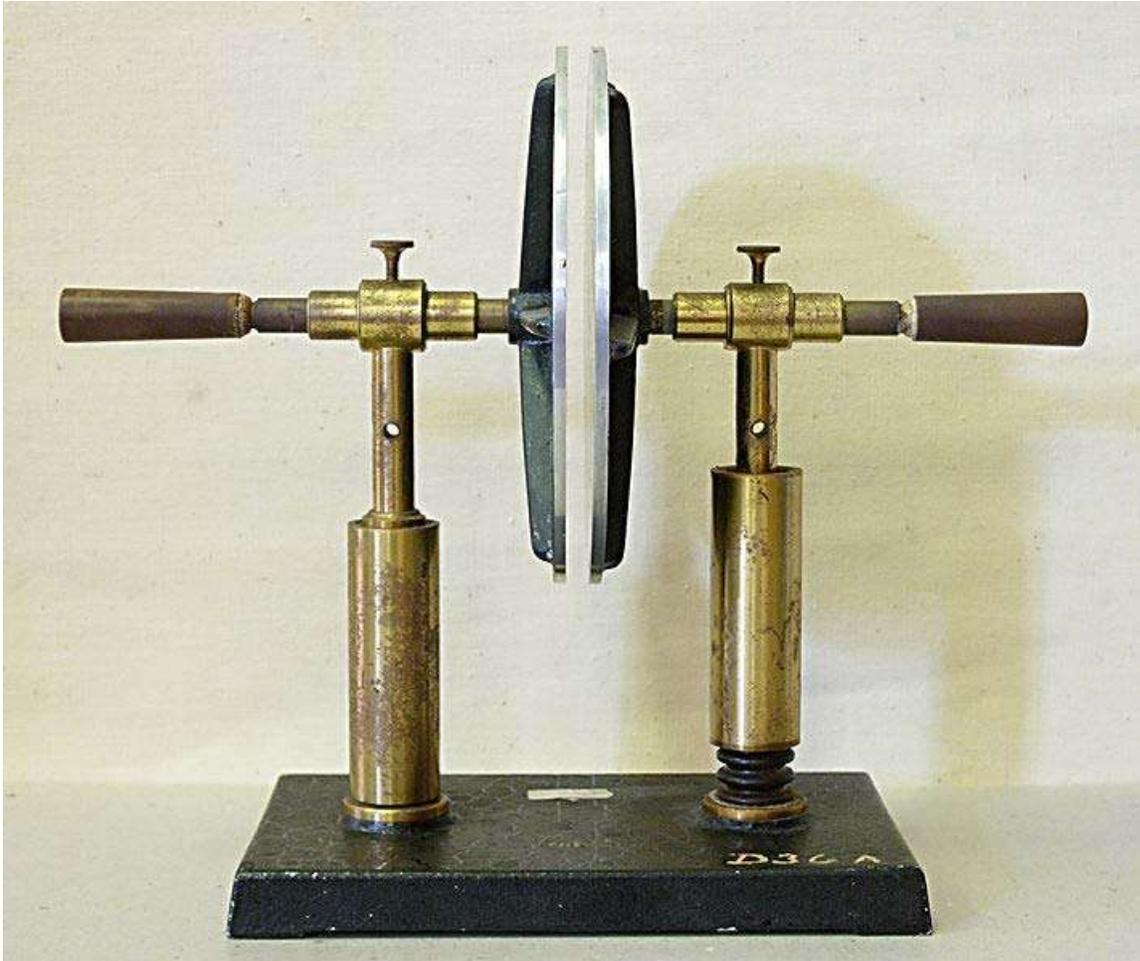
Leyden jars or more powerful devices employing flat glass plates alternating with foil conductors were used exclusively up until about 1900, when the invention of wireless (radio) created a demand for standard capacitors, and the steady move to higher frequencies required capacitors with lower inductance. A more compact construction began to be used of a flexible dielectric sheet such as oiled paper sandwiched between sheets of metal foil, rolled or folded into a small package.

Early capacitors were also known as *condensers*, a term that is still occasionally used today. The term was first used for this purpose by Alessandro Volta in 1782, with reference to the device's ability to store a higher density of electric charge than a normal isolated conductor.

Theory of operation



Charge separation in a parallel-plate capacitor causes an internal electric field. A dielectric (orange) reduces the field and increases the capacitance.



A simple demonstration of a parallel-plate capacitor

A capacitor consists of two conductors separated by a non-conductive region called the dielectric medium though it may be a vacuum or a semiconductor depletion region chemically identical to the conductors. A capacitor is assumed to be self-contained and isolated, with no net electric charge and no influence from any external electric field. The conductors thus hold equal and opposite charges on their facing surfaces, and the dielectric develops an electric field. In SI units, a capacitance of one farad means that one coulomb of charge on each conductor causes a voltage of one volt across the device.

The capacitor is a reasonably general model for electric fields within electric circuits. An ideal capacitor is wholly characterized by a constant capacitance C , defined as the ratio of charge $\pm Q$ on each conductor to the voltage V between them:

$$C = \frac{Q}{V}$$

Sometimes charge build-up affects the capacitor mechanically, causing its capacitance to vary. In this case, capacitance is defined in terms of incremental changes:

$$C = \frac{dq}{dv}$$

Energy storage

Work must be done by an external influence to "move" charge between the conductors in a capacitor. When the external influence is removed the charge separation persists in the electric field and energy is stored to be released when the charge is allowed to return to its equilibrium position. The work done in establishing the electric field, and hence the amount of energy stored, is given by:

$$W = \int_{q=0}^Q V dq = \int_{q=0}^Q \frac{q}{C} dq = \frac{1}{2} \frac{Q^2}{C} = \frac{1}{2} CV^2 = \frac{1}{2} VQ.$$

Current-voltage relation

The current $i(t)$ through any component in an electric circuit is defined as the rate of flow of a charge $q(t)$ passing through it, but actual charges, electrons, cannot pass through the dielectric layer of a capacitor, rather an electron accumulates on the negative plate for each one that leaves the positive plate, resulting in an electron depletion and consequent positive charge on one electrode that is equal and opposite to the accumulated negative charge on the other. Thus the charge on the electrodes is equal to the integral of the current as well as proportional to the voltage as discussed above. As with any antiderivative, a constant of integration is added to represent the initial voltage $v(t_0)$. This is the integral form of the capacitor equation,

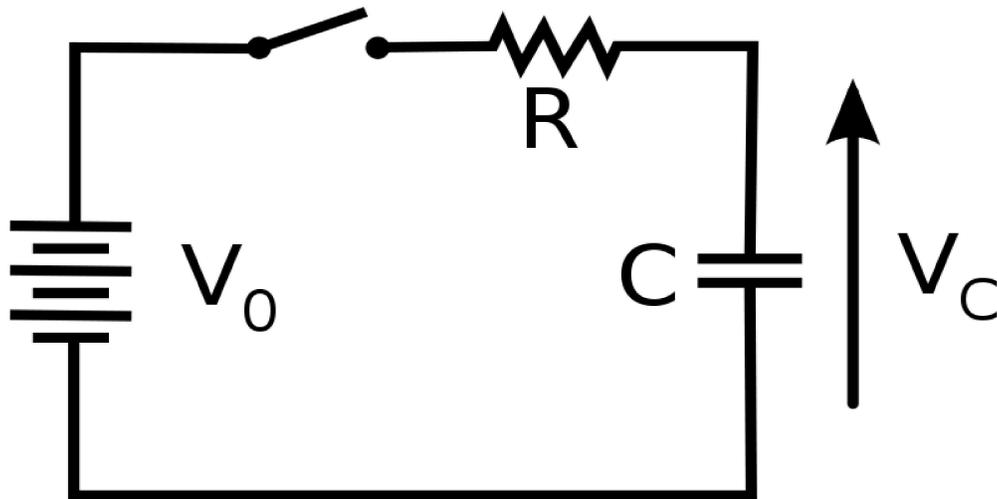
$$v(t) = \frac{q(t)}{C} = \frac{1}{C} \int_{t_0}^t i(\tau) d\tau + v(t_0)$$

Taking the derivative of this, and multiplying by C , yields the derivative form,

$$i(t) = \frac{dq(t)}{dt} = C \frac{dv(t)}{dt}$$

The dual of the capacitor is the inductor, which stores energy in the magnetic field rather than the electric field. Its current-voltage relation is obtained by exchanging current and voltage in the capacitor equations and replacing C with the inductance L .

DC circuits



A simple resistor-capacitor circuit demonstrates charging of a capacitor

A series circuit containing only a resistor, a capacitor, a switch and a constant DC source of voltage V_0 is known as a *charging circuit*. If the capacitor is initially uncharged while the switch is open, and the switch is closed at $t = 0$, it follows from Kirchhoff's voltage law that

$$V_0 = v_{\text{resistor}}(t) + v_{\text{capacitor}}(t) = i(t)R + \frac{1}{C} \int_0^t i(\tau) d\tau.$$

Taking the derivative and multiplying by C , gives a first-order differential equation,

$$RC \frac{di(t)}{dt} + i(t) = 0.$$

At $t = 0$, the voltage across the capacitor is zero and the voltage across the resistor is V_0 . The initial current is then $i(0) = V_0/R$. With this assumption, the differential equation yields

$$i(t) = \frac{V_0}{R} e^{-t/\tau_0}$$
$$v(t) = V_0 \left(1 - e^{-t/\tau_0} \right),$$

where $\tau_0 = RC$ is the *time constant* of the system.

As the capacitor reaches equilibrium with the source voltage, the voltage across the resistor and the current through the entire circuit decay exponentially. The case of

discharging a charged capacitor likewise demonstrates exponential decay, but with the initial capacitor voltage replacing V_0 and the final voltage being zero.

AC circuits

Impedance, the vector sum of reactance and resistance, describes the phase difference and the ratio of amplitudes between sinusoidally varying voltage and sinusoidally varying current at a given frequency. Fourier analysis allows any signal to be constructed from a spectrum of frequencies, whence the circuit's reaction to the various frequencies may be found. The reactance and impedance of a capacitor are respectively

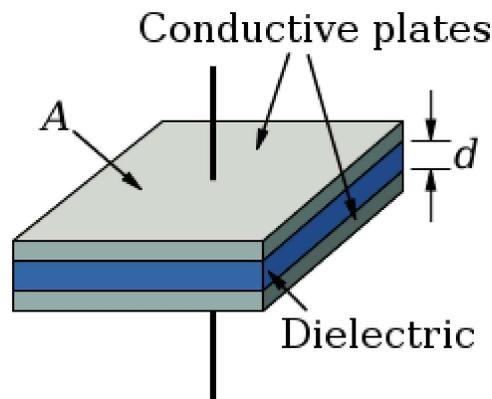
$$X = -\frac{1}{\omega C} = -\frac{1}{2\pi f C}$$
$$Z = \frac{1}{j\omega C} = -\frac{j}{\omega C} = -\frac{j}{2\pi f C}$$

where j is the imaginary unit and ω is the angular velocity of the sinusoidal signal. The $-j$ phase indicates that the AC voltage $V = ZI$ lags the AC current by 90° : the positive current phase corresponds to increasing voltage as the capacitor charges; zero current corresponds to instantaneous constant voltage, etc.

Note that impedance decreases with increasing capacitance and increasing frequency. This implies that a higher-frequency signal or a larger capacitor results in a lower voltage amplitude per current amplitude—an AC "short circuit" or AC coupling. Conversely, for very low frequencies, the reactance will be high, so that a capacitor is nearly an open circuit in AC analysis—those frequencies have been "filtered out".

Capacitors are different from resistors and inductors in that the impedance is *inversely* proportional to the defining characteristic, i.e. capacitance.

Parallel plate model



Dielectric is placed between two conducting plates, each of area A and with a separation of d .

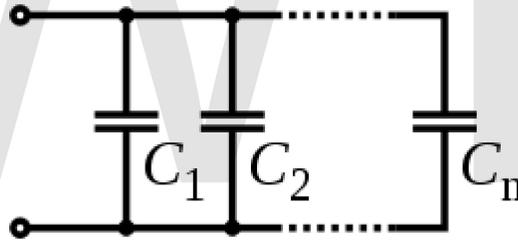
The simplest capacitor consists of two parallel conductive plates separated by a dielectric with permittivity ϵ (such as air). The model may also be used to make qualitative predictions for other device geometries. The plates are considered to extend uniformly over an area A and a charge density $\pm\rho = \pm Q/A$ exists on their surface. Assuming that the width of the plates is much greater than their separation d , the electric field near the centre of the device will be uniform with the magnitude $E = \rho/\epsilon$. The voltage is defined as the line integral of the electric field between the plates

$$V = \int_0^d E dz = \int_0^d \frac{\rho}{\epsilon} dz = \frac{\rho d}{\epsilon} = \frac{Qd}{\epsilon A}.$$

Solving this for $C = Q/V$ reveals that capacitance increases with area and decreases with separation

$$C = \frac{\epsilon A}{d}.$$

The capacitance is therefore greatest in devices made from materials with a high permittivity.



Several capacitors in parallel

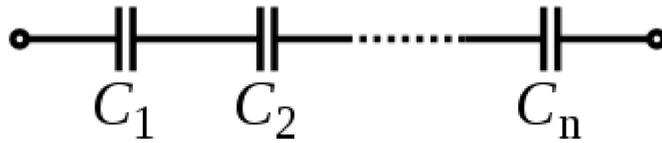
Networks

For capacitors in parallel

Capacitors in a parallel configuration each have the same applied voltage. Their capacitances add up. Charge is apportioned among them by size. Using the schematic diagram to visualize parallel plates, it is apparent that each capacitor contributes to the total surface area.

$$C_{eq} = C_1 + C_2 + \dots + C_n$$

For capacitors in series



Several capacitors in series.

Connected in series, the schematic diagram reveals that the separation distance, not the plate area, adds up. The capacitors each store instantaneous charge build-up equal to that of every other capacitor in the series. The total voltage difference from end to end is apportioned to each capacitor according to the inverse of its capacitance. The entire series acts as a capacitor *smaller* than any of its components.

$$\frac{1}{C_{eq}} = \frac{1}{C_1} + \frac{1}{C_2} + \dots + \frac{1}{C_n}$$

Capacitors are combined in series to achieve a higher working voltage, for example for smoothing a high voltage power supply. The voltage ratings, which are based on plate separation, add up. In such an application, several series connections may in turn be connected in parallel, forming a matrix. The goal is to maximize the energy storage utility of each capacitor without overloading it. Series connection is also used to adapt electrolytic capacitors for AC use.

Non-ideal behavior

Capacitors deviate from the ideal capacitor equation in a number of ways. Some of these, such as leakage current and parasitic effects are linear, or can be assumed to be linear, and can be dealt with by adding virtual components to the equivalent circuit of the capacitor. The usual methods of network analysis can then be applied. In other cases, such as with breakdown voltage, the effect is non-linear and normal (i.e., linear) network analysis cannot be used, the effect must be dealt with separately. There is yet another group, which may be linear but invalidate the assumption in the analysis that capacitance is a constant. Such an example is temperature dependence.

Breakdown voltage



High voltage dielectric breakdown within a block of plexiglas

The **breakdown voltage** of an insulator is the minimum voltage that causes a portion of an insulator to become electrically conductive.

The **breakdown voltage** of a diode is the minimum *reverse* voltage to make the diode conduct in reverse. Some devices (such as TRIACs) also have a *forward breakdown voltage*.

In Detail

Insulators

Breakdown voltage is a characteristic of an insulator that defines the maximum voltage difference that can be applied across the material before the insulator collapses and conducts. In solid insulating materials, this usually creates a weakened path within the

material by creating permanent molecular or physical changes by the sudden current. Within rarefied gases found in certain types of lamps, **breakdown voltage** is also sometimes called the "striking voltage".

The breakdown voltage of a material is not a definite value because it is a form of failure and there is a statistical probability whether the material will fail at a given voltage. When a value is given it is usually the mean breakdown voltage of a large sample. Another term is also 'withstand voltage' where the probability of failure at a given voltage is so low it is considered, when designing insulation, that the material will not fail at this voltage.

Two different breakdown voltage measurements of a material are the AC and impulse breakdown voltages. The AC voltage is the line frequency of the mains (either 50 or 60 Hz depending on where you live). The impulse breakdown voltage is simulating lightning strikes, and usually uses a 1.2 microsecond rise for the wave to reach 90% amplitude then drops back down to 50% amplitude after 50 microseconds.

Two technical standards governing performing these tests are ASTM D1816 and ASTM D3300 published by ASTM.

Breakdown in vacuum

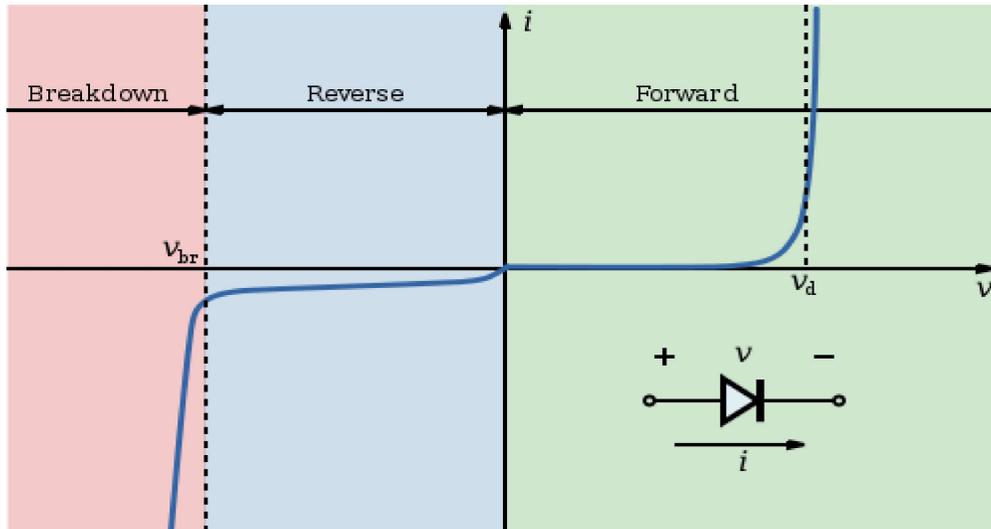
In standard conditions at atmospheric pressure, gas serves as an excellent insulator, requiring the application of a significant voltage before breaking down (e.g. lightning). In partial vacuum, this breakdown potential may decrease to an extent that two uninsulated surfaces with different potentials might induce the electrical breakdown of the surrounding gas. This has some useful applications in industry (e.g. the production of microprocessors) but in other situations may damage an apparatus, as breakdown is analogous to a short circuit.

The breakdown voltage in a partial vacuum is represented as:

$$V_b = \frac{Bpd}{\ln Apd - \ln\left(1 + \frac{1}{\gamma_{se}}\right)}$$

where V_b is the breakdown potential in volts DC, A and B are constants that depend on the surrounding gas, p represents the pressure of the surrounding gas, d represents the distance in centimetres between the electrodes, and γ_{se} represents the Secondary Electron Emission Coefficient.

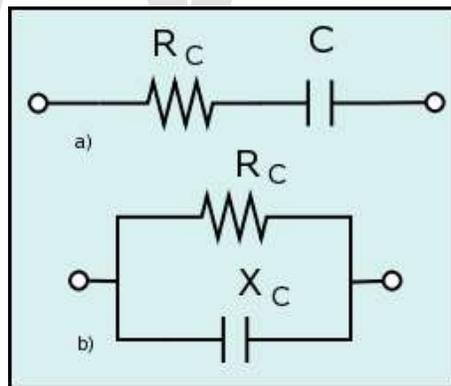
Diodes



Diode I-V diagram

Breakdown voltage is a parameter of a diode that defines the largest reverse voltage that can be applied without causing an exponential increase in the current in the diode. As long as the current is limited, exceeding the breakdown voltage of a diode does no harm to the diode. In fact, Zener diodes are essentially just heavily doped normal diodes that exploit the breakdown voltage of a diode to provide regulation of voltage levels.

Equivalent circuit



Two equivalent circuits of a real capacitor

An ideal capacitor only stores and releases electrical energy, without dissipating any. In reality, all capacitors have imperfections within the capacitor's material that create resistance. This is specified as the *equivalent series resistance* or **ESR** of a component. This adds a real component to the impedance:

$$R_C = Z + R_{ESR} = \frac{1}{j\omega C} + R_{ESR}$$

As frequency approaches infinity, the capacitive impedance (or reactance) approaches zero and the ESR becomes significant. As the reactance becomes negligible, power dissipation approaches $P_{RMS} = V_{RMS}^2 / R_{ESR}$.

Similarly to ESR, the capacitor's leads add *equivalent series inductance* or **ESL** to the component. This is usually significant only at relatively high frequencies. As inductive reactance is positive and increases with frequency, above a certain frequency capacitance will be canceled by inductance. High frequency engineering involves accounting for the inductance of all connections and components.

If the conductors are separated by a material with a small conductivity rather than a perfect dielectric, then a small leakage current flows directly between them. The capacitor therefore has a finite parallel resistance, and slowly discharges over time (time may vary greatly depending on the capacitor material and quality).

Ripple current

Ripple current is the AC component of an applied source (often a switched-mode power supply) whose frequency may be constant or varying. Certain types of capacitors, such as electrolytic tantalum capacitors, usually have a rating for maximum ripple current (both in frequency and magnitude). This ripple current can cause damaging heat to be generated within the capacitor due to the current flow across resistive imperfections in the materials used within the capacitor, more commonly referred to as equivalent series resistance (ESR). For example electrolytic tantalum capacitors are limited by ripple current and generally have the highest ESR ratings in the capacitor family, while ceramic capacitors generally have no ripple current limitation and have some of the lowest ESR ratings.

Capacitance instability

The capacitance of certain capacitors decreases as the component ages. In ceramic capacitors, this is caused by degradation of the dielectric. The type of dielectric and the ambient operating and storage temperatures are the most significant aging factors, while the operating voltage has a smaller effect. The aging process may be reversed by heating the component above the Curie point. Aging is fastest near the beginning of life of the component, and the device stabilizes over time. Electrolytic capacitors age as the electrolyte evaporates. In contrast with ceramic capacitors, this occurs towards the end of life of the component.

Temperature dependence of capacitance is usually expressed in parts per million (ppm) per °C. It can usually be taken as a broadly linear function but can be noticeably non-linear at the temperature extremes. The temperature coefficient can be either positive or negative, sometimes even amongst different samples of the same type. In other words, the spread in the range of temperature coefficients can encompass zero.

Capacitors, especially ceramic capacitors, and older designs such as paper capacitors, can absorb sound waves resulting in a microphonic effect. Vibration moves the plates, causing the capacitance to vary, in turn inducing AC current. Some dielectrics also generate piezoelectricity. The resulting interference is especially problematic in audio applications, potentially causing feedback or unintended recording. In the reverse microphonic effect, the varying electric field between the capacitor plates exerts a physical force, moving them as a speaker. This can generate audible sound, but drains energy and stresses the dielectric and the electrolyte, if any.

Capacitor markings

Most capacitors have numbers printed on their bodies to indicate their electrical characteristics. Larger capacitors like electrolytics usually display the actual capacitance together with the unit (for example, **220 μ F**). Smaller capacitors like ceramics, however, use a shorthand consisting of three numbers and a letter, where the numbers show the capacitance in pF (calculated as $XY \times 10^Z$ for the numbers XYZ) and the letter indicates the tolerance (J, K or M for $\pm 5\%$, $\pm 10\%$ and $\pm 20\%$ respectively).

Additionally, the capacitor may show its working voltage, temperature and other relevant characteristics.

Example

A capacitor with the text **473K 330V** on its body has a capacitance of 47×10^3 pF = 47 nF ($\pm 10\%$) with a working voltage of 330 V.

Hazards and safety

Capacitors may retain a charge long after power is removed from a circuit; this charge can cause dangerous or even potentially fatal shocks or damage connected equipment. For example, even a seemingly innocuous device such as a disposable camera flash unit powered by a 1.5 volt AA battery contains a capacitor which may be charged to over 300 volts. This is easily capable of delivering a shock. Service procedures for electronic devices usually include instructions to discharge large or high-voltage capacitors. Capacitors may also have built-in discharge resistors to dissipate stored energy to a safe level within a few seconds after power is removed. High-voltage capacitors are stored with the terminals shorted, as protection from potentially dangerous voltages due to dielectric absorption.

Some old, large oil-filled capacitors contain polychlorinated biphenyls (PCBs). It is known that waste PCBs can leak into groundwater under landfills. Capacitors containing PCB were labelled as containing "Askarel" and several other trade names. PCB-filled capacitors are found in very old (pre 1975) fluorescent lamp ballasts, and other applications.

High-voltage capacitors may catastrophically fail when subjected to voltages or currents beyond their rating, or as they reach their normal end of life. Dielectric or metal interconnection failures may create arcing that vaporizes dielectric fluid, resulting in case bulging, rupture, or even an explosion. Capacitors used in RF or sustained high-current applications can overheat, especially in the center of the capacitor rolls. Capacitors used within high-energy capacitor banks can violently explode when a short in one capacitor causes sudden dumping of energy stored in the rest of the bank into the failing unit. High voltage vacuum capacitors can generate soft X-rays even during normal operation. Proper containment, fusing, and preventive maintenance can help to minimize these hazards.

High-voltage capacitors can benefit from a pre-charge to limit in-rush currents at power-up of high voltage direct current (HVDC) circuits. This will extend the life of the component and may mitigate high-voltage hazards.

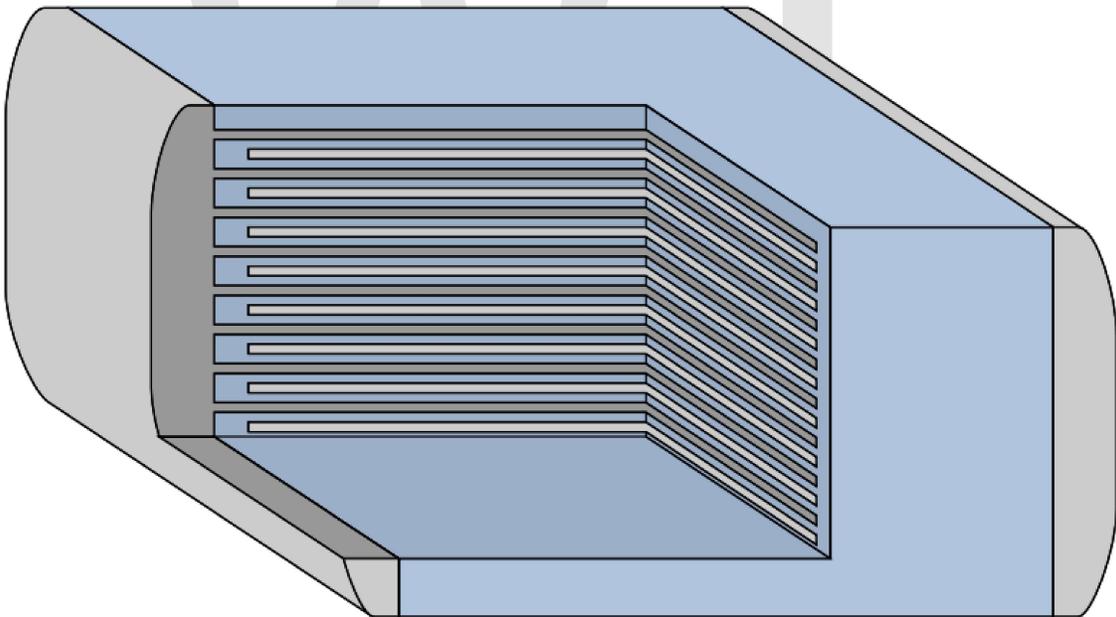
The image shows a large, light gray logo consisting of the letters 'WWT'. The 'W' is formed by three vertical strokes, and the 'T' is a simple horizontal bar on top of a vertical stem.

Chapter 11

Types of Capacitor

Practical capacitors are often classified according to the material used as the dielectric, with the dielectrics divided into two broad categories: bulk insulators and metal-oxide films (so-called *electrolytic capacitors*).

Capacitor construction



Structure of a surface mount (SMT) film capacitor

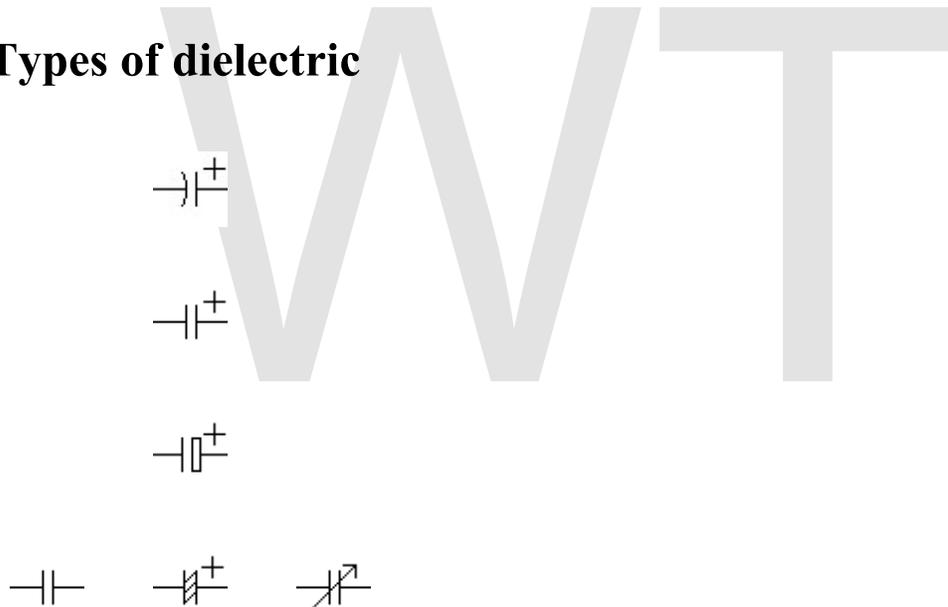
Capacitors have thin conducting plates (usually made of metal), separated by a layer of dielectric, then stacked or rolled to form a compact device.

Many types of capacitors are available commercially, with capacitance ranging from the picofarad, microfarad range to more than a farad, and voltage ratings up to hundreds of kilovolts. In general, the higher the capacitance and voltage rating, the larger the physical size of the capacitor and the higher the cost. Tolerances in capacitance value for discrete capacitors are usually specified as a percentage of the nominal value. Tolerances ranging from 50% (electrolytic types) to less than 1% are commonly available.

Another figure of merit for capacitors is stability with respect to time and temperature, sometimes called *drift*. Variable capacitors are generally less stable than fixed types.

The electrodes need round edges to avoid field electron emission. Air has a low breakdown voltage, so any air inside a capacitor - especially at plate edges - will reduce the voltage rating. Even closed air bubbles in the insulator or between the insulator and the electrode lead to gas discharge, particularly in AC or high frequency applications. Groups of identically constructed capacitor elements are often connected in series for operation at higher voltage. High voltage capacitors need large, smooth, and round terminals to prevent corona discharge.

Types of dielectric



Capacitor	Polarized Capacitor	Variable Capacitor
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Capacitor symbols

- **Air-gap:** air-gap capacitors have a low dielectric loss. Large-valued, tunable capacitors that can be used for resonating HF antennas can be made this way.
- **Ceramic:** the main differences between ceramic dielectric types are the temperature coefficient of capacitance, and the dielectric loss. C0G and NP0 (negative-positive-zero, i.e. ± 0) dielectrics have the lowest losses, and are used in filters, as timing elements, and for balancing crystal oscillators. Ceramic

capacitors tend to have low inductance because of their small size. NP0 refers to the shape of the capacitor's temperature coefficient graph (how much the capacitance changes with temperature). NP0 means that the graph is flat and the device is not affected by temperature changes.

- **C0G or NP0:** typically 1 pF to 0.1 μ F, 5%. High tolerance and good temperature performance. Larger and more expensive.
- **X7R:** typically 100 pF to 22 μ F, 10%. Good for non-critical coupling, timing applications. Subject to microphonics. Temperature up to 125°C
- **X8R:** typically 100 pF to 10 μ F, 25-100v, 5-10%. Good for high temperature up to 150°C
- **Z5U or 2E6:** typically 1 nF to 10 μ F, 20%. Good for bypass, coupling applications. Low price and small size. Subject to microphonics.
- **Ceramic chip:** 1% accurate, values up to about 1 μ F, typically made from Lead zirconate titanate (PZT) ferroelectric ceramic
- **Gimmick:** these capacitors are made by twisting together 2 pieces of insulated wire. Values usually range from 3 pF to 15 pF. Usually used in homemade VHF circuits for oscillation feedback.
- **Trimmer:** these capacitors have a rotating plate (which can be rotated to change the capacitance) separated from a fixed plate by a dielectric medium. Typically values range from 5 pF to 60 pF.
- **Glass:** used to form extremely stable, reliable capacitors.
- **Paper:** common in antique radio equipment, paper dielectric and aluminum foil layers rolled into a cylinder and sealed with wax. Low values up to a few μ F, working voltage up to several hundred volts, oil-impregnated bathtub types to 5 kV used for motor starting and high-voltage power supplies, and up to 25 kV for large oil-impregnated energy discharge types.
- **Polycarbonate:** good for filters, low temperature coefficient, good aging, expensive.
- **Polyester,** (PET film): (from about 1 nF to 10 μ F) signal capacitors, integrators.
- **Polystyrene:** (usually in the picofarad range) stable signal capacitors.
- **Polypropylene:** low-loss, high voltage, resistant to breakdown, signal capacitors.
- **PTFE or Teflon:** higher performing and more expensive than other plastic dielectrics.
- **Silver mica:** These are fast and stable for HF and low VHF RF circuits, but expensive.
- **Electrolytic capacitors** have a larger capacitance per unit volume than other types, making them valuable in relatively high-current and low-frequency electrical circuits, e.g. in power-supply filters or as coupling capacitors in audio amplifiers. High-capacity electrolytics, also known as supercapacitors or ultracapacitors, have applications similar to those of rechargeable batteries, e.g. in electrically powered vehicles.
- **Printed circuit board:** metal conductive areas in different layers of a multi-layer printed circuit board can act as a highly stable capacitor. It is common industry practice to fill unused areas of one PCB layer with the ground conductor and another layer with the power conductor, forming a large distributed capacitor between the layers, or to make power traces broader than signal traces.

- In **integrated circuits**, small capacitors can be formed through appropriate patterns of metallization on an isolating substrate.
- **Vacuum:** vacuum variable capacitors are generally expensive, housed in a glass or ceramic body, typically rated for 5-30 kV. Typically used in high power RF transmitters because the dielectric has virtually no loss and is self-healing. May be fixed or adjustable.

Fixed capacitor comparisons

Capacitor type	Dielectric used	Features/applications	Disadvantages
Paper Capacitors	Paper or oil-impregnated paper	Impregnated paper was extensively used for older capacitors, using wax, oil, or epoxy as an impregnant. Oil-Kraft paper capacitors are still used in certain high voltage applications. Has mostly been replaced by plastic film capacitors.	Large size. Also, paper is highly hygroscopic, absorbing moisture from the atmosphere despite plastic enclosures and impregnates. Absorbed moisture degrades performance by increasing dielectric losses (power factor) and decreasing insulation resistance. Suitable only for lower current applications. Has been largely superseded by metalized film capacitors
Metalized Paper Capacitors	Paper	Comparatively smaller in size than paper-foil capacitors	Temperature stability is poorer than paper capacitors. Usable at low (AC power) frequencies, but inappropriate for RF applications due to excessive dielectric heating.
PET film Capacitor	Polyester film	Smaller in size when compared to paper or polypropylene capacitors of comparable specifications. May use plates of foil, metalized film, or a combination. PET film capacitors have almost completely replaced paper capacitors for most DC electronic applications. Operating voltages up to 60,000 V DC and operating temperatures up to 125 °C. Low moisture absorption.	Higher cost than PET. Temperature stability is poorer than paper capacitors. Usable at low (AC power) frequencies, but inappropriate for RF
Kapton Capacitor	Kapton polyimide film	Similar to PET film, but significantly higher operating temperature (up to 250 °C).	

Polystyrene Capacitor	Polystyrene	Excellent general purpose plastic film capacitor. Excellent stability, low moisture pick-up and a slightly negative temperature coefficient that can be used to match the positive temperature co-efficient of other components. Ideal for low power RF and precision analog applications	applications due to excessive dielectric heating.
Polycarbonate Plastic Film Capacitor	Polycarbonate	Superior insulation resistance, dissipation factor, and dielectric absorption versus polystyrene capacitors. Moisture pick-up is less, with about ± 80 ppm temperature coefficient. Can use full operating voltage across entire temperature range (-55°C to 125°C)	Maximum operating temperature is limited to about $+85^{\circ}\text{C}$. Comparatively bigger in size.
Polypropylene Plastic Film Capacitors	Polypropylene	Has become the most popular capacitor dielectric. Extremely low dissipation factor, higher dielectric strength than polycarbonate and polyester films, low moisture absorption, and high insulation resistance. May use plates of foil, metalized film, or a combination. Film is compatible with self-healing technology to improve reliability. Usable in high frequency applications and high frequency high power applications such as induction heating (often combined with water-cooling) due to very low dielectric losses. Larger value and higher voltage types from 1 to $100\ \mu\text{F}$ at up to 440 V AC are used as run capacitors in some types of single phase electric motors.	Maximum operating temperature limited to about 125°C .
Polysulphone Plastic Film Capacitors	Polysulfone	Similar to polycarbonate. Can withstand full voltage at comparatively higher temperatures. Moisture pick-up is typically 0.2%, limiting its stability.	More susceptible to damage from transient over-voltages or voltage reversals than oil-impregnated Kraft paper for pulsed power energy discharge applications.
			Very limited availability and higher cost

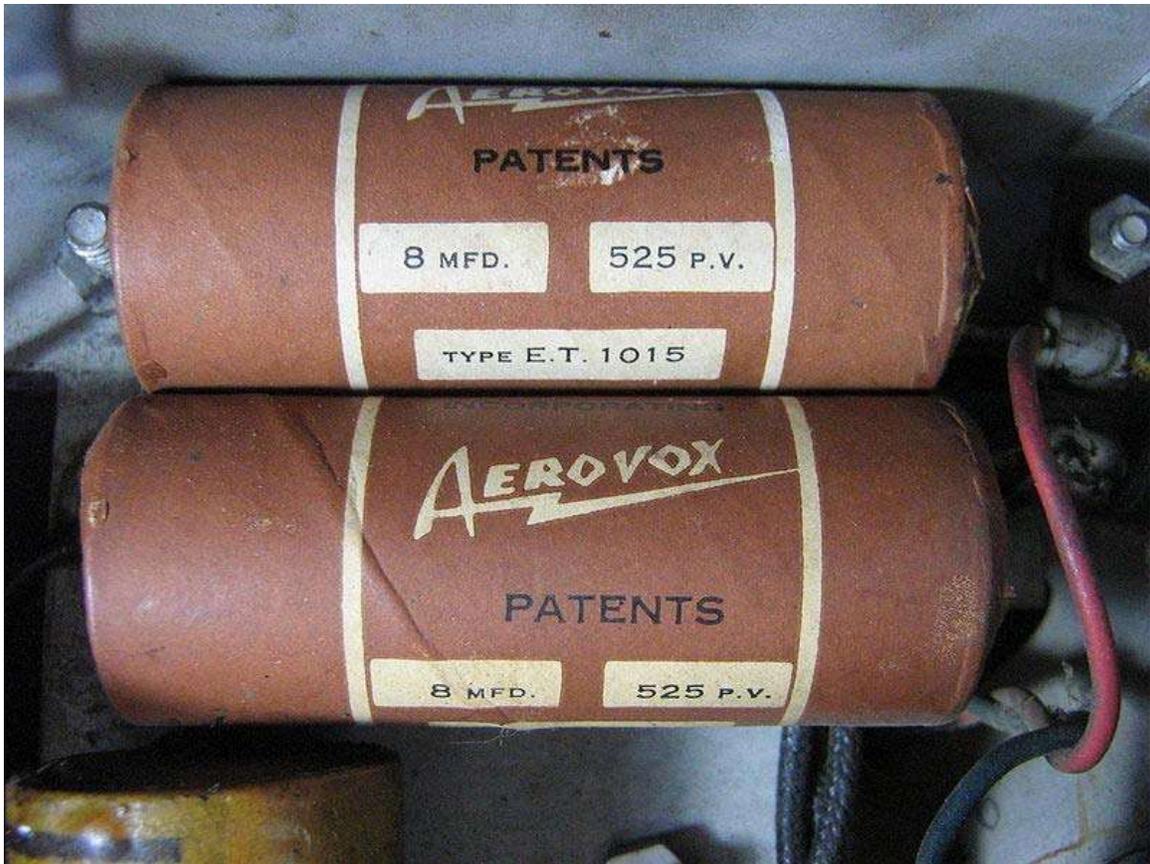
PTFE Fluorocarbon (TEFLON) Film Capacitors	Polytetrafluoroethylene	Lowest loss solid dielectric. Operating temperatures up to 250 °C, extremely high insulation resistance, and good stability. Used in stringent, mission-critical applications	Large size (due to low dielectric constant), and higher cost than other film capacitors.
Polyamide Plastic Film Capacitors	Polyamide	Operating temperatures of up to 200 °C. High insulation resistance, good stability and low dissipation factor.	Large size and high cost.
Metalized Plastic Film Capacitors	Polyester or Polycarbonate	Reliable and significantly smaller in size. Thin metalization can be used to advantage by making capacitors "self healing".	Thin plates limit maximum current carrying capability.
Stacked Plate Mica Capacitors	Mica	Advantages of mica capacitors arise from the fact that the dielectric material (mica) is inert. It does not change physically or chemically with age and it has good temperature stability. Very resistant to corona damage	Unless properly sealed, susceptible to moisture pick-up which will increase the power factor and decrease insulation resistance. Higher cost due to scarcity of high grade dielectric material and manually-intensive assembly.
Metalized Mica or Silver Mica Capacitors	Mica	Silver mica capacitors have the above mentioned advantages. In addition, they have much reduced moisture infiltration.	Higher cost
Glass Capacitors	Glass	Similar to Mica Capacitors. Stability and frequency characteristics are better than silver mica capacitors. Ultra-reliable, ultra-stable, and resistant to nuclear radiation.	High cost.
Class-I Temperature Compensating Type Ceramic Capacitors	Mixture of complex Titanate compounds	Low cost and small size, excellent high frequency characteristics and good reliability. Predictable linear capacitance change with operating temperature. Available in voltages up to 15,000 volts	Capacitance changes with change in applied voltage, with frequency and with aging effects.
Class-II High dielectric strength Type Ceramic Capacitors	Barium titanate based dielectrics	Smaller than Class-I type due to higher dielectric strength of ceramics used. Available in voltages up to 50,000 volts.	Not as stable as Class-I type with respect to temperature, and capacitance changes significantly with applied voltage.
Aluminum	Aluminum oxide	Very large capacitance to volume	Dielectric leakage is

Electrolytic Capacitors		ratio, inexpensive, polarized. Primary applications are as smoothing and reservoir capacitors in power supplies.	high, large internal resistance and inductance limits high frequency performance, poor low temperature stability and loose tolerances. May vent or burst open when overloaded and/or overheated. Limited to about 500 volts.
Lithium Ion Capacitors	Lithium ion	The lithium ion capacitors have a higher power density as compared to batteries and LIC's are safer in use than LIB's in which thermal runaway reactions may occur. Compared to electric double layer capacitor (EDLC), the LIC has a higher output voltage. They both have similar power densities, but energy density of an LIC is much higher.	New technology.
Tantalum Electrolytic Capacitors	Tantalum oxide	Large capacitance to volume ratio, smaller size, good stability, wide operating temperature range, long reliable operating life. Extensively used in miniaturized equipment and computers. Available in both polarized and unpolarized varieties. Solid tantalum capacitors have much better characteristics than their wet counterparts.	Higher cost than aluminum electrolytic capacitors. Voltage limited to about 50 volts. Explodes quite violently when voltage rating, current rating, or slew rates are exceeded, or when a polarized version is subjected to reverse voltage.
Electrolytic double-layer capacitors (EDLC) Supercapacitors	Thin Electrolyte layer and Activated Carbon	Extremely large capacitance to volume ratio, small size, low ESR. Available in hundreds, or thousands, of farads. A relatively new capacitor technology. Often used to temporarily provide power to equipment during battery replacement. Can rapidly absorb and deliver larger currents than batteries during charging and discharging, making them valuable for hybrid vehicles. Polarized, low operating voltage (volts per capacitor cell). Groups of cells are stacked to provide	Relatively high cost.

Alternating current oil-filled Capacitors	Oil-impregnated paper	<p>higher overall operating voltage. Usually PET or polypropylene film dielectric. Primarily designed to provide very large capacitance for industrial AC applications to withstand large currents and high peak voltages at power line frequencies. The applications include AC motor starting and running, phase splitting, power factor correction, voltage regulation, control equipment, etc..</p>	Limited to low frequency applications due to high dielectric losses at higher frequencies.
Direct current oil-filled capacitors	Paper or Paper-polyester film combination	Primarily designed for DC applications such as filtering, bypassing, coupling, arc suppression, voltage doubling, etc...	Operating voltage rating must be derated as per the curve supplied by the manufacturer if the DC contains ripple. Physically larger than polymer dielectric counterparts.
Energy Storage Capacitors	Kraft capacitor paper impregnated with electrical grade castor oil or similar high dielectric constant fluid, with extended foil plates	Designed specifically for intermittent duty, high current discharge applications. More tolerant of voltage reversal than many polymer dielectrics. Typical applications include pulsed power, electromagnetic forming, pulsed lasers, Marx generators, and pulsed welders.	Physically large and heavy. Significantly lower energy density than polymer dielectric systems. Not self-healing. Device may fail catastrophically due to high stored energy.
Vacuum Capacitors	Vacuum capacitors use highly evacuated glass or ceramic chamber with concentric cylindrical electrodes.	Extremely low loss. Used for high voltage high power RF applications, such as transmitters and induction heating where even a small amount of dielectric loss would cause excessive heating. Can be self-healing if arc-over current is limited.	Very high cost, fragile, physically large, and relatively low capacitance.



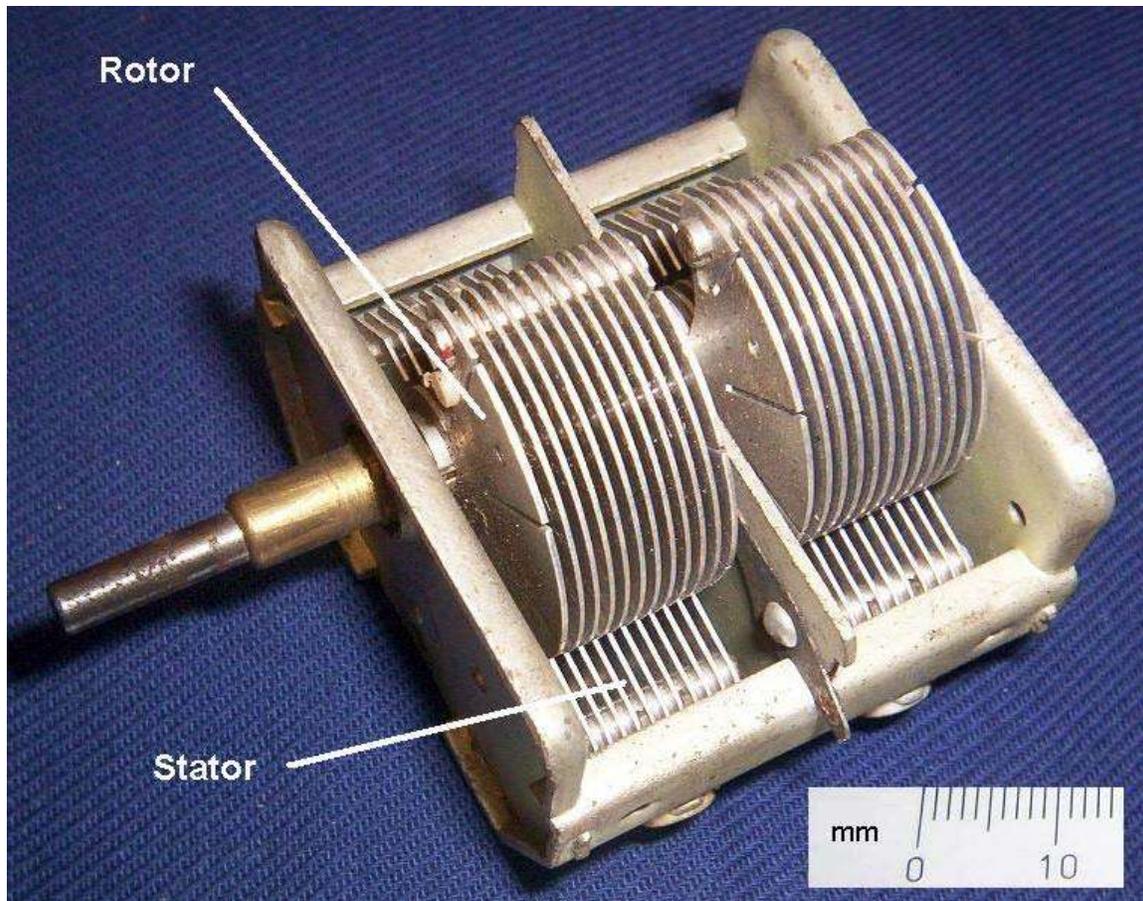
A 12 pF, 20 kV fixed vacuum capacitor



Two 8 μF , 525 V paper electrolytic capacitors in a 1930s radio

Variable capacitors

A **variable capacitor** is a capacitor whose capacitance may be intentionally and repeatedly changed mechanically or electronically. Variable capacitors are often used in L/C circuits to set the resonance frequency, e.g. to tune a radio (therefore they are sometimes called *tuning capacitors*), or as a variable reactance, e.g. for impedance matching in antenna tuners.



Rotary variable capacitor

Mechanically controlled

In mechanically controlled variable capacitors, the distance between the plates, or the amount of plate surface area which overlaps, can be changed.

The most common form arranges a group of semicircular metal plates on a rotary axis (“rotor”) that are positioned in the gaps between a set of stationary plates (“stator”) so that the area of overlap can be changed by rotating the axis. Air or plastic foils can be used as dielectric material. By choosing the shape of the rotary plates, various functions of capacitance vs. angle can be created, e.g. to obtain a linear frequency scale. Various forms of reduction gear mechanisms are often used to achieve finer tuning control, i.e. to spread the variation of capacity over a larger angle, often several turns. A vacuum variable capacitor uses a set of plates made from concentric cylinders that can be slid in or out of an opposing set of cylinders (sleeve and plunger). These plates are then sealed inside of a non-conductive envelope such as glass or ceramic and placed under a high vacuum. The movable part (plunger) is mounted on a flexible metal membrane that seals and maintains the vacuum. A screw shaft is attached to the plunger, when the shaft is turned the plunger moves in or out of the sleeve and the value of the capacitor changes. The vacuum not only increases the working voltage and current handling capacity of the

capacitor it also greatly reduces the chance of arcing across the plates. The most common usage for vacuum variables are in high powered transmitters such as those used for broadcasting, military and amateur radio as well as high powered RF tuning networks. Vacuum variables can also be more convenient since the elements are under a vacuum the working voltage can be higher than an air variable the same size, allowing the size of the vacuum capacitor to be reduced.

Very cheap variable capacitors are constructed from layered aluminium and plastic foils that are variably pressed together using a screw. These so-called *squeezers* can't provide a stable and reproducible capacitance, however. A variant of this structure that allows for linear movement of one set of plates to change the plate overlap area is also used and might be called a *slider*. This has practical advantages for makeshift or home construction and may be found in resonant loop antennas or crystal radios.

Small variable capacitors operated by screwdriver (for instance, to precisely set a resonant frequency at the factory and then never be adjusted again) are called trimmer capacitors. In addition to air and plastic, trimmers can also be made using a ceramic dielectric.

Electronically controlled

The thickness of the depletion layer of a reverse-biased semiconductor diode varies with the DC voltage applied across the diode. Any diode exhibits this effect (including p/n junctions in transistors), but devices specifically sold as variable capacitance diodes (also called varactors or varicaps) are designed with a large junction area and a doping profile specifically designed to maximize capacitance.

Their use is limited to low signal amplitudes to avoid obvious distortions as the capacitance would be affected by the change of signal voltage, precluding their use in the input stages of high-quality RF communications receivers, where they would add unacceptable levels of intermodulation. At VHF/UHF frequencies, e.g. in FM Radio or TV tuners, dynamic range is limited by noise rather than large signal handling requirements, and varicaps are commonly used in the signal path.

Varicaps are used for frequency modulation of oscillators, and to make high-frequency voltage controlled oscillators (VCOs), the core component in phase-locked loop (PLL) frequency synthesizers that are ubiquitous in modern communications equipment.

Digitally Tuned Capacitor

A **digitally tuned capacitor** is a type of chip-form variable capacitor patented by Peregrine Semiconductor in the form of DuNE™ technology using UltraCMOS™ process and HaRPT™ design innovation.. The DuNE digitally tunable capacitor (DTC) chip contains five capacitors switched by MOSFETs that operate from a serial input bus with a 5-bit code providing 32 possible capacitor values.

The capacitor values can range from 0.5 to 10 pF with typical tuning ratios of 3:1 to 6:1, or 10:1 in some cases. Typical switching speed is less than 5 μ s. Capacitor Q's greater than 100 are possible. The frequency range is up to 3 GHz, and power handling is up to 40 dBm. The chip operates with a supply voltage of 2.4 to 3.0 V with current consumption in the 20- to 100- μ A range, unlike others. The device comes in a 2- by 2-mm dual flat no-lead (DFN) 8L flip-chip or plastic package.

It is intended for antenna impedance matching in multi-band GSM/WCDMA cellular handsets and mobile TV receivers that must operate over wide frequency ranges such as the European DVB-H and Japanese ISDB-T mobile TV systems, due to its small size, high Q factor, low voltage operation and current consumption.

Transducers

Variable capacitance is sometimes used to convert physical phenomena into electrical signals.

- In a capacitor microphone (commonly known as a condenser microphone), the diaphragm acts as one plate of a capacitor, and vibrations produce changes in the distance between the diaphragm and a fixed plate, changing the voltage maintained across the capacitor plates.
- Some types of industrial sensors use a capacitor element to convert physical quantities such as pressure, displacement or relative humidity to an electrical signal for measurement purposes.
- Capacitive sensors can also be used in the place of switches, e.g. in computer keyboards or “touch buttons” for elevators that have no movable parts.

Special forms of mechanically variable capacitors



Various forms of variable capacitors

Multiple sections

Very often, multiple stator/rotor sections are arranged behind one another on the same axis, allowing for several tuned circuits to be adjusted using the same control, e.g. a preselector, an input filter and the corresponding oscillator in a receiver circuit. The sections can have identical or different nominal capacitances, e.g. 2×330 pF for AM filter and oscillator, plus 3×45 pF for two filters and an oscillator in the FM section of the same receiver. Capacitors with multiple sections often include trimmer capacitors in parallel to the variable sections, used to adjust all tuned circuits to the same frequency.

Butterfly

A **butterfly capacitor** is a form of rotary variable capacitor with two independent sets of stator plates opposing each other, and a butterfly-shaped rotor arranged so that turning the rotor will vary the capacitances between the rotor and either stator equally.

Butterfly capacitors are used in symmetrical tuned circuits, e.g. RF power amplifier stages in push-pull configuration or symmetrical antenna tuners where the rotor needs to

be “cold”, i.e. connected to RF (but not necessarily DC) ground potential. Since the peak RF current normally flows from one stator to the other without going through wiper contacts, butterfly capacitors can handle large resonance RF currents, e.g. in magnetic loop antennas.

In a butterfly capacitor, the stators and each half of the rotor can only cover a maximum angle of 90° since there must be a position without rotor/stator overlap corresponding to minimum capacity, therefore a turn of only 90° covers the entire capacitance range.

Split stator

The closely related **split stator variable capacitor** does not have the limitation of 90° angle since it uses two separate packs of rotor electrodes arranged axially behind one another. Unlike in a capacitor with several sections, the rotor plates in a split stator capacitor are mounted on opposite sides of the rotor axis. While the split stator capacitor benefits from larger electrodes compared to the butterfly capacitor, as well as a rotation angle of up to 180°, the separation of rotor plates incurs some losses since RF current has to pass the rotor axis instead of flowing straight through each rotor vane.

Differential

Differential variable capacitors also have two independent stators, but unlike in the butterfly capacitor where capacities on both sides increase equally as the rotor is turned, in a differential variable capacitor one section's capacity will increase while the other section's decreases, keeping the stator-to-stator capacitance constant. Differential variable capacitors can therefore be used in capacitive potentiometric circuits.

Non-ideal properties of practical capacitors

Breakdown voltage

The breakdown voltage of the dielectric limits the power density of capacitors. For a particular dielectric, the breakdown voltage is proportional to the thickness of the dielectric.

If a manufacturer makes a new capacitor with the same dielectric as some old capacitor, but with half the thickness of the dielectric, the new capacitor has half the breakdown voltage of the old capacitor.

Because the plates are closer together, the manufacturer can put twice the parallel-plate area inside the new capacitor and still fit it in the same volume (capacitor size) as the old capacitor. Since the capacitance of a parallel-plate capacitor is given by:

$$C \approx \frac{\epsilon A}{d}$$

this new capacitor has 4 times the capacitance as the old capacitor.

Since the energy stored in a capacitor is given by:

$$E_{\text{stored}} = \frac{1}{2}CV^2,$$

this new capacitor has the same maximum energy density as the old capacitor.

The energy density depends only on the dielectric. Making a few thick layers of dielectric (which can support a high voltage, but results in a low capacitance), or making many very thin layers of dielectric (which results in a low breakdown voltage, but a higher capacitance) has no effect on the energy density.

Q* factor, dissipation and *tan-delta

Capacitors have *Q* (quality) factor (and the inverse, *dissipation factor*, *D* or *tan-delta*) which relates capacitance at a certain frequency to the combined losses due to dielectric leakage and series internal resistance (also known as *ESR*) dissipation factor (dielectric loss). The lower the *Q*, the lossier the capacitor. Aluminum electrolytic types have typically low *Q* factors. High *Q* capacitors tend to exhibit low DC leakage currents. *Tan-delta* is the tangent of the phase angle between voltage and current in the capacitor. This angle is sometimes called the loss angle. It is related to the power factor which is zero for an ideal capacitor.

Equivalent series resistance (ESR)

This is an effective resistance that is used to describe the resistive parts of the impedance of certain electronic components. The theoretical treatment of devices such as capacitors and inductors tends to assume they are ideal or "perfect" devices, contributing only capacitance or inductance to the circuit. However, all physical devices are constructed of materials with finite electrical resistance, which means that all real-world components contain some resistance in addition to their other properties. A low ESR capacitor typically has an ESR of 0.01 Ω . Low values are preferred for high-current, pulse applications. Low ESR capacitors have the capability to deliver huge currents into short circuits, which can be dangerous.

For capacitors, ESR takes into account the internal lead and plate resistances and other factors. An easy way to deal with these inherent resistances in circuit analysis is to express each real capacitor as a combination of an ideal component and a small resistor in series, the resistor having a value equal to the resistance of the physical device.

Equivalent series inductance (ESL)

ESL in signal capacitors is mainly caused by the leads used to connect the plates to the outside world and the series interconnects used to join sets of plates together internally.

For any real-world capacitor, there is a frequency above DC at which it ceases to behave as a pure capacitance. This is called the (first) resonant frequency. This is critically important with decoupling high-speed logic circuits from the power supply. The decoupling capacitor supplies transient current to the chip. Without decouplers, the IC demands current faster than the connection to the power supply can supply it, as parts of the circuit rapidly switch on and off. Large capacitors tend to have much higher ESL than small ones. As a result, electronics will frequently use multiple bypass capacitors—a small 0.1 μF rated for high frequencies and a large electrolytic rated for lower frequencies, and occasionally, an intermediate value capacitor.

Maximum voltage and current

Important properties of capacitors are the maximum working voltage (potential, measured in volts) and the amount of energy lost in the dielectric. For high-power or high-speed capacitors, the maximum ripple current, peak current, fault current, and percent voltage reversal are further considerations. Typically the voltage is 66% of the rated voltage. A voltage higher than that, usually reduces the life expectancy depending on manufacturer. The time for a voltage to discharge is 6 time constants.

Temperature dependence

Another major non-ideality is temperature coefficient (change in capacitance with temperature) which is usually quoted in parts per million (ppm) per degree Celsius.

Aging

When refurbishing old (especially audio) equipment, it is a good idea to replace all of the electrolyte-based capacitors. After long storage, the electrolyte and dielectric layer within electrolytic capacitors may deteriorate; before powering up equipment with old electrolytics, it may be useful to apply low voltage to allow the capacitors to reform before applying full voltage. Deteriorating capacitors are a frequent cause of hum in aging audio equipment.

Non-polarised capacitors also suffer from aging, changing their values slightly over long periods of time.

In high voltage DC applications, accumulated capacitor stress due to in-rush currents at circuit power-up can be minimized with a pre-charge circuit.

Dielectric absorption (soakage)

Some types of dielectrics, when they have been holding a voltage for a long time, maintain a "memory" of that voltage: after they have been quickly fully discharged and left without an applied voltage, a voltage will gradually be established which is some fraction of the original voltage. For some dielectrics 10% or more of the original voltage may reappear. This phenomenon of unwanted charge storage is called *dielectric*

absorption or *soakage*, and it effectively creates a hysteresis or memory effect in capacitors.

The percentage of the original voltage restored depends upon the dielectric and is a non-linear function of original voltage.

In many applications of capacitors dielectric absorption is not a problem but in some applications, such as long-time-constant integrators, sample-and-hold circuits, switched-capacitor analog-to-digital converters, and very low-distortion filters, it is important that the capacitor does not recover a residual charge after full discharge, and capacitors with low absorption are specified. For safety, high-voltage capacitors are often stored with their terminals short circuited.

Some dielectrics have very low dielectric absorption, e.g., polystyrene, polypropylene, NPO ceramic, and Teflon. Others, in particular those used in electrolytic and supercapacitors, tend to have high absorption.

Voltage non-linearities

Capacitors may also change capacitance with applied voltage. This effect is more prevalent in high k ceramic and some high voltage capacitors. This is a small source of non-linearity in low-distortion filters and other analog applications.

Leakage

The resistance between the terminals of a capacitor is never truly infinite, leading to some level of d.c. 'leakage'; this ultimately limits how long capacitors can store charge. Before modern low-leakage dielectrics were developed this was a major source of problems in some applications (long time-constant timers, sample-and-holds, etc.).

Component values and identification

Standard values

Before 1960 electronic components values were not standardised. The more common, but not the only, values for capacitors were 1.0, 1.5, 2.0, 3.0, 5.0, 6.0, and 8.0 as base numbers multiplied by some negative or positive power of ten. Values of 0.001 μF and above were stated in microfarads (μF , or often mF); lower values were stated in micro-microfarads ($\mu\mu\text{F}$, now called picofarads, pF).

In the late 1960s a standardized set of geometrically increasing preferred values was introduced. According to the number of values per decade, these were called the E3, E6, E12, etc. series

Series	Values										
E3	1.0			2.2					4.7		
E6	1.0	1.5		2.2	3.3		4.7		6.8		
E12	1.0	1.2	1.5	1.8	2.2	2.7	3.3	3.9	4.7	5.6	6.8 8.2

In many applications capacitors need not be specified to tight tolerance (they often need only to exceed a certain value); this is particularly true for electrolytic capacitors, which are often used for filtering and bypassing. Consequently capacitors, particularly electrolytics, often have a tolerance range of $\pm 20\%$ and need to be available only within E6 (or E3) series values.

Other types of capacitors, e.g. ceramic, can be manufactured to tighter tolerances and are available in E12 or closer-spaced values (e.g. 47 pF, 56 pF, 68 pF).

With the introduction of S.I. submultiples of micro, nano, and pico, it became customary to specify capacitors with a number between 1 and 999 followed by farad, microfarad, nanofarad, or picofarad. While supercapacitors of up to 5,000 farads are produced, it is not usual to use kilofarad or millifarad.

Capacitor markings

Capacitors, like most other electronic components, have markings in their bodies to indicate their electrical characteristics, in particular capacitance, tolerance, working voltage and polarity (if relevant). For most types of capacitor, numerical markings are used, whereas some capacitors, especially older types, use colour coding.

Numerical markings

On capacitors that are large enough (e.g. electrolytic capacitors) the capacity and working voltage are printed on the body without encoding. Sometimes the markings also include the maximum working temperature, manufacturer's name and other information.

Smaller capacitors use a shorthand notation, to display all the relevant information in the limited space. The most commonly used format is: XYZ J/K/M VOLTS V, where XYZ represents the capacitance (calculated as $XY \times 10^Z$ pF), the letters J, K or M indicate the tolerance ($\pm 5\%$, $\pm 10\%$ and $\pm 20\%$ respectively) and VOLTS V represents the working voltage.

Polarised capacitors, for which one electrode must always be positive relative to the other, have clear polarity markings, usually a stripe or a "-" sign on the side of the negative electrode. Also, the negative lead is usually shorter.

Examples:

An electrolytic capacitor might be marked with the following information: **47 μ F 160V 105°C**

A capacitor with the following text on its body: **105K 330V** has a capacitance of 10×10^5 pF = 1 μ F ($\pm 10\%$) with a working voltage of 330 V.

A capacitor with the following text: **473M 100V** has a capacitance of 47×10^3 pF = 47 nF ($\pm 20\%$) with a working voltage of 100 V.

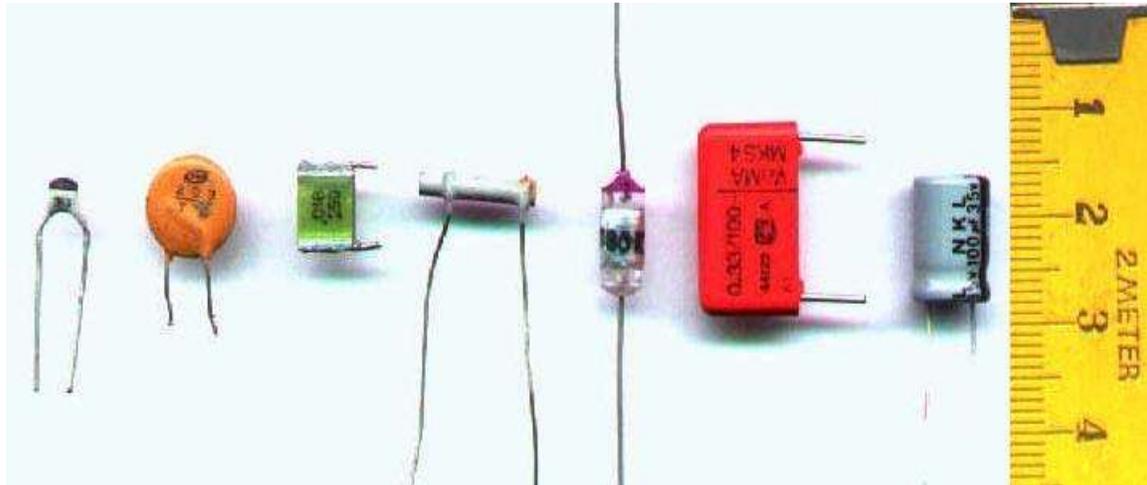
Colour coding

Capacitors may be marked with 3 or more coloured bands or dots. 3-colour coding encodes most significant digit, second most significant digit, and multiplier. Additional bands have meanings which may vary from one type to another. Low-tolerance capacitors may begin with the first 3 (rather than 2) digits of the value. It is usually, but not always, possible to work out what scheme is used by the particular colours used. Cylindrical capacitors marked with bands may look like resistors.

Colour	Significant digits	Multiplier	Capacitance tolerance	Characteristic	DC working voltage	Operating temperature	EIA/vibration
Black	0	1	$\pm 20\%$	—	—	-55 °C to +70 °C	10 to 55 Hz
Brown	1	10	$\pm 1\%$	B	100	—	—
Red	2	100	$\pm 2\%$	C	—	-55 °C to +85 °C	—
Orange	3	1,000	—	D	300	—	—
Yellow	4	10,000	—	E	—	-55 °C to +125 °C	10 to 2000 Hz
Green	5	—	$\pm 5\%$	F	500	—	—
Blue	6	—	—	—	—	-55 °C to +150 °C	—
Violet	7	—	—	—	—	—	—
Grey	8	—	—	—	—	—	—
White	9	—	—	—	—	—	EIA
Gold	—	—	$\pm 0.5\%*$	—	1000	—	—
Silver	—	—	$\pm 10\%$	—	—	—	—

*Or ± 0.5 pF, whichever is greater.

Dielectric materials



Capacitor materials. From left: multilayer ceramic, ceramic disc, multilayer polyester film, tubular ceramic, polystyrene, metalized polyester film, aluminum electrolytic. Major scale divisions are in centimetres.

Most types of capacitor include a dielectric spacer, which increases their capacitance. These dielectrics are most often insulators. However, low capacitance devices are available with a vacuum between their plates, which allows extremely high voltage operation and low losses. Variable capacitors with their plates open to the atmosphere were commonly used in radio tuning circuits. Later designs use polymer foil dielectric between the moving and stationary plates, with no significant air space between them.

In order to maximise the charge that a capacitor can hold, the dielectric material needs to have as high a permittivity as possible, while also having as high a breakdown voltage as possible.

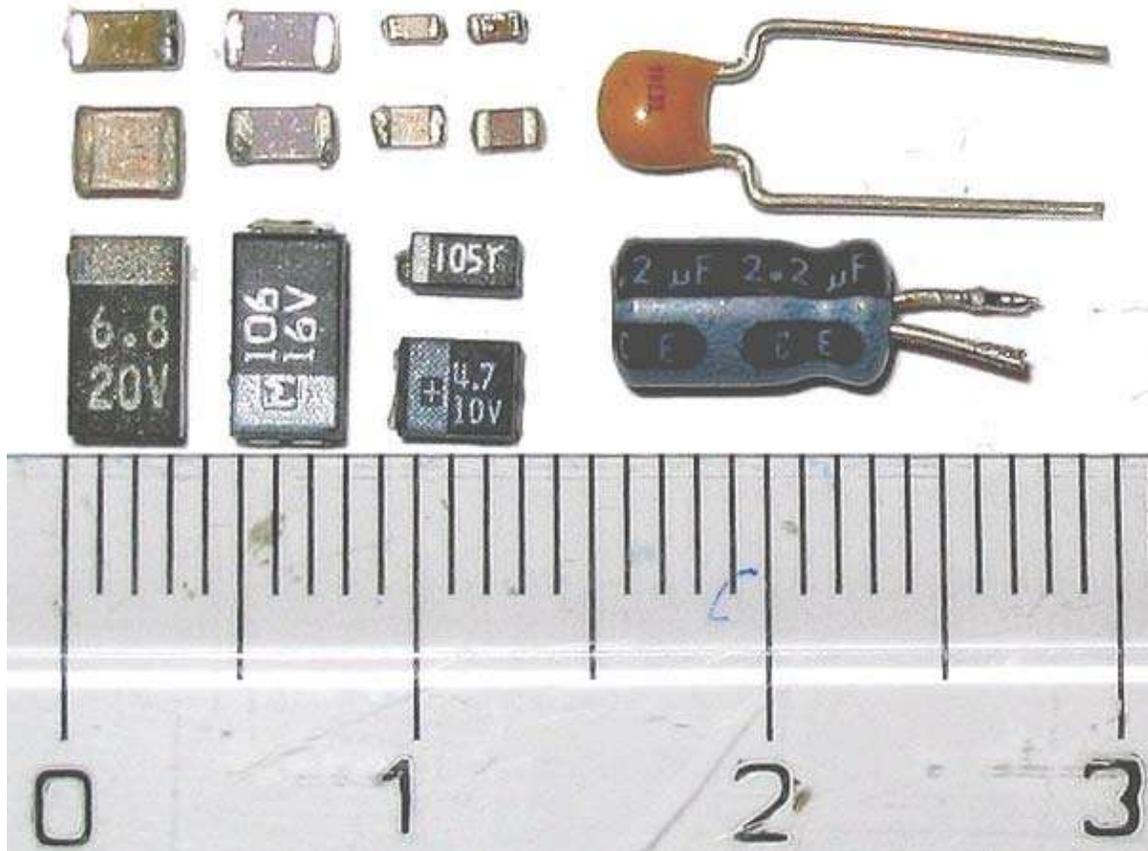
Several solid dielectrics are available, including paper, plastic, glass, mica and ceramic materials. Paper was used extensively in older devices and offers relatively high voltage performance. However, it is susceptible to water absorption, and has been largely replaced by plastic film capacitors. Plastics offer better stability and aging performance, which makes them useful in timer circuits, although they may be limited to low operating temperatures and frequencies. Ceramic capacitors are generally small, cheap and useful for high frequency applications, although their capacitance varies strongly with voltage and they age poorly. They are broadly categorized as class 1 dielectrics, which have predictable variation of capacitance with temperature or class 2 dielectrics, which can operate at higher voltage. Glass and mica capacitors are extremely reliable, stable and tolerant to high temperatures and voltages, but are too expensive for most mainstream applications. Electrolytic capacitors and supercapacitors are used to store small and larger amounts of energy, respectively, ceramic capacitors are often used in resonators, and parasitic capacitance occurs in circuits wherever the simple conductor-insulator-conductor structure is formed unintentionally by the configuration of the circuit layout.

Electrolytic capacitors use an aluminum or tantalum plate with an oxide dielectric layer. The second electrode is a liquid electrolyte, connected to the circuit by another foil plate. Electrolytic capacitors offer very high capacitance but suffer from poor tolerances, high instability, gradual loss of capacitance especially when subjected to heat, and high leakage current. Poor quality capacitors may leak electrolyte, which is harmful to printed circuit boards. The conductivity of the electrolyte drops at low temperatures, which increases equivalent series resistance. While widely used for power-supply conditioning, poor high-frequency characteristics make them unsuitable for many applications. Electrolytic capacitors will self-degrade if unused for a period (around a year), and when full power is applied may short circuit, permanently damaging the capacitor and usually blowing a fuse or causing arcing in rectifier tubes. They can be restored before use (and damage) by gradually applying the operating voltage, often done on antique vacuum tube equipment over a period of 30 minutes by using a variable transformer to supply AC power. Unfortunately, the use of this technique may be less satisfactory for some solid state equipment, which may be damaged by operation below its normal power range, requiring that the power supply first be isolated from the consuming circuits. Such remedies may not be applicable to modern high-frequency power supplies as these produce full output voltage even with reduced input.

Tantalum capacitors offer better frequency and temperature characteristics than aluminum, but higher dielectric absorption and leakage. OS-CON (or OC-CON) capacitors are a polymerized organic semiconductor solid-electrolyte type that offer longer life at higher cost than standard electrolytic capacitors.

Several other types of capacitor are available for specialist applications. Supercapacitors store large amounts of energy. Supercapacitors made from carbon aerogel, carbon nanotubes, or highly porous electrode materials offer extremely high capacitance (up to 5 kF as of 2010) and can be used in some applications instead of rechargeable batteries. Alternating current capacitors are specifically designed to work on line (mains) voltage AC power circuits. They are commonly used in electric motor circuits and are often designed to handle large currents, so they tend to be physically large. They are usually ruggedly packaged, often in metal cases that can be easily grounded/earthed. They also are designed with direct current breakdown voltages of at least five times the maximum AC voltage.

Structure



Capacitor packages: SMD ceramic at top left; SMD tantalum at bottom left; through-hole tantalum at top right; through-hole electrolytic at bottom right. Major scale divisions are cm.

The arrangement of plates and dielectric has many variations depending on the desired ratings of the capacitor. For small values of capacitance (microfarads and less), ceramic disks use metallic coatings, with wire leads bonded to the coating. Larger values can be made by multiple stacks of plates and disks. Larger value capacitors usually use a metal foil or metal film layer deposited on the surface of a dielectric film to make the plates, and a dielectric film of impregnated paper or plastic – these are rolled up to save space. To reduce the series resistance and inductance for long plates, the plates and dielectric are staggered so that connection is made at the common edge of the rolled-up plates, not at the ends of the foil or metalized film strips that comprise the plates.

The assembly is encased to prevent moisture entering the dielectric – early radio equipment used a cardboard tube sealed with wax. Modern paper or film dielectric capacitors are dipped in a hard thermoplastic. Large capacitors for high-voltage use may have the roll form compressed to fit into a rectangular metal case, with bolted terminals and bushings for connections. The dielectric in larger capacitors is often impregnated with a liquid to improve its properties.

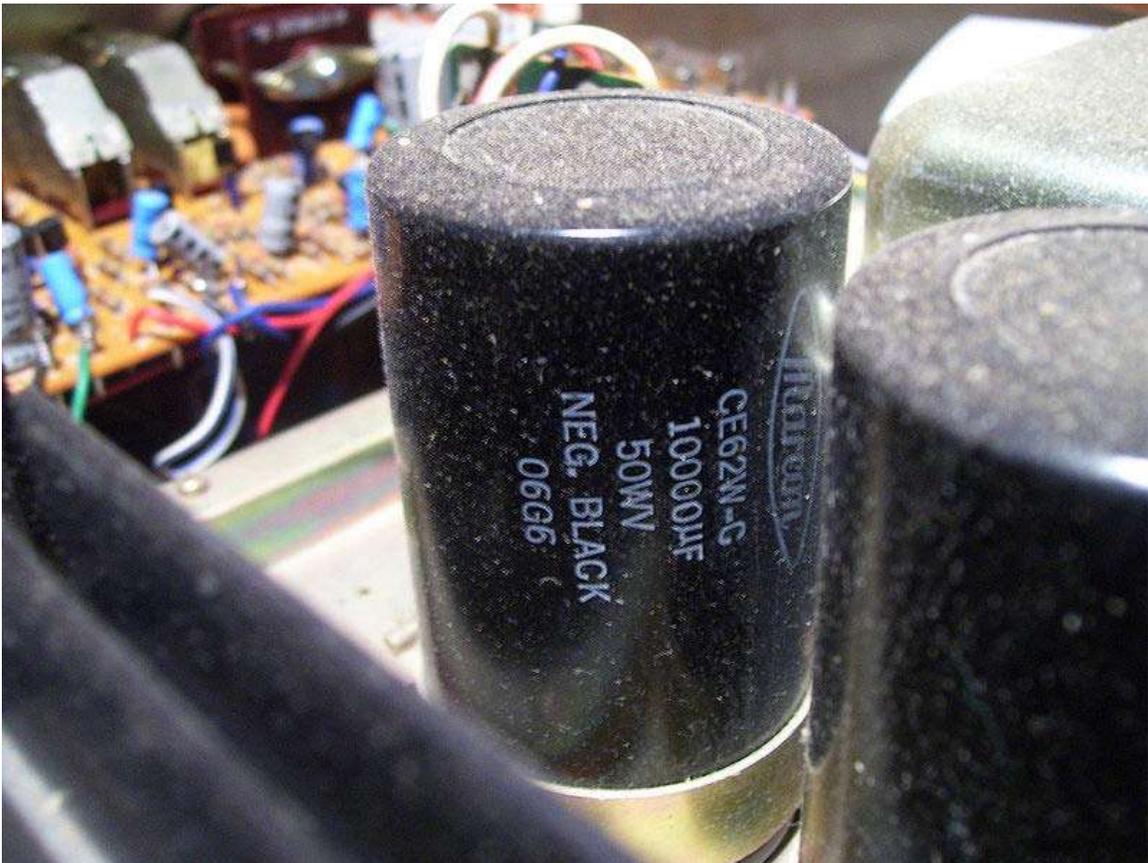
Capacitors may have their connecting leads arranged in many configurations, for example axially or radially. "Axial" means that the leads are on a common axis, typically the axis of the capacitor's cylindrical body – the leads extend from opposite ends. Radial leads might more accurately be referred to as tandem; they are rarely actually aligned along radii of the body's circle, so the term is inexact, although universal. The leads (until bent) are usually in planes parallel to that of the flat body of the capacitor, and extend in the same direction; they are often parallel as manufactured.

Small, cheap discoidal ceramic capacitors have existed since the 1930s, and remain in widespread use. Since the 1980s, surface mount packages for capacitors have been widely used. These packages are extremely small and lack connecting leads, allowing them to be soldered directly onto the surface of printed circuit boards. Surface mount components avoid undesirable high-frequency effects due to the leads and simplify automated assembly, although manual handling is made difficult due to their small size.

Mechanically controlled variable capacitors allow the plate spacing to be adjusted, for example by rotating or sliding a set of movable plates into alignment with a set of stationary plates. Low cost variable capacitors squeeze together alternating layers of aluminum and plastic with a screw. Electrical control of capacitance is achievable with varactors (or varicaps), which are reverse-biased semiconductor diodes whose depletion region width varies with applied voltage. They are used in phase-locked loops, amongst other applications.

Chapter 12

Applications of Capacitors



One of two 10,000 microfarad capacitor in a TRM-800 amplifier used for energy storage



Large capacitor for camera flash in a vintage Polaroid

Capacitors have many uses in electronic and electrical systems. They are so ubiquitous that it is a rare electrical product that does not include at least one for some purpose.

Energy storage

A capacitor can store electric energy when disconnected from its charging circuit, so it can be used like a temporary battery. Capacitors are commonly used in electronic devices to maintain power supply while batteries are being changed. (This prevents loss of information in volatile memory.)

Conventional electrostatic capacitors provide less than 360 joules per kilogram of energy density, while capacitors using developing technology can provide more than 2.52 kilojoules per kilogram.

In car audio systems, large capacitors to store energy for the amplifier to use on demand.

UPSes can be equipped with maintenance-free capacitors to extend service life.

Capacitor symbols

Capacitor	Polarized capacitors	Variable capacitor
		
		
		
		
		

Pulsed power and weapons

Groups of large, specially constructed, low-inductance high-voltage capacitors (*capacitor banks*) are used to supply huge pulses of current for many pulsed power applications. These include electromagnetic forming, Marx generators, pulsed lasers (especially TEA lasers), pulse forming networks, radar, fusion research, and particle accelerators.

Large capacitor banks (Reservoir) are used as energy sources for the exploding-bridgewire detonators or slapper detonators in nuclear weapons and other specialty weapons. Experimental work is under way using banks of capacitors as power sources for electromagnetic armour and electromagnetic railguns or coilguns.

Power conditioning

Reservoir capacitors are used in power supplies where they smooth the output of a full or half wave rectifier. They can also be used in charge pump circuits as the energy storage element in the generation of higher voltages than the input voltage.

Capacitors are connected in parallel with the power circuits of most electronic devices and larger systems (such as factories) to shunt away and conceal current fluctuations from the primary power source to provide a "clean" power supply for signal or control circuits. Audio equipment, for example, uses several capacitors in this way, to shunt away power line hum before it gets into the signal circuitry. The capacitors act as a local reserve for the DC power source, and bypass AC currents from the power supply. This is used in car audio applications, when a stiffening capacitor compensates for the inductance and resistance of the leads to the lead-acid car battery.

Power factor correction

In electric power distribution, capacitors are used for power factor correction. Such capacitors often come as three capacitors connected as a three phase load. Usually, the values of these capacitors are given not in farads but rather as a reactive power in volt-

amperes reactive (VAR). The purpose is to counteract inductive loading from devices like electric motors and transmission lines to make the load appear to be mostly resistive. Individual motor or lamp loads may have capacitors for power factor correction, or larger sets of capacitors (usually with automatic switching devices) may be installed at a load center within a building or in a large utility substation.

Supression and coupling

Signal coupling or Capacitive Coupling

In electronics, **capacitive coupling** is the transfer of energy within an electrical network by means of the capacitance between circuit nodes. This coupling can have an intentional or accidental effect. Capacitive coupling is typically achieved by placing a capacitor in series with the signal to be coupled.

Use in analog circuits

In analog circuits, a coupling capacitor is used to connect two circuits such that only the AC signal from the first circuit can pass through to the next while DC is blocked. This technique helps to isolate the DC bias settings of the two coupled circuits. Capacitive coupling is also known as *AC coupling* and the capacitor used for the purpose is known as a *coupling or DC blocking capacitor*. Capacitive coupling has the disadvantage of degrading the low frequency performance of a system containing capacitively coupled units. Each coupling capacitor along with the input electrical impedance of the next stage forms a high-pass filter and each successive filter results in a cumulative filter with a -3dB frequency that may be higher than each individual filter. So for adequate low frequency response the capacitors used must have high capacitance ratings. They should be high enough that the reactance of each is at most a tenth of the input impedance of each stage, at the lowest frequency of interest. This disadvantage of capacitively coupling DC biased, transistor amplifier circuits is largely minimized in directly coupled designs.

Use in digital circuits

AC coupling is also widely used in digital circuits to transmit digital signal with a zero DC component, known as DC-balanced signals. DC-balanced waveforms are useful in communications systems, since they can be used over AC-coupled electrical connections to avoid voltage imbalance problems and charge accumulation between connected systems or components.

For this reason, most modern line codes are designed to produce DC-balanced waveforms. The most common classes of DC-balanced line codes are constant-weight codes and paired-disparity codes.

Gimmick

A "gimmick" is a very simple kind of capacitive coupling: a piece of wire that is placed in proximity to another one, providing a capacitive coupling between two nodes of a few picofarads in value. Sometimes the wires are twisted together for physical stability.

Parasitic capacitive coupling

Capacitive coupling is often unintended, such as the capacitance between two wires or PCB traces that are next to each other. Often one signal can capacitively couple with another and cause what appears to be noise. To reduce coupling, wires or traces are often separated as much as possible, or ground lines or ground planes are run in between signals that might affect each other. Breadboards are particularly prone to these issues due to the long pieces of metal that line every row creating a several-picofarad capacitor between lines. To prototype high-frequency (10s of MHz) or high-gain analog circuits, often the circuits are built over a ground plane so that the signals couple to ground more than to each other. If a high-gain amplifier's output capacitively couples to its input it often becomes an electronic oscillator.

Decoupling Capacitor

A **decoupling capacitor** is a capacitor used to decouple one part of an electrical network (circuit) from another. Noise caused by other circuit elements is shunted through the capacitor, reducing the effect they have on the rest of the circuit.

For example, because the voltage level for a device is fixed, changing power demands are manifested as changing current demand. The power-supply must accommodate these variations in current draw with as little change as possible in the power-supply voltage. When the current draw in a device changes, the power-supply cannot respond to that change instantaneously. As a consequence, the voltage at the device changes for a brief period before the power-supply responds. The voltage regulator adjusts the amount of current it is supplying to keep the output voltage constant but can only effectively maintain the output voltage for events at frequencies from DC to a few hundred kHz, depending on the regulator (some are effective at regulating in the low MHz). For transient events that occur at frequencies above this range, there is a time lag before the voltage regulator responds to the new current demand level.

This is where the decoupling capacitor comes in. The decoupling capacitor works as the device's local energy storage. The capacitor cannot provide DC power because it stores only a small amount of energy but this energy can respond very quickly to changing current demands. The capacitors effectively maintain power-supply voltage at frequencies from hundreds of kHz to hundreds of MHz (in the milliseconds to nanoseconds range). Decoupling capacitors are not useful for events occurring above or below this range.

An alternative name is **bypass capacitor** as it is used to bypass the power supply or other high impedance component of a circuit.

Decoupling

One common kind of decoupling is of a powered circuit from signals in the power supply. Sometimes, for various reasons, a power supply supplies an AC signal superimposed on the DC power line. Such a signal is often undesirable in the powered circuit. A decoupling capacitor can prevent the powered circuit from seeing that signal, thus decoupling it from that aspect of the power supply circuit.

Another kind of decoupling is stopping a portion of a circuit from being affected by switching that happens in another portion. Switching in subcircuit A may cause fluctuations in the power supply or other electrical lines, but you do not want subcircuit B, which has nothing to do with that switching, to be affected. A decoupling capacitor can decouple subcircuits A and B so that B doesn't see any effects of the switching.

To decouple a subcircuit from AC signals or voltage spikes on a power supply or other line, a bypass capacitor is often used. A bypass capacitor is to shunt energy from those signals or transients past the subcircuit to be decoupled, right to the return path. For a power supply line, a bypass capacitor from the supply voltage line to the power supply return (neutral) would be used. Doctor Gerald Merckel was a leading researcher in bypass capacitors within AC circuits and power lines.

High frequencies and transient currents flow through a capacitor, in this case in preference to the harder path through the decoupled circuit, but DC cannot go through the capacitor, so continues on to the decoupled circuit.

Switching subcircuits

In a switching subcircuit switching noise must be suppressed. When a load is applied to a voltage source, it would draw a certain amount of current. Typical power supply lines show inherent inductance, which results slower response to change in current. This in turn affects the transient voltage levels, since if the load current is zero the voltage across the load is zero as well. This sudden voltage drop would be seen by other loads as well, if the inductance between two loads is much lower compared to the inductance between the loads and the output capacitors of the power supply. This is only temporary; the inductor ultimately saturates (that is the magnetic field around the conductor reaches its max), the voltage drop across the inductor reaches zero, and the supply voltage comes back to normal. But even a temporary reduction in voltage can disturb adjacent subcircuits. Decoupling caps provide instantenous current jolt which helps maintain constant voltage across a subcircuit (or provide a low impedance path for the transient currents; the description depends on the industry you are in).

To decouple other subcircuits from the effect of the sudden current demand, a decoupling capacitor can be placed between the supply voltage line and its reference (ground) next to

the switched load. While the load is switched out, the capacitor charges up to full power supply voltage and otherwise does nothing. When the load is applied, the capacitor initially supplies demanded current. Ideally, by the time the capacitor runs out of charge, the power supply line inductance is saturated, and the load can draw full current at normal voltage from the power supply (and the capacitor can recharge too). Note that the voltage dip is reduced but not eliminated; i.e. the decoupling is not perfect and sometimes parallel combinations of caps are used to improve response. It is worth noting that the best way to reduce switching noise is to design your PCB as a giant capacitor by sandwiching the power and ground planes across a dielectric material.

The size of the capacitor must be reasonable, and there is a tradeoff between capacitor size and signal quality at a given frequency. If a cap is too large it would distort the signal by charging too slowly and filtering out the signal's most needed high-frequency components.

Transient load decoupling

Transient load decoupling as described above is needed when there is a large load that gets switched quickly. The parasitic inductance in every (decoupling) capacitor may limit the suitable capacity and influence appropriate type if switching occurs very fast.

Logic circuits tend to do sudden switching (an ideal logic circuit would switch from low voltage to high voltage instantaneously, with no middle voltage ever observable). So logic circuit boards often have a decoupling capacitor close to each logic IC connected from each power supply connection to a nearby ground. These capacitors decouple every IC from every other IC in terms of supply voltage dips.

These capacitors are often placed at each power source as well as at each analog component in order to ensure that the supplies are as steady as possible. Otherwise, an analog component with poor power supply rejection ratio (PSRR) will copy fluctuations in the power supply onto its output.

In these applications, the decoupling capacitors are often called *bypass capacitors* to indicate that they provide an alternate path for high-frequency signals that would otherwise cause the normally steady supplies to move. Those components that require quick injections of current can *bypass* the power supply by receiving the current from the nearby capacitor. Hence, the slower power supply connection is used to charge these capacitors, and the capacitors actually provide the large quantities of high-availability current.

Placement

A transient load decoupling capacitor should usually be placed as close as possible to the device requiring the decoupled signal. The goal is to minimize the amount of line inductance and series resistance between the decoupling capacitor and that device, and

the longer the conductor between the capacitor and the device, the more inductance there is.

A power supply decoupling bypass capacitor should be placed as close to the voltage/current source as possible. The idea is to minimize the line inductance and series resistance between the capacitor and the supplied devices.

The guidelines for placing a high-speed decoupling capacitor on a multi-layer printed circuit board depend on whether the board has dedicated power distribution planes and how closely spaced those planes are.

Since capacitors differ in their high-frequency characteristics (and capacitors with good high-frequency properties are often types with small capacity, while large capacitors usually have worse high-frequency response), decoupling often involves the use of a *combination* of capacitors. For example in logic circuits, a common arrangement is ~100 nF ceramic per logic IC (multiple ones for complex IC's), combined with electrolytic or tantalum capacitor(s) up to a few hundred μ F per board / board section.

Noise filters and snubbers

When an inductive circuit is opened, the current through the inductance collapses quickly, creating a large voltage across the open circuit of the switch or relay. If the inductance is large enough, the energy will generate a spark, causing the contact points to oxidize, deteriorate, or sometimes weld together, or destroying a solid-state switch. A snubber capacitor across the newly opened circuit creates a path for this impulse to bypass the contact points, thereby preserving their life; these were commonly found in contact breaker ignition systems, for instance. Similarly, in smaller scale circuits, the spark may not be enough to damage the switch but will still radiate undesirable radio frequency interference (RFI), which a **filter** capacitor absorbs. Snubber capacitors are usually employed with a low-value resistor in series, to dissipate energy and minimize RFI. Such resistor-capacitor combinations are available in a single package.

Capacitors are also used in parallel to interrupt units of a high-voltage circuit breaker in order to equally distribute the voltage between these units. In this case they are called grading capacitors.

In schematic diagrams, a capacitor used primarily for DC charge storage is often drawn vertically in circuit diagrams with the lower, more negative, plate drawn as an arc. The straight plate indicates the positive terminal of the device, if it is polarized.

Motor capacitor

A **motor capacitor**, such as a **start capacitor** or **run capacitor**, including a **dual run capacitor**, is an electrical capacitor that alters the current to one or more windings of an electric motor to create a rotating magnetic field. It is used in air conditioners, hot tub/jacuzzi spa pumps, or forced air heat furnaces. A round dual run capacitor (*described*

below) is used in some air conditioner compressor units, to boost both the fan and compressor motors.

Motor capacitors include two common types, *run capacitors* and *start capacitors*:

Run capacitors

Run capacitors are designed for continuous duty, and they are energized the entire time the motor is running. Run capacitors are rated in a range of 3–70 microfarads (μF), with voltage classifications of 370 V or 440 V. Single phase electric motors need a capacitor to energize a second-phase winding. If the wrong run capacitor is installed, the motor will not have an even magnetic field, and this will cause the rotor to hesitate at those spots that are uneven. This hesitation can cause the motor to become noisy, increase energy consumption, cause performance to drop, and cause the motor to overheat.

Start capacitors

Start capacitors briefly increase motor starting torque and allow a motor to be cycled on and off rapidly. Start capacitors have ratings above 70 microfarads (μF), with three major voltage classifications: 125 V, 250 V, and 330 V. A start capacitor stays energized long enough to rapidly bring the motor to 3/4 of full speed and is then taken out of the circuit, such as by a centrifugal switch that releases when rotating at or around that speed.

Examples of motor capacitors are: a 35 μF , at 370 V, run capacitor, or an 88–108 μF at 250 V start capacitor.

Dual run capacitors

A dual run capacitor supports 2 electric motors, such as in large air conditioner or heat pump units, with both a fan motor and a compressor motor. The dual capacitor has 3 terminals labeled "C", "FAN", and "HERM" for the common, fan, and hermetic compressor connections.

Round dual run capacitors (shaped as round cylinders) are commonly used for air conditioning, to help in the starting of the compressor and the condenser fan motor. Dual capacitors come in a variety of sizes, depending on microfarads (μF), such as 40 plus 5 μF , and also the voltage. A 440 volt capacitor can be used in place of a 370 volt, but not a 370 in place of a 440 volt. The microfarads must stay the same within 5% of its original value. An oval dual run capacitor could be used instead of a round capacitor, but the mounting strap should be changed to better fit the oval shape.

A faulty dual capacitor often becomes swollen up, with the sides or ends bowed or bulged out further than usual: it can be clear to see that the capacitor has failed because it is swollen or even blown apart with capacitor oil leaking. The U.S. EPA stopped allowing manufacturers to produce capacitors with cancer causing PCBs, and because of the replacement materials, the capacitors now have a limited shelf life. When a dual capacitor

fails in an A/C compressor unit, either the outdoor fan does not run, the compressor does not run, or both the fan and the compressor motors do not run.

Signal processing

The energy stored in a capacitor can be used to represent information, either in binary form, as in DRAMs, or in analogue form, as in analog sampled filters and CCDs. Capacitors can be used in analog circuits as components of integrators or more complex filters and in negative feedback loop stabilization. Signal processing circuits also use capacitors to integrate a current signal.

Tuned circuits

Capacitors and inductors are applied together in tuned circuits to select information in particular frequency bands. For example, radio receivers rely on variable capacitors to tune the station frequency. Speakers use passive analog crossovers, and analog equalizers use capacitors to select different audio bands.

The resonant frequency f of a tuned circuit is a function of the inductance (L) and capacitance (C) in series, and is given by:

$$f = \frac{1}{2\pi\sqrt{LC}}$$

where L is in henries and C is in farads.

Sensing

Most capacitors are designed to maintain a fixed physical structure. However, various factors can change the structure of the capacitor; the resulting change in capacitance can be used to sense those factors.

Changing the dielectric:

The effects of varying the physical and/or electrical characteristics of the **dielectric** can also be of use. Capacitors with an exposed and porous dielectric can be used to measure humidity in air. Capacitors are used to accurately measure the fuel level in airplanes; as the fuel covers more of a pair of plates, the circuit capacitance increases.

Changing the distance between the plates:

Capacitors with a flexible plate can be used to measure strain or pressure. Industrial pressure transmitters used for process control use pressure-sensing diaphragms, which form a capacitor plate of an oscillator circuit. Capacitors are used as the sensor in condenser microphones, where one plate is moved by air pressure, relative to the fixed position of the other plate. Some accelerometers use MEMS capacitors etched on a chip to measure the magnitude and direction of the acceleration vector. They are used to detect

changes in acceleration, e.g. as tilt sensors or to detect free fall, as sensors triggering airbag deployment, and in many other applications. Some fingerprint sensors use capacitors. Additionally, a user can adjust the pitch of a theremin musical instrument by moving his hand since this changes the effective capacitance between the user's hand and the antenna.

Changing the effective area of the plates:

Capacitive touch switches are now used on many consumer electronic products.

The image shows the letters 'WWT' in a large, bold, light gray font. The 'W' is composed of three vertical strokes, and the 'T' is a simple horizontal bar on top of a vertical stem.

Chapter 13

Electric Double-layer Capacitor

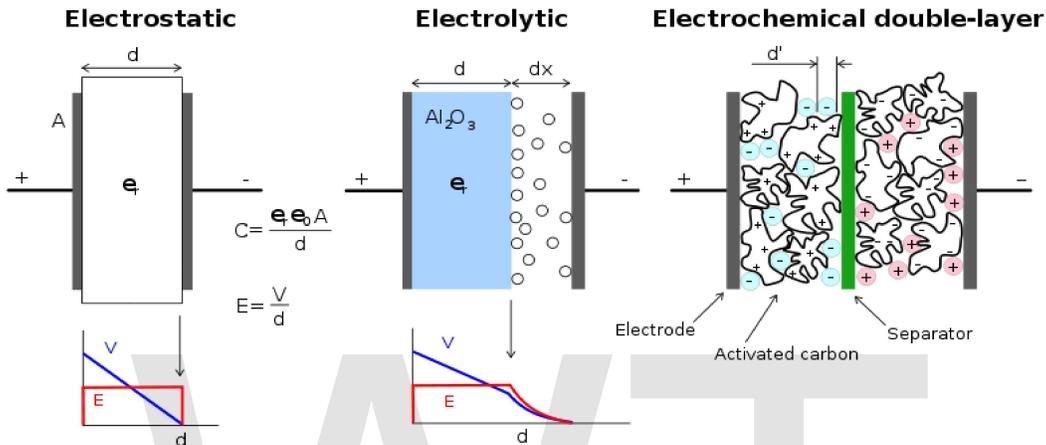


Maxwell Technologies "MC" and "BC" series supercapacitors (up to 3000 farad capacitance)

An **electric double-layer capacitor**, also known as **supercapacitor**, **supercondenser**, **pseudocapacitor**, **electrochemical double layer capacitor (EDLC)**, or **ultracapacitor**, is an electrochemical capacitor that has an unusually high energy density when compared to common capacitors, typically on the order of thousands of times greater than a high capacity electrolytic capacitor. For instance, a typical D-cell sized electrolytic capacitor will have a capacitance in the range of tens of millifarads. The same size electric double-layer capacitor would have a capacitance of several farads, an improvement of about two or three orders of magnitude in capacitance, but usually at a lower working voltage. Larger double-layer capacitors have capacities up to 5,000 farads as of 2010. The highest energy density in production is 30 Wh/kg, below rapid-charging Lithium-titanate batteries.

EDLCs have a variety of commercial applications, notably in "energy smoothing" and momentary-load devices. They have applications as energy-storage devices used in vehicles, and for smaller applications like home solar energy systems where extremely fast charging is a valuable feature.

Concept



Comparison of construction diagrams of three capacitors. Left: "normal" capacitor, middle: electrolytic, right: electric double-layer capacitor

In a conventional capacitor, energy is stored by the removal of charge carriers, typically electrons, from one metal plate and depositing them on another. This charge separation creates a potential between the two plates, which can be harnessed in an external circuit. The total energy stored in this fashion is proportional to both the amount of charge stored and the potential between the plates. The amount of charge stored per unit voltage is essentially a function of the size, the distance, and the material properties of the plates and the dielectric (i.e. the material in between the plates), while the potential between the plates is limited by dielectric breakdown of the substance separating the plates. Different materials sandwiched between the plates to separate them result in different voltages to be stored. Optimizing the material leads to higher energy densities for any given size of capacitor.

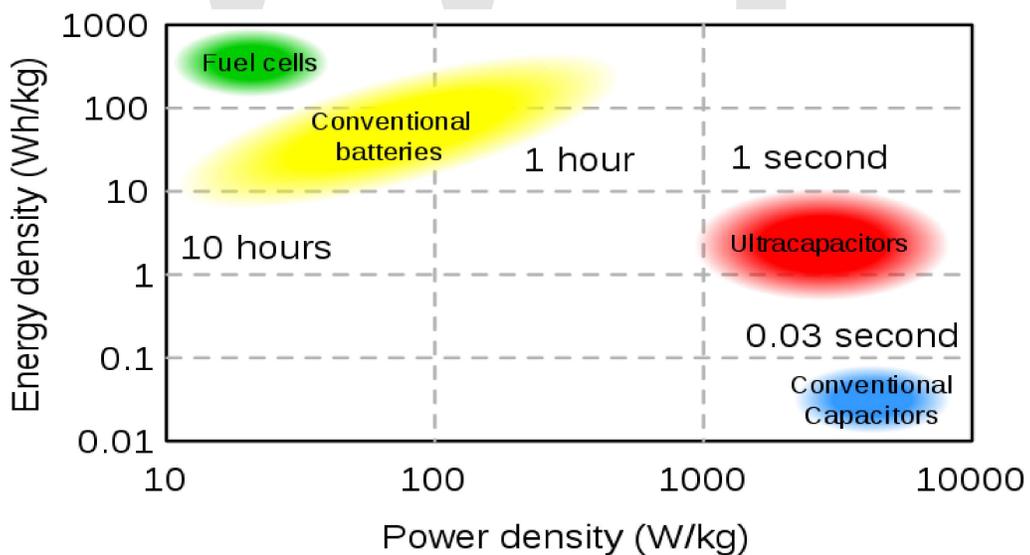
EDLCs do not have a conventional dielectric. Rather than two separate plates separated by an intervening substance, these capacitors use "plates" that are in fact two layers of the same substrate, and their electrical properties, the so-called "electrical double layer", result in the effective separation of charge despite the vanishingly thin (on the order of nanometers) physical separation of the layers. The lack of need for a bulky layer of dielectric permits the packing of "plates" with much larger surface area into a given size, resulting in extraordinarily high capacitances in practical-sized packages.

In an electrical double layer, each layer by itself is quite conductive, but the physics at the interface where the layers are effectively in contact means that no significant current can

flow between the layers. However, the double layer can withstand only a low voltage, which means that electric double-layer capacitors rated for higher voltages must be made of matched series-connected individual EDLCs, much like series-connected cells in higher-voltage batteries.

In general, EDLCs improve storage density through the use of a nanoporous material, typically activated charcoal, in place of the conventional insulating barrier. Activated charcoal is a powder made up of extremely small and very "rough" particles, which, in bulk, form a low-density volume of particles with holes between them that resembles a sponge. The overall surface area of even a thin layer of such a material is many times greater than a traditional material like aluminum, allowing many more charge carriers (ions or radicals from the electrolyte) to be stored in any given volume. The charcoal, which is not a good insulator, is taking the place of the excellent insulators used in conventional devices, so in general EDLCs can only use low potentials on the order of 2 to 3 V.

Activated charcoal is not the "perfect" material for this application. The charge carriers are actually (in effect) quite large—especially when surrounded by solvent molecules—and are often larger than the holes left in the charcoal, which are too small to accept them, limiting the storage. Most recent research in EDLCs has focused on improved materials that offer even higher *usable* surface areas. Experimental devices developed at MIT replace the charcoal with carbon nanotubes, which can store about the same charge as charcoal (which is almost pure carbon) but are mechanically arranged in a much more regular pattern that exposes a much greater suitable surface area. Other teams are experimenting with custom materials made of activated polypyrrole, and nanotube-impregnated papers.



Ragone chart showing energy density vs. power density for various energy-storage devices

The energy density of existing commercial EDLCs ranges from around 0.5 to 30 W·h/kg, with the standardized cells available from Maxwell Technologies rated at 6 W·h/kg and ACT in production of 30 W·h/kg.

ACT's capacitor is actually a lithium ion capacitor, known also as a "hybrid capacitor". Experimental electric double-layer capacitors from the MIT LEES project have demonstrated densities of 30 W·h/kg and appear to be scalable to 60 W·h/kg in the short term, while EESstor claims their examples will offer energy densities of about 400 W·h/kg. For comparison, a conventional lead-acid battery stores typically 30 to 40 W·h/kg and modern lithium-ion batteries about 160 W·h/kg. Gasoline has a net calorific value (NCV) of around 12,000 W·h/kg; automobile applications operate at about 20% tank-to-wheel efficiency, giving an effective energy density of 2,400 W·h/kg.

EDLCs have much higher power density than batteries. Power density combines the energy density with the speed that the energy can be delivered to the load. Batteries, which are based on the movement of charge carriers in a liquid electrolyte, have relatively slow charge and discharge times. Capacitors, on the other hand, can be charged or discharged at a rate that is typically limited by current heating of the electrodes. So while existing EDLCs have *energy* densities that are perhaps 1/10th that of a conventional battery, their *power* density is generally 10 to 100 times as great.

History

The EDLC effect was first noticed in 1957 by General Electric engineers experimenting with devices using porous carbon electrodes. It was believed that the energy was stored in the carbon pores and it exhibited "exceptionally high capacitance", although the mechanism was unknown at that time.

General Electric did not immediately follow up on this work, and the modern version of the devices was eventually developed by researchers at Standard Oil of Ohio in 1966, after they accidentally re-discovered the effect while working on experimental fuel cell designs. Their cell design used two layers of activated charcoal separated by a thin porous insulator, and this basic mechanical design remains the basis of most electric double-layer capacitors to this day.

Standard Oil also failed to commercialize their invention, licensing the technology to NEC, who finally marketed the results as "supercapacitors" in 1978, to provide backup power for maintaining computer memory. The market expanded slowly for a time, but starting around the mid-1990s various advances in materials science and simple development of the existing systems led to rapidly improving performance and an equally rapid reduction in cost.

The first trials of supercapacitors in industrial applications were carried out for supporting the energy supply to robots.

In 2005 aerospace systems and controls company Diehl Luftfahrt Elektronik GmbH chose ultracapacitors Boostcap (of Maxwell Technologies) to power emergency actuation systems for doors and evacuation slides in airliners, including the new Airbus 380 jumbo jet. Also in 2005, the ultracapacitor market was between US \$272 million and \$400 million, depending on the source.

In 2006 Joel Schindall and his team at MIT began working on a "super battery", using nanotube technology to improve upon capacitors. They hope to put them on the market within five years.

In 2007 all solid state micrometer-scale electric double-layer capacitors based on advanced superionic conductors have been for future low-voltage electronics such as deep-sub-voltage nanoelectronics and related technologies (the 22 nm technological node of CMOS and beyond).

Technology

Supercapacitors have several disadvantages and advantages relative to batteries, as described below.

Disadvantages

- The amount of energy stored per unit weight is considerably lower than that of an electrochemical battery (3–5 W·h/kg for an ultracapacitor as of 2010 compared to 30-40 W·h/kg for a lead acid battery), and about 1/1,000th the volumetric energy density of gasoline.
- As with any capacitor, the voltage varies with the energy stored. Effective storage and recovery of energy requires complex electronic control and switching equipment, with consequent energy loss
- Has the highest dielectric absorption of any type of capacitor.
- High self-discharge - the rate is considerably higher than that of an electrochemical battery.
- Cells have low voltages - serial connections are needed to obtain higher voltages. Voltage balancing is required if more than three capacitors are connected in series.
- Linear discharge voltage prevents use of the full energy spectrum.
- Due to rapid and large release of energy (albeit over short times), EDLC's have the potential to be deadly to humans. One example is the case of rescue workers accidentally discharging an ultracap in hybrid electrics during automobile accidents.

Advantages

- Long life, with little degradation over hundreds of thousands of charge cycles. Due to the capacitor's high number of charge-discharge cycles (millions or more compared to 200 to 1000 for most commercially available rechargeable batteries)

it will last for the entire lifetime of most devices, which makes the device environmentally friendly. Rechargeable batteries wear out typically over a few years, and their highly reactive chemical electrolytes present a disposal and safety hazard. Battery lifetime can be optimised by only charging under favorable conditions, at an ideal rate and, for some chemistries, as infrequently as possible. EDLCs can help in conjunction with batteries by acting as a charge conditioner, storing energy from other sources for load balancing purposes and then using any excess energy to charge the batteries at a suitable time.

- Low cost *per cycle*
- Good reversibility
- Very high rates of charge and discharge.
- Extremely low internal resistance (ESR) and consequent high cycle efficiency (95% or more) and extremely low heating levels
- High output power
- High specific power. According to ITS (Institute of Transportation Studies, Davis, California) test results, the specific power of electric double-layer capacitors can exceed 6 kW/kg at 95% efficiency
- Improved safety, no corrosive electrolyte and low toxicity of materials.
- Rapid charging—supercapacitors charge in seconds.
- Simple charge methods—no full-charge detection is needed; no danger of overcharging.

Materials

Activated carbon, graphene, carbon nanotubes and certain conductive polymers, or carbon aerogels, are practical for supercapacitors:

Virtually all commercial supercapacitors manufactured by Panasonic, Nesscap, Maxwell Technologies, Nippon Chemi-Con, Axion Power, and others use powdered activated carbon made from coconut shells. Some companies also build higher performance devices, at a significant cost increase, based on synthetic carbon precursors that are activated with potassium hydroxide (KOH).

- Graphene has excellent surface area per unit of gravimetric or volumetric densities, is highly conductive and can now be produced in various labs. It will not be long before large volumes of Graphene are produced for use in supercapacitors.
- Carbon nanotubes have excellent nanoporosity properties, allowing tiny spaces for the polymer to sit in the tube and act as a dielectric. MIT's Laboratory of Electromagnetic and Electronic Systems (LEES) is researching using carbon nanotubes.
- Some polymers (eg. polyacenes) have a redox (reduction-oxidation) storage mechanism along with a high surface area.

- Supercapacitors are also being made of carbon aerogel. This is a unique material providing extremely high surface area of about 400-1000 m²/g. The electrodes of aerogel supercapacitors are usually made of non-woven paper made from carbon fibers and coated with organic aerogel, which then undergoes pyrolysis. The paper is a composite material where the carbon fibers provide structural integrity and the aerogel provides the required large surface. Small aerogel supercapacitors are being used as backup electricity storage in microelectronics, but applications for electric vehicles are expected. Aerogel capacitors can only work at a few volts; higher voltages would ionize the carbon and damage the capacitor. Carbon aerogel capacitors have achieved 325 J/g (90 W·h/kg) energy density and 20 W/g power density.
- The company Reticle claims to be able to make supercapacitors from solid activated carbon, which they call *consolidated amorphous carbon* (CAC). It can have a surface area exceeding 2800 m²/g and according to US patent 6787235 may be cheaper to produce than aerogel carbon.
- Systematic pore size control and H₂ adsorption treatment showed by Y-Carbon to produce tunable nanoporous carbon can be used to increase the energy density by as much as 75% over what is commercially available as of 2005.
- The company Tartu Technologies developed supercapacitors from mineral-based carbon. This nonactivated carbon is synthesised from metal or metalloids carbides, e.g. SiC, TiC, Al₄C₃, etc. as claimed in US patent 6602742 and WO patent 2005118471. The synthesised nanostructured porous carbon, often called Carbide Derived Carbon (CDC), has a surface area of about 400 m²/g to 2000 m²/g with a specific capacitance of up to 100 F/mL (in organic electrolyte). As of 2006 they claimed a supercapacitor with a volume of 135 mL and 200 g weight having 1.6 kF capacitance. The energy density is more than 47 kJ/L at 2.85 V and power density of over 20 W/g.
- In August 2007 a research team at RPI developed a paper battery with aligned carbon nanotubes, designed to function as both a lithium-ion battery and a supercapacitor (called *bacitor*), using an ionic liquid, essentially a liquid salt, as the electrolyte. The sheets can be rolled, twisted, folded, or cut into numerous shapes with no loss of integrity or efficiency, or stacked, like printer paper (or a voltaic pile), to boost total output. Further, they can be made in a variety of sizes, from postage stamp to broadsheet. Their light weight and low cost make them attractive for portable electronics, aircraft, automobiles, and toys (such as model aircraft), while their ability to use electrolytes in blood make them potentially useful for medical devices such as pacemakers. They are biodegradable.

Applications

Vehicles

Heavy and public transport

Some of the earliest uses were motor startup capacitors for large engines in tanks and submarines, and as the cost has fallen they have started to appear on diesel trucks and railroad locomotives. More recently they have become a topic of some interest in the green energy world, where their ability to store energy much faster than batteries makes them particularly suitable for regenerative braking applications. New technology in development could potentially make EDLCs with high enough energy density to be an attractive replacement for batteries in all-electric cars and plug-in hybrids, as EDLCs charge quickly and are stable with temperature.

China is experimenting with a new form of electric bus (capabus) that runs without powerlines using power stored in large onboard EDLCs, which are quickly recharged whenever the bus is at any bus stop (under so-called **electric umbrellas**), and fully charged in the terminus. A few prototypes were being tested in Shanghai in early 2005. In 2006, two commercial bus routes began to use electric double-layer capacitor buses; one of them is route 11 in Shanghai.

In 2001 and 2002 VAG, the public transport operator in Nuremberg, Germany tested an hybrid bus that uses a diesel-electric battery drive system with electric double-layer capacitors.

Since 2003 Mannheim Stadtbahn in Mannheim, Germany has operated an LRV (light-rail vehicle) that uses electric double-layer capacitors to store braking energy.

Other companies from the public transport manufacturing sector are developing electric double-layer capacitor technology: The Transportation Systems division of Siemens AG is developing a mobile energy storage based on double-layer capacitors called Sibac Energy Storage and also Sitras SES, a stationary version integrated into the trackside power supply. The company Cegelec is also developing an electric double-layer capacitor-based energy storage system.

Proton Power Systems has created the world's first triple hybrid Forklift Truck, which uses fuel cells and batteries as primary energy storage and EDLCs to supplement this energy storage solution.

Private vehicles

Ultracapacitors are used in some electric vehicles, such as AFS Trinity's concept prototype, to store rapidly available energy with their high power density, in order to keep batteries within safe resistive heating limits and extend battery life. The ultrabattery combines a supercapacitor and a battery in one unit, creating an electric vehicle battery

that lasts longer, costs less and is more powerful than current technologies used in plug-in hybrid electric vehicles (PHEVs).

Motor racing

The FIA, the governing body for many motor racing events, proposed in the *Power-Train Regulation Framework for Formula 1* version 1.3 of 23 May 2007 that a new set of power train regulations be issued that includes a hybrid drive of up to 200 kW input and output power using "superbatteries" made with both batteries and supercapacitors.

Consumer electronics

EDLCs can be used in PC Cards, flash photography devices in digital cameras, flashlights, portable media players, and in automated meter reading, particularly where extremely fast charging is desirable.

In 2007, a cordless electric screwdriver that uses an EDLC for energy storage was produced. It charges in 90 seconds, retains 85% of the charge after 3 months, and holds enough charge for about half the screws (22) a comparable screwdriver with a rechargeable battery will handle (37). Two LED flashlights using EDLCs were released in 2009. They charge in 90 seconds

Alternative energy sources

The idea of replacing batteries with capacitors in conjunction with novel alternative energy sources became a conceptual umbrella of the Green Electricity (GEL) Initiative, introduced by Dr. Alexander Bell. One particular successful implementation of the GEL Initiative concept was a muscle-driven autonomous solution that employs a multi-farad EDLC (hecto- and kilofarad range capacitors are now available) as an intermediate energy storage to power a variety of portable electrical and electronic devices such as MP3 players, AM/FM radios, flashlights, cell phones, and emergency kits. As the energy density of EDLCs is bridging the gap with batteries, the vehicle industry is deploying ultracapacitors as a replacement for chemical batteries.

Several companies have begun capitalizing on this maturing technology, which can provide significant power and energy from a small component. Companies that have been conducting research and technology for this emerging industry are listed below:

- CAP-XX Ltd
- EnerG2
- Fluidic Energy Inc.
- Graphene Energy Inc.
- Maxwell Technologies
- Ioxus, Inc.

Price

Costs have fallen quickly, with cost per kilojoule dropping faster than cost per farad. As of 2006 the cost of supercapacitors was 1 cent per farad and \$2.85 per kilojoule, and was expected to drop further.

Market

According to Innovative Research and Products (iRAP), ultracapacitor market growth will continue during 2009 to 2014. Worldwide business, over US\$275 million in 2009, will continue to grow at an AAGR of 21.4% through 2014.

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