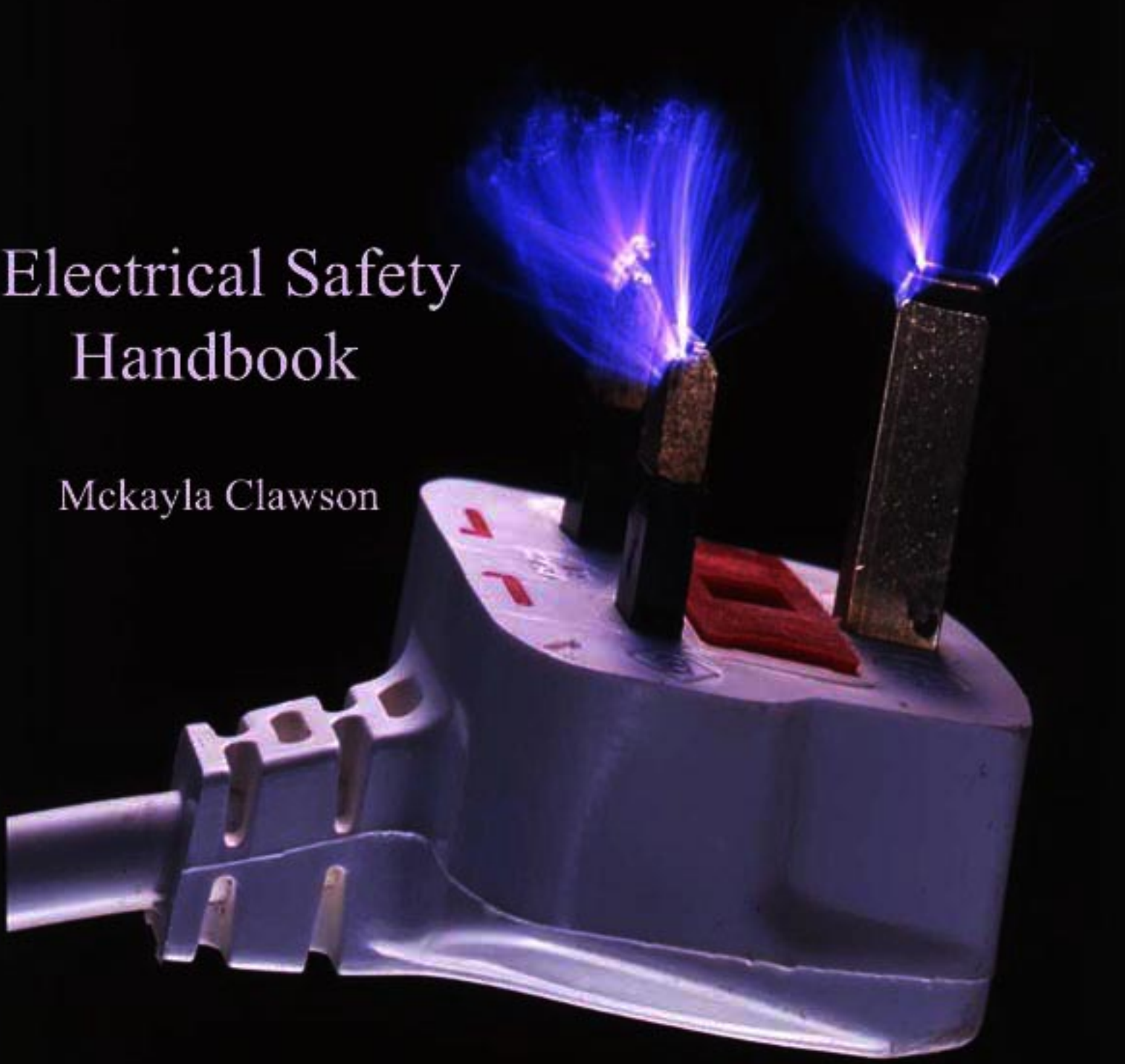
Electrical Safety Handbook

Mckayla Clawson



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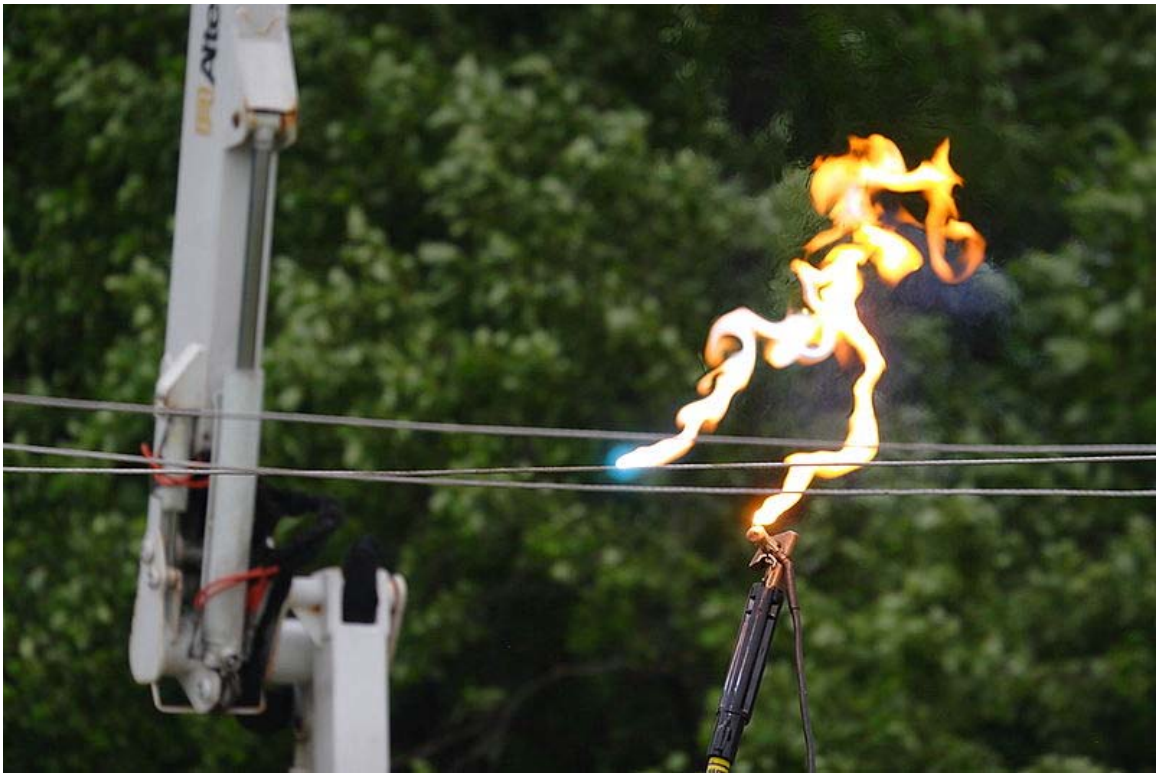
Electric Shock

Electrical injury

A person who was affected by a nearby lightning strike. Note the slight branching redness travelling up his leg from the effects of the current.

ICD-10 T75.4



1700 volts burns a grounded hot dog

Electric shock of a (human) body with any source of electricity that causes a sufficient current through the skin, muscles or hair. Typically, the expression is used to denote an unwanted exposure to electricity, hence the effects are considered undesirable.

The minimum current a human can feel depends on the current type (AC or DC) and frequency. A person can feel at least 1 mA (rms) of AC at 60 Hz, while at least 5 mA for DC. The current may, if it is high enough, cause tissue damage or fibrillation which leads to cardiac arrest. 60 mA of AC (rms, 60 Hz) or 300–500 mA of DC can cause fibrillation. A sustained electric shock from AC at 120 V, 60 Hz is an especially dangerous source of ventricular fibrillation because it usually exceeds the let-go threshold, while not delivering enough initial energy to propel the person away from the source. However, the potential seriousness of the shock depends on paths through the body that the currents take. Death caused by an electric shock is called electrocution.

If the voltage is less than 200 V, then the human skin, more precisely the stratum corneum, is the main contributor to the impedance of the body in the case of a macroshock—the passing of current between two contact points on the skin. The characteristics of the skin are non-linear however. If the voltage is above 450–600 V, then dielectric breakdown of the skin occurs. The protection offered by the skin is lowered by perspiration, and this is accelerated if electricity causes muscles to contract above the let-go threshold for a sustained period of time.

If an electrical circuit is established by electrodes introduced in the body, bypassing the skin, then the potential for lethality is much higher if a circuit though the heart is established. This is known as a microshock. Currents of only 10 μA can be sufficient to cause fibrillation in this case. This is a concern in modern hospital settings when the patient is connected to multiple devices.

Signs and symptoms

Burns

Heating due to resistance can cause extensive and deep burns. Voltage levels of 500 to 1000 volts tend to cause internal burns due to the large energy (which is proportional to the duration multiplied by the square of the voltage divided by resistance) available from the source. Damage due to current is through tissue heating. It is a relatively unknown fact that more electrical workers die from burns than from an electric shock. In fact, only around 20% of deaths are the result of electric shock.

Ventricular fibrillation

A domestic power supply voltage (110 or 230 V), 50 or 60 Hz AC current through the chest for a fraction of a second may induce ventricular fibrillation at currents as low as 60 mA. With DC, 300 to 500 mA is required. If the current has a direct pathway to the heart (e.g., via a cardiac catheter or other kind of electrode), a much lower current of less than 1 mA (AC or DC) can cause fibrillation. If not immediately treated by defibrillation, fibrillations are usually lethal because all the heart muscle cells move independently instead of in the coordinated pulses needed to pump blood to maintain circulation. Above 200 mA, muscle contractions are so strong that the heart muscles cannot move at all.

Neurological effects

Current can cause interference with nervous control, especially over the heart and lungs. Repeated or severe electric shock which does not lead to death has been shown to cause neuropathy. Recent research has found that functional differences in neural activation during spatial working memory and implicit learning oculomotor tasks have been identified in electrical shock victims.

When the current path is through the head, it appears that, with sufficient current, loss of consciousness almost always occurs swiftly. (This is borne out by some limited self-experimentation by early designers of the electric chair and by research from the field of animal husbandry, where electric stunning has been extensively studied.)

Arc-flash hazards

One major corporation found that up to 80 percent of its electrical injuries involve thermal burns due to arcing faults. The arc flash in an electrical fault produces the same type of light radiation from which electric welders protect themselves using face shields

with dark glass, heavy leather gloves, and full-coverage clothing. The heat produced may cause severe burns, especially on unprotected flesh. The blast produced by vaporizing metallic components can break bones and irreparably damage internal organs. The degree of hazard present at a particular location can be determined by a detailed analysis of the electrical system, and appropriate protection worn if the electrical work must be performed with the electricity on.

Pathophysiology

Body resistance

The voltage necessary for electrocution depends on the current through the body and the duration of the current. Ohm's law states that the current drawn depends on the resistance of the body. The resistance of human skin varies from person to person and fluctuates between different times of day. The NIOSH states "Under dry conditions, the resistance offered by the human body may be as high as 100,000 Ohms. Wet or broken skin may drop the body's resistance to 1,000 Ohms," adding that "high-voltage electrical energy quickly breaks down human skin, reducing the human body's resistance to 500 Ohms."

The International Electrotechnical Commission gives the following values for the total body impedance of a hand to hand circuit for dry skin, large contact areas, 50 Hz AC currents (the columns contain the distribution of the impedance in the population percentile; for example at 100 V 50% of the population had an impedance of 1875Ω or less):

Voltage	5%	50%	95%
25 V	1,750 Ω	3,250 Ω	6,100 Ω
100 V	1,200 Ω	1,875 Ω	3,200 Ω
220 V	1,000 Ω	1,350 Ω	2,125 Ω
1000 V	700 Ω	1,050 Ω	1,500 Ω

Point of entry

- Macroshock: Current across intact skin and through the body. Current from arm to arm, or between an arm and a foot, is likely to traverse the heart, therefore it is much more dangerous than current between a leg and the ground. This type of shock by definition must pass into the body through the skin.
- Microshock: Very small, current source with a pathway directly connected to the heart tissue. The shock is required to be administered from inside the skin, directly to the heart i.e. a pacemaker lead, or a guide wire, conductive catheter etc. connected to a source of current. This is a largely theoretical hazard as modern devices used in these situations include protections against such currents.

Lethality

The lethality of an electric shock is dependent on several variables:

1. Current (the higher the current, the more likely it is lethal)
2. Duration (the longer the duration, the more likely it is lethal — safety switches may limit time of current flow)
3. Pathway (if current flows through the heart muscle, it is more likely to be lethal)
4. Voltage (the higher the voltage, the lower the resistance and the more likely dielectric breakdown occurs)

Other issues affecting lethality are frequency, which is an issue in causing cardiac arrest or muscular spasms, and pathway—if the current passes through the chest or head there is an increased chance of death. From a main circuit or power distribution panel the damage is more likely to be internal, leading to cardiac arrest..

The comparison between the dangers of alternating current and direct current has been a subject of debate ever since the War of Currents in the 1880s.

It is sometimes suggested that human lethality is most common with alternating current at 100–250 volts; however, death has occurred below this range, with supplies as low as 32 volts. Assuming a steady current flow (as opposed to static electricity), shocks above 2700 volts are often fatal, with those above 11000 volts being usually fatal. Shocks with voltages over 40,000 volts are almost invariably fatal. However, Harry F. Mcgrew came into direct contact with a 340,000 volt transmission line in Huntington Canyon, Utah, and survived. According to the Guinness Book of World Records, this is the largest known electric shock that was survived. Brian Latasa also survived a 230,000 volt shock in Griffith Park, Los Angeles, according to Guinness.

Epidemiology

There were 550 electrocutions in the US in 1993, which translates to 2.1 deaths per million inhabitants. At that time, the incidence of electrocutions was decreasing. Electrocutions in the workplace make up the majority of these fatalities. From 1980–1992, an average of 411 workers were killed each year by electrocution.

Chapter 2

Earth Potential Rise

In electrical engineering, **Earth Potential Rise (EPR)** also called **Ground Potential Rise (GPR)** occurs when a large current flows to earth through an earth grid impedance. The potential relative to a distant point on the Earth is highest at the point where current enters the ground, and declines with distance from the source. Ground potential rise is a concern in the design of electrical substations because the high potential may be a hazard to people or equipment. The potential gradient (drop of voltage with distance) may be so high that a person could be injured due to the voltage developed between two feet, or between the ground on which the person is standing and a metal object. Any conducting object connected to the substation earth ground, such as telephone wires, rails, fences, or metallic piping, may also be energized at the ground potential in the substation. This transferred potential is a hazard to people and equipment outside the substation.

Causes

Earth potential rise (EPR) is caused by electrical faults that occur at electrical substations, power plants, or high-voltage transmission lines. Short-circuit current flows through the plant structure and equipment and into the grounding electrode at station. The resistance of the Earth is finite, so current injected into the earth at the grounding electrode produces a potential rise with respect to a distant reference point. The resulting potential rise can cause hazardous voltage, many hundreds of yards (metres) away from the actual fault location. Many factors determine the level of hazard, including: available fault current, soil type, soil moisture, temperature, underlying rock layers, and clearing time to interrupt a fault.

Safety

Earth potential rise is a safety issue in the coordination of power and telecommunications services. An EPR event at a site such as an electrical distribution substation may expose personnel, users or structures to hazardous voltages.

Step and touch potentials

"Step potential" is the voltage between the feet of a person standing near an energized grounded object. It is equal to the difference in voltage, given by the voltage distribution curve, between two points at different distances from the "electrode". A person could be at risk of injury during a fault simply by standing near the grounding point.

"Touch potential" is the voltage between the energized object and the feet of a person in contact with the object. It is equal to the difference in voltage between the object and a point some distance away. The touch potential could be nearly the full voltage across the grounded object if that object is grounded at a point remote from the place where the person is in contact with it. For example, a crane that was grounded to the system neutral and that contacted an energized line would expose any person in contact with the crane or its uninsulated load line to a touch potential nearly equal to the full fault voltage.

"Mesh potential" is a factor calculated when a grid of grounding conductors is installed. Mesh potential is the difference between the metallic object connected to the grid, and the potential of the soil within the grid. It is significant because a person may be standing inside the grid at a point with a large potential relative to the grid itself.

Mitigation

An engineering analysis of the power system under fault conditions can be used to determine whether or not hazardous step and touch voltages will develop. The result of this analysis can show the need for protective measures and can guide the selection of appropriate precautions.

Several methods may be used to protect employees from hazardous ground-potential gradients, including equipotential zones, insulating equipment, and restricted work areas.

1. The creation of an equipotential zone will protect a worker standing within it from hazardous step and touch potentials. Such a zone can be produced through the use of a metal mat connected to the grounded object. In some cases, a grounding grid can be used to equalize the voltage within the grid. Equipotential zones will not, however, protect employees who are either wholly or partially outside the protected area. Bonding conductive objects in the immediate work area can also be used to minimize the potential between the objects and between each object and ground. (Bonding an object outside the work area can increase the touch potential to that object in some cases, however.)

2. The use of insulating equipment, such as rubber gloves, can protect employees handling grounded equipment and conductors from hazardous touch potentials. The insulating equipment must be rated for the highest voltage that can be impressed on the grounded objects under fault conditions (rather than for the full system voltage).

3. Restricting employees from areas where hazardous step or touch potentials could arise can protect employees not directly involved in the operation being performed. Employees

on the ground in the vicinity of transmission structures should be kept at a distance where step voltages would be insufficient to cause injury. Employees should not handle grounded conductors or equipment likely to become energized to hazardous voltages unless the employees are within an equipotential zone or are protected by insulating equipment.

In cases such as an electrical substation, it is common practice to cover the surface with a high-resistivity layer of crushed stone or asphalt. The surface layer provides a high resistance between feet and ground grid and is an effective method to reduce the step and touch potential hazard.

Calculations

In principle, the potential of the earth grid $\mathbf{V_{grid}}$ can be calculated using Ohm's Law if the fault current ($\mathbf{I_f}$) and resistance of the grid ($\mathbf{Z_{grid}}$) are known.

$$\mathbf{V}_{grid} = \mathbf{I}_f \times \mathbf{Z}_{grid}$$

While the fault current from a distribution or transmission system can usually be calculated or estimated with precision, calculation of the earth grid resistance is more complicated. Difficulties in calculation arise from the extended and irregular shape of practical ground grids, and the varying resistivity of soil at different depths.

At points outside the earth grid, the potential rise decreases. The simplest case of the potential at a distance is the analysis of a driven rod electrode in homogeneous earth. The voltage profile is given by the following equation.

$$\mathbf{V}_r = \frac{\rho \mathbf{I}}{2\pi \mathbf{r_x}}$$

where

$\mathbf{r_x}$ is a point beyond the edge of the earth grid.
$\mathbf{V}_r$ is the voltage at distance $\mathbf{r_x}$ from the earth grid, in volts.
ρ is the resistivity of the earth, in Ω·m.
$\mathbf{I}$ is the earth fault current, in amperes.

This case is a simplified system; practical earthing systems are more complex than a single rod, and the soil will have varying resistivity. It can, however, reliably be said that the resistance of a ground grid is inversely proportional to the area it covers; this rule can be used to quickly assess the degree of difficulty for a particular site. Programs running on desktop personal computers can model ground resistance effects and produce detailed calculations of ground potential rise, using various techniques including the finite element method.

Standards and regulations

The US Occupational Safety and Health Administration (OSHA) has designated EPR as a "known hazard" and has issued regulations governing the elimination of this hazard in the work place.

IEEE Std. 80-2000 is a standard that addresses the calculation and mitigation of Step & Touch Potentials to acceptable levels.

Chapter 3

Earthing System

In electricity supply systems, an **earthing 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 (grounding) systems vary considerably among different countries.

A *protective earth* (PE) connection ensures that all exposed conductive surfaces are at the same electrical potential as the surface of the Earth, to avoid the risk of electrical shock if a person touches a device in which an insulation fault has occurred. It ensures that in the case of an insulation fault (a "short circuit"), a very high current flows, which will trigger an overcurrent protection device (fuse, circuit breaker) that disconnects the power supply.

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 interference 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.

IEC terminology

International standard IEC 60364 distinguishes three families of earthing arrangements, using the two-letter codes **TN**, **TT**, and **IT**.

The first letter indicates the connection between earth and the power-supply equipment (generator or transformer):

T

Direct connection of a point with earth (Latin: terra);

I
: No point is connected with earth (isolation), except perhaps via a high impedance.

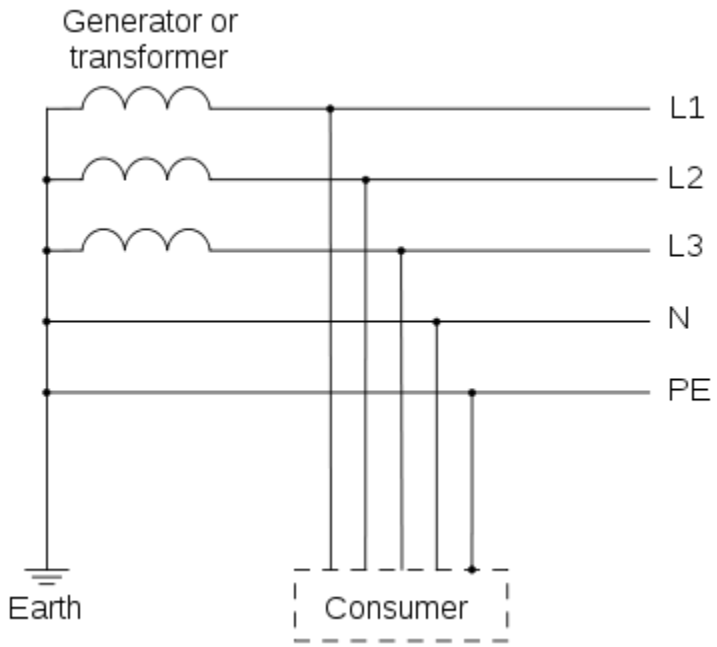
The second letter indicates the connection between earth and the electrical device being supplied:

T
: Direct connection of a point with earth

N
: Direct connection to neutral at the origin of installation, which is connected to the earth

TN networks

In a **TN** earthing system, one of the points in the generator or transformer is connected with earth, usually the star point in a three-phase system. The body of the electrical device is connected with earth via this earth connection at the transformer.



The conductor that connects the exposed metallic parts of the consumer is called *protective earth* (*PE*). The conductor that connects to the star point in a three-phase system, or that carries the return current in a single-phase system, is called *neutral* (*N*). Three variants of TN systems are distinguished:

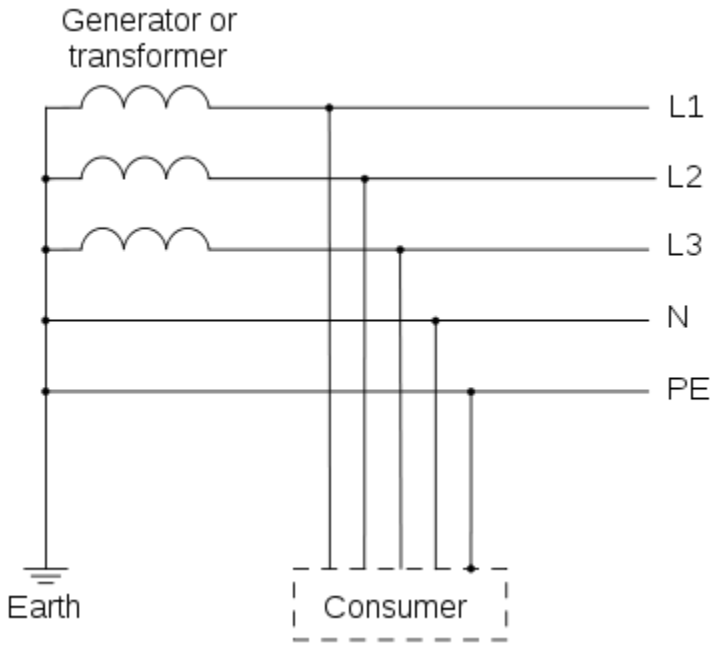
TN−S
: PE and N are separate conductors that are connected together only near the power source.

TN−C

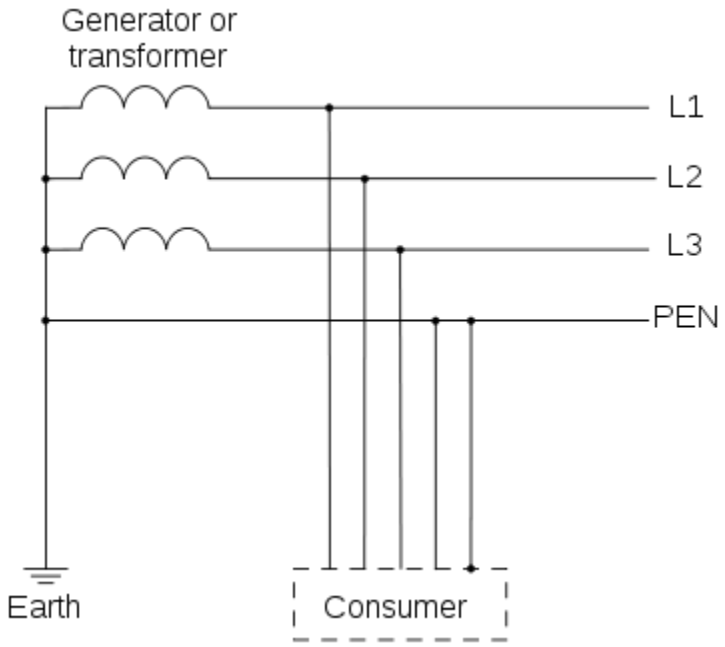
A combined PEN conductor fulfills the functions of both a PE and an N conductor. Rarely used.

TN−C−S

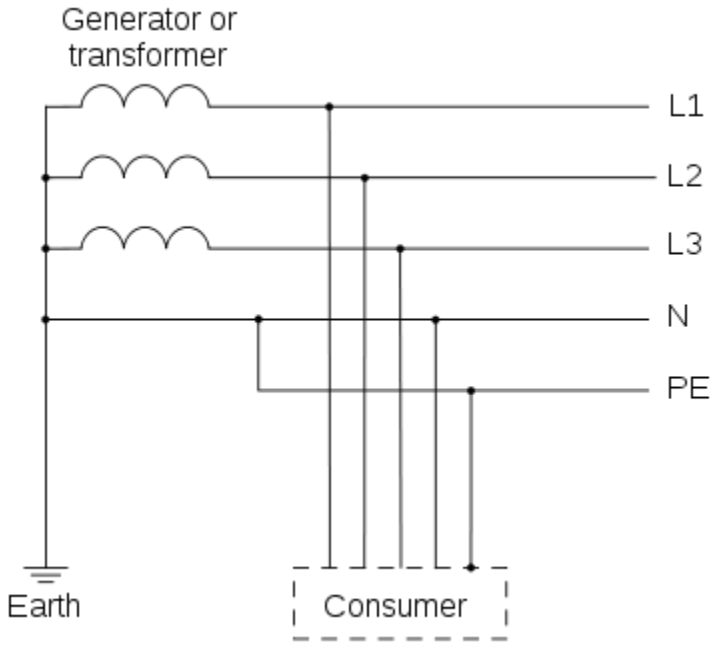
Part of the system uses a combined PEN conductor, which is at some point split up into separate PE and N lines. The combined PEN conductor typically occurs between the substation and the entry point into the building, and separated in the service head. In the UK, this system is also known as *protective multiple earthing (PME)*, because of the practice of connecting the combined neutral-and-earth conductor to real earth at many locations, to reduce the risk of broken neutrals - with a similar system in Australia being designated as *multiple earthed neutral (MEN)*.



TN-S: separate protective earth (PE) and neutral (N) conductors from transformer to consuming device, which are not connected together at any point after the building distribution point.



TN-C: combined PE and N conductor all the way from the transformer to the consuming device.



TN-C-S earthing system: combined PEN conductor from transformer to building distribution point, but separate PE and N conductors in fixed indoor wiring and flexible power cords.

It is possible to have both TN-S and TN-C-S supplies from the same transformer. For example, the sheaths on some underground cables corrode and stop providing good earth connections, and so homes where "bad earths" are found get converted to TN-C-S.

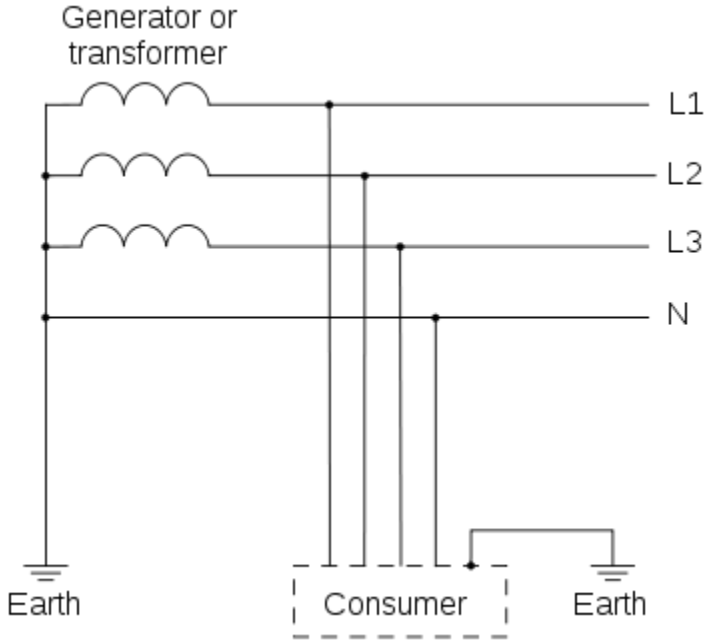
TT network

In a **TT** earthing system, the protective earth connection of the consumer is provided by a local connection to earth, independent of any earth connection at the generator.

The big advantage of the TT earthing system is the fact that it is clear of high and low frequency noises that come through the neutral wire from various electrical equipment connected to it. This is why TT has always been preferable for special applications like telecommunication sites that benefit from the interference-free earthing. Also, TT does not have the risk of a broken neutral.

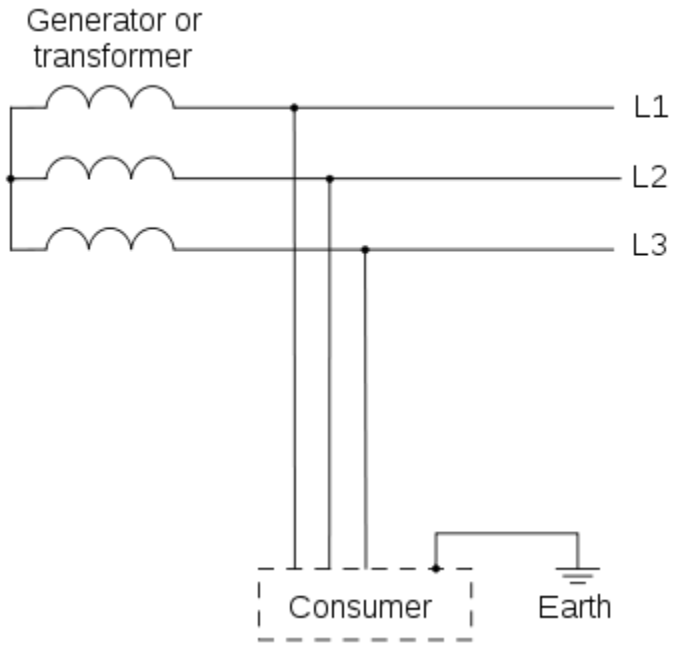
In locations where power is distributed overhead and TT is used, installation earth conductors are not at risk should any overhead distribution conductor be fractured by, say, a fallen tree or branch.

In pre-RCD era, the TT earthing system was unattractive for general use because of its worse capability of accepting high currents in case of a live-to-PE short circuit (in comparison with TN systems). But as residual current devices mitigate this disadvantage, the TT earthing system becomes attractive for premises where all AC power circuits are RCD-protected.



IT network

In an **IT** network, the distribution system has no connection to earth at all, or it has only a high impedance connection. In such systems, an insulation monitoring device is used to monitor the impedance. For safety reasons this network is not accepted under European norms.



Other terminologies

While the national wiring regulations for buildings of many countries follow the IEC 60364 terminology, in North America (United States and Canada), the term "equipment grounding conductor" refers to equipment grounds and ground wires on branch circuits, and "grounding electrode conductor" is used for conductors bonding an earth ground rod (or similar) to a service panel. "Grounded conductor" is the system "neutral".

Properties

Cost

- TN networks save the cost of a low-impedance earth connection at the site of each consumer. Such a connection (a buried metal structure) is required to provide *protective earth* in IT and TT systems.
- TN-C networks save the cost of an additional conductor needed for separate N and PE connections. However, to mitigate the risk of broken neutrals, special cable types and lots of connections to earth are needed.
- TT networks require proper RCD protection.

Fault path impedance

If the fault path between accidentally energized objects and the supply connection has low impedance, the fault current will be so large that the circuit overcurrent protection device (fuse or circuit breaker) will open to clear the ground fault. Where the earthing system does not provide a low-impedance metallic conductor between equipment enclosures and supply return (such as in a TT separately earthed system), fault currents are smaller, and will not necessarily operate the overcurrent protection device. In such case a residual current detector is installed to detect the current leaking to ground and interrupt the circuit.

Safety

- In TN, an insulation fault is very likely to lead to a high short-circuit current that will trigger an overcurrent circuit-breaker or fuse and disconnect the L conductors. With TT systems, the earth fault loop impedance can be too high to do this, or too high to do it quickly, so an RCD (or formerly ELCB) is usually employed. The provision of a Residual-current device (RCD) or ELCB to ensure safe disconnection makes these installations EEBAD (Earthed Equipotential Bonding and Automatic Disconnection).
- Many 1950s and earlier earlier TT installations in the UK may lack this important safety feature. Non-EEBAD installations are capable of the whole installation CPC (Circuit Protective Conductor) remaining live for extended periods under fault conditions, which is a real danger.
- In TN-S and TT systems (and in TN-C-S beyond the point of the split), a residual-current device can be used as an additional protection. In the absence of any insulation fault in the consumer device, the equation $I_{L1}+I_{L2}+I_{L3}+I_N = 0$ holds, and an RCD can disconnect the supply as soon as this sum reaches a threshold (typically 10-500 mA). An insulation fault between either L or N and PE will trigger an RCD with high probability.
- In IT and TN-C networks, residual current devices are far less likely to detect an insulation fault. In a TN-C system, they would also be very vulnerable to unwanted triggering from contact between earth conductors of circuits on different RCDs or with real ground, thus making their use impracticable. Also, RCDs usually isolate the neutral core. Since it is unsafe to do this in a TN-C system, RCDs on TN-C should be wired to only interrupt the live conductor.
- In single-ended single-phase systems where the Earth and neutral are combined (TN-C, and the part of TN-C-S systems which uses a combined neutral and earth core), if there is a contact problem in the PEN conductor, then all parts of the earthing system beyond the break will rise to the potential of the L conductor. In an unbalanced multi-phase system, the potential of the earthing system will move towards that of the most loaded live conductor. Therefore, TN-C connections must not go across plug/socket connections or flexible cables, where there is a higher probability of contact problems than with fixed wiring. There is also a risk if a cable is damaged, which can be mitigated by the use of concentric cable construction and/or multiple earth electrodes. Due to the (small) risks of the lost

neutral, use of TN-C-S supplies is banned for caravans and boats in the UK, and it is often recommended to make outdoor wiring TT with a separate earth electrode.

- In IT systems, a single insulation fault is unlikely to cause dangerous currents to flow through a human body in contact with earth, because no low-impedance circuit exists for such a current to flow. However, a first insulation fault can effectively turn an IT system into a TN system, and then a second insulation fault can lead to dangerous body currents. Worse, in a multi-phase system, if one of the live conductors made contact with earth, it would cause the other phase cores to rise to the phase-phase voltage relative to earth rather than the phase-neutral voltage. IT systems also experience larger transient overvoltages than other systems.
- In TN-C and TN-C-S systems, any connection between the combined neutral-and-earth core and the body of the earth could end up carrying significant current under normal conditions, and could carry even more under a broken neutral situation. Therefore, main equipotential bonding conductors must be sized with this in mind; use of TN-C-S is inadvisable in situations such as petrol stations, where there is a combination of lots of buried metalwork and explosive gases.

Electromagnetic compatibility

- In TN-S and TT systems, the consumer has a low-noise connection to earth, which does not suffer from the voltage that appears on the N conductor as a result of the return currents and the impedance of that conductor. This is of particular importance with some types of telecommunication and measurement equipment.
- In TT systems, each consumer has its own connection to earth, and will not notice any currents that may be caused by other consumers on a shared PE line.

Regulations

- In the United States National Electrical Code and Canadian Electrical Code the feed from the distribution transformer uses a combined neutral and grounding conductor, but within the structure separate neutral and protective earth conductors are used (TN-C-S). The neutral must be connected to the earth (ground) conductor only on the supply side of the customer's disconnecting switch. Additional connections of neutral to ground within the customer's wiring are prohibited.
- In Argentina, France (TT) and Australia (TN-C-S), the customers must provide their own ground connections.
- Japan is governed by PSE law, and uses TT earthing in most installations.
- In Australia, the Multiple Earthed Neutral (MEN) earthing system is used and is described in Section 5 of AS 3000. For an LV customer, it is a TN-C system from the transformer in the street to the premises, (the neutral is earhed multiple times along this segment), and a TN-S system inside the installation, from the Main Switchboard downwards. Looked at as a whole, it is a TN-C-S system.

Application examples

- Most modern homes in Europe have a TN-C-S earthing system. The combined neutral and earth occurs between the nearest transformer substation and the service cut out (the fuse before the meter). After this, separate earth and neutral cores are used in all the internal wiring.
- Older urban and suburban homes in the UK tend to have TN-S supplies, with the earth connection delivered through the lead sheath of the underground lead-and-paper cable.
- Some older homes, especially those built before the invention of residual-current circuit breakers and wired home area networks, use an in-house TN-C arrangement. This is no longer recommended practice.
- Laboratory rooms, medical facilities, construction sites, repair workshops, mobile electrical installations, and other environments that are supplied via engine-generators where there is an increased risk of insulation faults, often use an IT earthing arrangement supplied from isolation transformers. To mitigate the two-fault issues with IT systems, the isolation transformers should supply only a small number of loads each and/or should be protected with an insulation monitoring device (generally used only by medical, railway or military IT systems, because of cost).
- In remote areas, where the cost of an additional PE conductor outweighs the cost of a local earth connection, TT networks are commonly used in some countries, especially in older properties or in rural areas, where safety might otherwise be threatened by the fracture of an overhead PE conductor by, say, a fallen tree branch. TT supplies to individual properties are also seen in mostly TN-C-S systems where an individual property is considered unsuitable for TN-C-S supply.
- In Australia, and Israel the TN-C-S system is in use; however, the wiring rules currently state that, in addition, each customer must provide a separate connection to earth via both a water pipe bond (if metallic water pipes enter the consumer's premises) and a dedicated earth electrode. In Australia, new installations must also bond the foundation concrete re-enforcing under wet areas to the earth conductor (AS3000), typically increasing the size of the earthing, and provides an equipotential plane in areas such as bathrooms. In older installations, it is not uncommon to find only the water pipe bond, and it is allowed to remain as such, but the additional earth electrode must be installed if any upgrade work is done. The protective earth and neutral conductors are combined until the consumer's neutral link (located on the customer's side of the electricity meter's neutral connection) - beyond this point, the protective earth and neutral conductors are separate.

Chapter 4

Electrical Bonding and Antistatic Wrist Strap

Electrical Bonding

Electrical bonding is the practice of intentionally electrically connecting all metallic non-current carrying items in a room or building as protection from electric shock. If a failure of electrical insulation occurs, all metal objects in the room will have the same electrical potential, so that an occupant of the room cannot touch two objects with significantly different potentials. Even if the connection to a distant earth ground is lost, the occupant will be protected from dangerous potential differences.

Bonding refers to the fact that in a building with electricity it is normal for safety reasons to connect all metal objects such as pipes together to the mains earth to form an equipotential zone. This is done in the UK because many buildings are supplied with a single phase supply cable where the neutral and earth conductors are combined. Close to the electricity meter this conductor is divided into two, the *earth* terminal and the wire going to the neutral busbar in the consumer unit. In the event of a break in a neutral connection this *earth* terminal provided by the supply company will be at a potential (relative to the true earth) which is the same as the live wire (phase wire) coming to the home.

Examples of articles that may be bonded include metallic water piping systems, gas piping, airplanes, ducts for central heating and air conditioning systems, and exposed metal parts of buildings such as hand rails, stairs, ladders, platforms and floors.

If a person was to touch the metal (earthed casing) of an electrical device during the a fault condition and be in contact with a metal object connected to a remote earth then they would get an electric shock. If all metal objects are connected together, all the metal

objects in the building will be at the same potential. It then will not be possible to get a shock by touching two 'earthed' objects at once.

Bonding is particularly important for swimming pools and fountains. In pools and fountains, any metallic object (other than conductors of the power circuit)over a certain size must be bonded to assure that all conductors are equipotential and do not provide a hazardous conductive path. Since it is buried in the ground, a pool can be a better ground than the electric panel ground. With all the conducting elements bonded, it is less likely that electric current will find a path through a swimmer. In concrete pools even the reinforcing bars of the concrete must be connected to the bonding system to ensure no dangerous potential gradients are produced during a fault.

How the earth protects

In a system with a grounded (earthed) neutral, connecting all non-current-carrying metallic parts of equipment to earth ground at the main service panel, will ensure that current due to faults (such as a "hot" wire touching the frame or chassis of the device) will be diverted to earth. In a TN system where there is a direct connection from the installation earth to the transformer neutral, earthing will allow the branch circuit over-current protection (a fuse or circuit breaker) to detect the fault rapidly and interrupt the circuit.

In the case of a TT system where the impedance is high due to the lack of direct connection to the transformer neutral, an RCD (Residual-Current Device, sometimes known as a Residual Current Circuit Breaker or Ground Fault Circuit Interrupter) must be used to provide disconnection. RCDs are also used in other situations where rapid disconnection of small earth faults (including a human touching a live wire by accident, or damage) is desired.

Equipotential bonding

Equipotential bonding involves joining together metalwork that is or may be earthed so that it is at the same potential (i.e., voltage) everywhere. Such is commonly used under transformer banks by power companies and under large computer installations.

Equipotential bonding is done from the Service Panel consumer unit (also known as a fuse box, breaker box, or distribution board) to incoming water and gas services. It is also done in bathrooms where all exposed metal that leaves the bathroom including metal pipes and the earths of electrical circuits must be bonded together to ensure that they are always at the same potential. Isolated metal objects including metal fittings fed by plastic pipe (water in a thin pipe is actually a very poor conductor) are not required to be bonded. European and North American practices differ here; equipotential bonding in bathrooms is not required by North American codes, although it is required around swimming pools.

In Australia and South Africa, a house's earth cables must be connected both to an earthing rod/stake driven into the ground and also to the plumbing.

Exact rules for electrical installations vary by country, locality, or supplying power company.

Aircraft electrical bonding

In aircraft, electrical bonding prevents static electricity build-up that can interfere with radio and navigational equipment. Bonding also provides lightning protection by allowing the current to pass through the airframe with minimum arcing. Bonding prevents dangerous static discharges in aircraft fuel tanks and hoses.

Antistatic Wrist Strap

An **antistatic wrist strap**, **ESD wrist strap**, or **ground bracelet** is an antistatic device used to safely ground a person working on electronic equipment, to prevent the buildup of static electricity on their body, which can result in electrostatic discharge (ESD). It is used in the electronics industry by workers working on electronic devices which can be damaged by ESD, and also sometimes by people working around explosives, to prevent electric sparks which could set off an explosion. It consists of a stretchy band of fabric with fine conductive fibers woven into it. The fibers are usually made of carbon or carbon-filled rubber, and the strap is bound with a stainless steel clasp or plate. They are usually used in conjunction with an antistatic mat on the workbench, or a special static-dissipating plastic laminate on the workbench surface.

An antistatic wrist strap with crocodile clip.

The wrist strap is usually worn on the nondominant hand (the left wrist for a right-handed person). It is connected to ground through a coiled retractable cable and 1 megohm resistor, which allows high-voltage charges to leak through but prevents a shock hazard when working with low-voltage parts. Where higher voltages are present, extra resistance (0.75 megohm per 250 V) is added in the path to ground to protect the wearer from excessive currents; this typically takes the form of a 4 megohm resistor in the coiled cable (or, more usually, a 2 megohm resistor at each end). Very cheap wrist straps do not have conductive fabric and instead use the fabric to hold the metal plate against the skin, which can result in reduced ESD protection over time as the metal corrodes.

Wrist straps in industry usually connect to Earth Bonding Points (part of the grounding system) via either a 4 mm plug or 10 mm press stud, whereas personally owned straps are likely to be connected to ground via a crocodile clip.

In addition to wrist straps, ankle and heel straps are used in industry to bleed away accumulated charge from a body. These devices are usually not tethered to earth ground, but instead incorporate high resistance in their construction, and work by dissipating electrical charge to special floor tiles. Such straps are used when workers need to be

mobile in a work area and a grounding cable would get in the way, such as in an operating theatre.

Wireless or Dissipative wrist straps are available, but they are widely considered as pseudoscientific hoax products. The claims of the operating principles vary from "Ion Neutralization, Skin Effect, Point Discharge and Corona Discharge Effect" to "Selglard electric halo principles".

Disposable ground straps used during installation of computer equipment

Chapter 5

Electrical Equipment in Hazardous Areas

In electrical engineering, a **hazardous location** is defined as a place where concentrations of flammable gases, vapors, or dusts occur. Electrical equipment that must be installed in such locations is especially designed and tested to ensure it does not initiate an explosion, due to arcing contacts or high surface temperature of equipment.

For example a household light switch may emit a small, harmless visible spark when switching; in an ordinary atmosphere this arc is of no concern, but if a flammable vapor is present, the arc might start an explosion. Electrical equipment intended for use in a chemical factory or refinery is designed either to contain any explosion within the device, or is designed not to produce sparks with sufficient energy to trigger an explosion.

Many strategies exist for safety in electrical installations. The simplest strategy is to minimize the amount of electrical equipment installed in a hazardous area, either by keeping the equipment out of the area altogether or by making the area less hazardous by process improvements or ventilation with clean air. Intrinsic safety and non-incendive equipment and wiring methods are practices where apparatus is designed with low power levels and low stored energy, so that an arc produced during normal functioning of the equipment or as the result of equipment failure has insufficient energy to initiate ignition of the explosive mixture. Equipment enclosures can be pressurized with clean air or inert gas and designed with various controls to remove power or provide notification in case of supply or pressure loss of such gases. Arc-producing elements of the equipment can also be isolated from the surrounding atmosphere by encapsulation, immersion in oil, sand, etc. Heat producing elements such as motor winding, electrical heaters, including heat tracing and lighting fixtures are often designed to limit their maximum temperature below the autoignition temperature of the material involved. Both external and internal temperatures are taken into consideration.

As in most fields of electrical installation, different countries have approached the standardization and testing of equipment for hazardous areas in different ways. As world

trade becomes more important in distribution of electrical products, international standards are slowly converging so that a wider range of acceptable techniques can be approved by national regulatory agencies.

Area classification is required by governmental bodies, for example OSHA and compliance is enforced. Documentation requirements are varied. Often an area classification plan-view is provided to identify equipment ratings and installation techniques to be used for each classified plant area. The plan may contain the list of chemicals with their group and temperature rating, and elevation details shaded to indicate Class, Division(Zone) and group combination. The area classification process would require the participation of operations, maintenance, safety, electrical and instrumentation professionals, the use of process diagrams and material flows, MSDS and any pertinent documents, information and knowledge to determine the hazards and their extent and the countermeasures to be employed. Area classification documentations are reviewed and updated to reflect process changes.

History

Soon after the introduction of electric power into coal mines, it was discovered that lethal explosions could be touched off by electrical equipment such as lighting, signals, or motors. The hazard of fire damp or methane accumulation in mines was well known by the time electricity was introduced, along with the danger of suspended coal dust. However, at least two British mine explosions were attributed to an electric bell signal system. In this system, two bare wires were run along the length of a drift, and any miner desiring to signal the surface would momentarily touch the wires to each other or bridge the wires with a metal tool. The inductance of the signal bell coils, combined with breaking of contacts by exposed metal surfaces, resulted in sparks which could ignite methane, causing an explosion.

Divisions or Zones (Gases, vapors and dust)

In an industrial plant such as a refinery or Chemical process plant, handling of large quantities of flammable liquids and gases creates a risk of leaks. In some cases the gas, ignitable vapor or dust is present all the time or for long periods. Other areas would have a dangerous concentration of flammable substances only during process upsets, equipment deterioration between maintenance periods, or during an incident. Refineries and chemical plants are then divided into areas of risk of release of gas, vapor or dust known as divisions or zones. The process of determining the type and size of these hazardous areas is called area classification. Guidance on assessing the extent of the hazard is given in the NFPA 497 Standard, or API 500 and according to their adaptation by other areas gas zones is given in the current edition of IEC 60079.10. For hazardous dusts, the guiding standard is IEC 61421.10.

Typical gas hazards are from hydrocarbon compounds.

Safe area

An area such as a residence or office would be classed as safe area, where the only risk of a release of explosive or flammable gas would be such things as the propellant in an aerosol spray. The only explosive or flammable liquid would be paint and brush cleaner. These are classed as very low risk of causing an explosion and are more of a fire risk (although gas explosions in residential buildings do occur). Safe area on chemical and other plant are present where the hazardous gas is diluted to a concentration below 25% of its lower flammability limit (or lower explosive limit (LEL)).

Division 2 or Zone 2 area

This is a step up from the safe area. In this zone the gas, vapor or mist would only be present under abnormal conditions (most often leaks under abnormal conditions). As a general guide, unwanted substances should only be present under 10 hours/year or 0–0.1% of the time.

Division 1 or Zone 1 area

Gas, vapor or mist will be present or expected to be present for long periods of time under normal running. As a guide this can be defined as 10–1000 hours/year or 0.1–10% of the time.

Zone 0 area

Gas or vapor is present all of the time (over 1000 hours/year or >10% of the time). Usually this would be the vapor space above the liquid in the top of a tank or drum. The ANSI/NEC classification method consider this environment a Division 1 area

Zones (dusts)

In the case of dusts there is still a chance of explosion. An old system of area classification to a British standard used a system of letters to designate the zones. This has been replaced by a European numerical system, as set out in directive 1999/92/EU implemented in the UK as the Dangerous Substances and Explosives Atmospheres Regulations 2002

The boundaries and extent of these three dimensional zones should be decided by a competent person. There must be a site plan drawn up of the factory with the zones marked on.

The zone definitions are:

Zone 20

A place in which an explosive atmosphere in the form of a cloud of combustible dust in air is present continuously, or for long periods, or frequently.

Zone 21

A place in which an explosive atmosphere in the form of a cloud of combustible dust in air is likely to occur in normal operation occasionally.

Zone 22

A place in which an explosive atmosphere in the form of a cloud of combustible dust is not likely to occur in normal operation, but if it does occur will persist for a short period only

Gas groups

Explosive gases, vapors and dusts have different chemical properties that affect the likelihood and severity of an explosion. Such properties include flame temperature, minimum ignition energy, upper and lower explosive limits, and molecular weight. Empirical testing is done to determine parameters such as the maximum experimental safe gap, minimum ignition current, explosion pressure and time to peak pressure, spontaneous ignition temperature, and maximum rate of pressure rise. Every substance has a differing combination of properties but it is found that they can be ranked into similar ranges, simplifying the selection of equipment for hazardous areas.

Flammability of combustible liquids are defined by their flash-point. The flash-point is the temperature at which the material will generate sufficient quantity of vapor to form an ignitable mixture. It is a critical data in determining whether the area needs to be classified or not. A material may have a relatively low autoignition temperature yet its flash-point is above the ambient temperature then the area may not need to be classified. Conversely if the same material is processed(heated) above ambient temperature and the handling temperature is above its flash-point, the area MUST be classified. (NFPA reference needed)

Each chemical gas or vapour used in industry is classified into a gas group.

Group	**Representative Gases**
I	All Underground Coal Mining. Firedamp (methane)
IIA	Industrial methane, propane, petrol and the majority of industrial
IIB	Ethylene, coke oven gas and other industrial gases
IIC	Hydrogen, acetylene, carbon disulphide

Apparatus marked IIB can also be used for IIA gases. IIC marked equipment can be used for both IIA and IIB. If a piece of equipment has just II and no A, B, or C after then it is suitable for any gas group.

A list must be drawn up of every chemical gas or vapor that is on the refinery/chemical complex and included in the site plan of the classified areas. The above groups are formed in order of how volatile the gas or vapor would be if it was ignited, IIC being the most volatile and IIA being the least. The groups also indicate how much energy is required to ignite the gas by spark ignition, Group IIA requiring the most energy and IIC the least.

Temperature classification

Another important consideration is the temperature classification of the electrical equipment. The surface temperature or any parts of the electrical equipment that maybe exposed to the hazardous atmosphere should be tested that it does not exceeds 80% of the auto-ignition temperature of the specific gas or vapor in the area where the equipment is intended to be used.

The temperature classification on the electrical equipment label will be one of the following (in degree Celsius):

USA°C	UK °C	Germany °C Continuous - Short Time
T1 - 450	T3A - 180	T1 - 450	G1: 360 - 400
T2 - 300	T3B - 165	T2 - 300	G2: 240 - 270
T2A - 280	T3C - 160	T3 - 200	G3: 160 - 180
T2B - 260	T4 - 135	T4 - 135	G4: 110 - 125
T2C - 230	T4A - 120	T5 - 100	G5: 80 - 90
T2D - 215	T5 - 100	T6 - 85	
T3 - 200	T6 - 85		

The above table tells us that the surface temperature of a piece of electrical equipment with a temperature classification of T3 will not rise above 200 °C.

Auto-ignition temperatures (vapors & gases)

The auto-ignition temperature of a liquid, gas or vapor is the temperature at which the substance will ignite without any external heat source. The exact temperature value determined depends on the laboratory test conditions and apparatus. Such temperatures for common substances are:

Gas	Temperature
Methane	580 °C
Hydrogen	560 °C
Propane	493 °C
Ethylene	425 °C
Acetylene	305 °C
Naphtha	290 °C
Carbon disulfide	102 °C

The surface of a high pressure steam pipe may be above the autoignition temperature of some fuel/air mixtures.

Auto-ignition temperatures (dust)

The auto-ignition temperature of a dust is usually higher than that of vapours & gases. Examples for common materials are:

Substance	Temperature
Sugar	460 °C
Wood	340 °C
Flour	340 °C
Grain dust	300 °C
Tea	300 °C

Type of protection

To ensure safety in a given situation, equipment is placed into protection level categories according to manufacture method and suitability for different situations. Category 1 is the highest safety level and Category 3 the lowest. Although there are many types of protection, a few are detailed

	Ex Code	Notified Body Name	Description	Location	Use
Flameproof	d	Will have a CENELEC Hexagon followed by apparatus group and Safety Category	Equipment is robust can stand an explosion from within, without transmitting the flame to the outside Equipment has flameproof gaps (max 0.006" propane/ethylene, 0.004" acetylene /hydrogen)	Zone 1 if gas group & temp. class correct	Motors, lighting, junction boxes
Increased Safety	e	Will have a CENELEC Hexagon followed by apparatus group and Safety Category	Equipment is very robust and components are made to a high quality		Motors, lighting, junction boxes
Oil Filled	o	Will have a CENELEC	Equipment components are	Zone 2 or Zone 1, depending	Heavy current equipment

		Hexagon followed by apparatus group and Safety Category	completely covered with a layer of oil	on edition of the standard used.	
Sand/Powder /Quartz Filled	q	Will have a CENELEC Hexagon followed by apparatus group and Safety Category	Equipment components are completely covered with a layer of Sand, powder or quartz	Zone 2	Electronics, telephones, chokes
Encapsulated	m	Will have a CENELEC Hexagon followed by apparatus group and Safety Category	Equipment components of the equipment are usually encased in a resin type material	Zone 1 (Ex mb) or Zone 0 (Ex ma)	Electronics (no heat)
Pressurised /purged	p	Will have a CENELEC Hexagon followed by apparatus group and Safety Category	Equipment is pressurised with a positive pressure; gas cannot get in for air coming out or equipment is purged with a diluting gas such as air. If air is used, it is ducted in from outside the hazardous area.	Zone 1	Analysers, motors, control boxes, computers
Intrinsically safe	i	Will have a CENELEC Hexagon followed by apparatus group and Safety Category	Any arcs or sparks in this equipment has insufficient energy (heat) to ignite a vapour Equipment can be installed in ANY housing provided to IP54 A 'Zener Barrier' or	'ia': Zone 0 & 1 'ib': Zone 1	Instrumentation, measurement, control

			'opto isol' or 'galvanic' unit may be used to assist with certification.		
Non Incendive	n	Now CENELEC recognised; so will have a hexagon followed by apparatus group and Safety Category	Equipment is non-incendive or non-sparking.	Zone 2	Motors, lighting, junction boxes, electronic equipment
Special Protection	S	Has a BASEEFA Crown Not CENELEC recognised; no hexagon.	This method, being by definition special, has no specific rules. In effect it is any method which can be shown to have the required degree of safety in use. Much early equipment having Ex s protection was designed with encapsulation and this has now been incorporated into IEC 60079-18 [Ex m]. Ex s is a coding referenced in IEC 60079-0. The use of EPL and ATEX Category directly is an alternative for “s” marking.	Zone 1 depending upon Manufacturers Certification.	As its certification states

Multiple Protection

Many items of EEx rated equipment will employ more than one method of protection in different components of the apparatus. These would be then labeled with each of the individual methods. For example a socket outlet labeled EEx'de' might have a case made to EEx 'e' and switches that are made to EEx 'd'.

Hazardous Locations Classifications Descriptions - ANSI/NFPA(NEC)terms

Class I, Div. 1 - Where ignitable concentrations of flammable gases, vapors or liquids are present within the atmosphere under normal operation conditions.

Class I, Div. 2 - Where ignitable concentrations of flammable gases, vapors, or liquids are present within the atmosphere under abnormal operating conditions.

Class II, Div. 1 - Where ignitable concentrations of combustible dusts are present within the atmosphere under normal operation conditions.

Class II, Div. 2 - Where ignitable concentrations of combustible dust are present within the atmosphere under abnormal operating conditions.

Class III, Div. 1 - Where easily ignitable fibers or materials producing combustible flyings are present within the atmosphere under normal operation conditions.

Class III, Div. 2 - Where easily ignitable fibers or materials producing combustible flyings are present within the atmosphere under abnormal operating conditions.

Common Materials within Associated Class & Group Ratings, such as "Class I, Division 1, Group A":

Class I Areas: Group A: Acetylene / Group B: Hydrogen / Group C: Propane and Ethylene / Group D: Benzene, Butane & Propane

Class II Areas: Group E: Metal Dust / Group F: Carbon & Charcoal / Group G: Flour, Starch, Wood & Plastic

Class III Areas: NO GROUP: Cotton & Sawdust

Equipment category

The equipment category indicates the level of protection offered by the equipment.

Category 1 equipment may be used in zone 0, zone 1 or zone 2 areas.

Category 2 equipment may be used in zone 1 or zone 2 areas.

Category 3 equipment may only be used in zone 2 areas.

Labeling

All equipment certified for use in hazardous areas must be labelled to show the type and level of protection applied.

1. In Europe the label must show: -

a) The CE mark.

b) The code number of the certifying body for the ‘quality certificate’.

c) CE marking is complemented with the Ex mark, followed by the indication of the Group, Category and, if group II equipment, the indication relating to gases (G) or dust (D). For example: - Ex II 1 G (Explosion protected, Group 2, Category 1, Gas)

2. In addition, the normative marking will be able to establish the specific type or types of protection being used, for example: -

EEx ia IIC T4. (Type ia, Group 2C gases, Temperature category 4).

EEx nA II T3 X (Type n, non-sparking, Group 2 gases, Temperature category 3, special conditions apply).

3. The suitability of equipment for the specific hazardous area in the ANSI/NFPA(NEC) regulated market is required to be tested by a NRTL(Nationally Recognized Testing Laboratory). Such institutes are UL, FM or ETL, just to name a few.

a) Dependent on the specific equipment and the applicable division the label will always list the Class(es), Division(s) and may list the Group(s) and temperature Code.

b) Directly adjacent on the label one will find the mark of the listing agency.

c) Some manufacturers claim "suitability" or "built-to" hazardous areas in their technical literature, but in effect lack the testing agency's certification and thus unacceptable for the AHJ (Authority Having Jurisdiction) to permit operation of the electrical installation/system.

4. Also included in the marking are: -

a) The manufacturers name or trademark and address.

b) The apparatus type, name and serial number.

c) Year of manufacture.

d) Any special conditions of use.

e) The NEMA enclosure rating or IP code may also be indicated, but it is usually independent of the Classified Area suitability.

5. Manufacturers will provide specific installation instructions that must be followed for:

a) the equipment to function properly, and

b) to provide the designed protection in the Classified Area according to the listing.

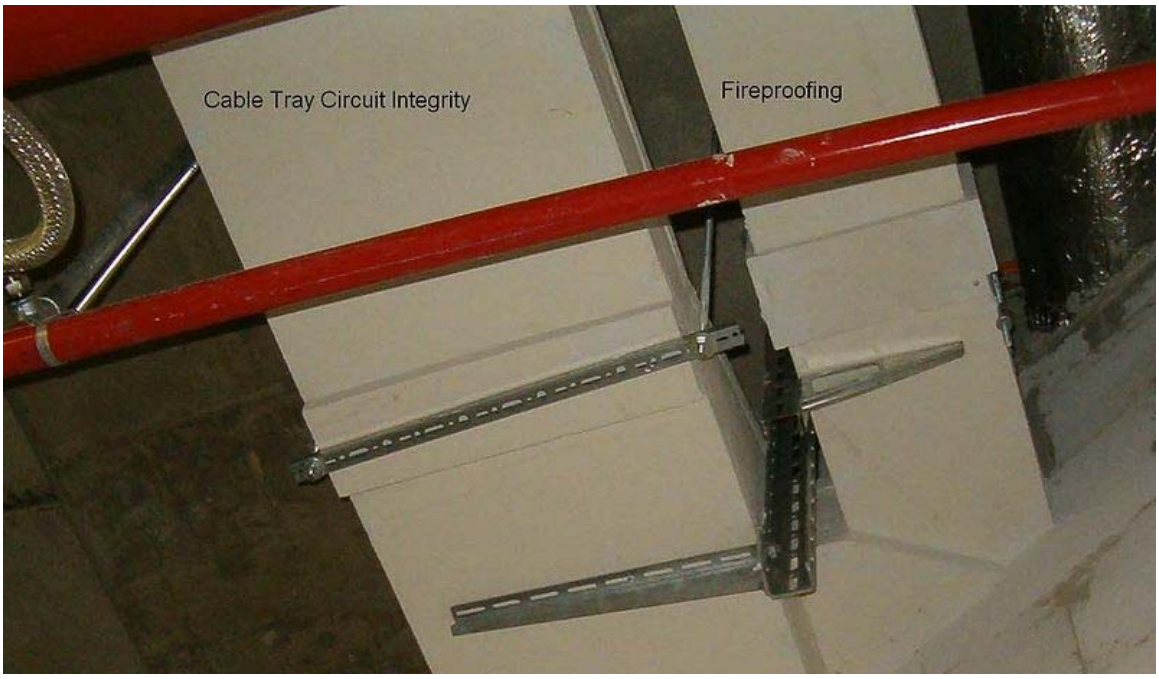
British standards

Industrial electrical equipment for hazardous area has to conform to standard BS 60079 and in some cases, certified as meeting that standard. Independent test houses (known as Notified Bodies)are established in most European countries, and a certificate from any of these will be accepted across the EU. The DTI appoint and maintain a list of Notified Bodies within the UK, of which Sira and Baseefa are the most well known. All equipment certified for use in hazardous areas must be labelled to show the level of protection offered.

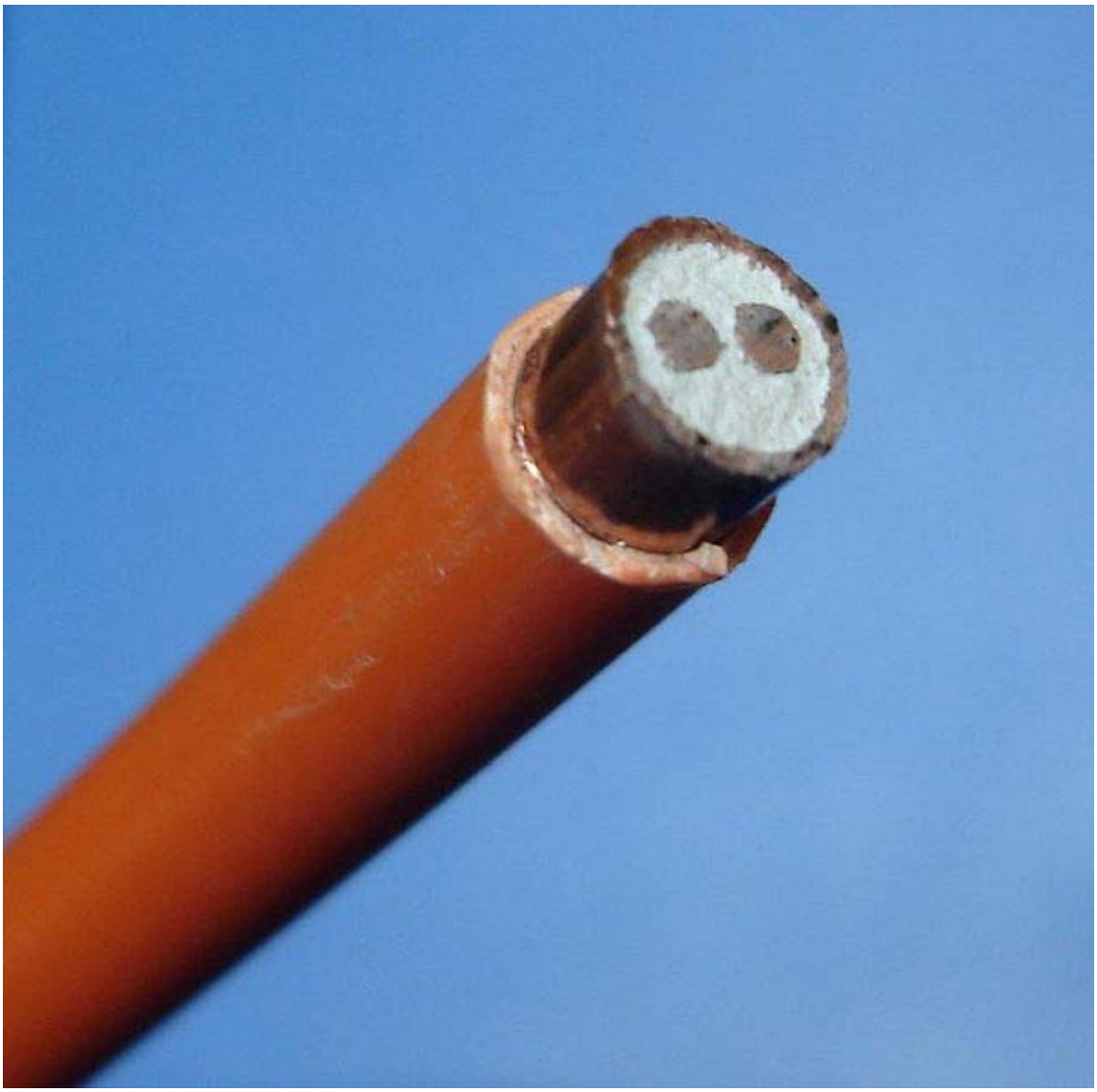
Chapter 6

Circuit Integrity

Circuit integrity fireproofing of cable trays in Lingen/Ems, Germany using calcium silicate board system qualified to DIN 4102.

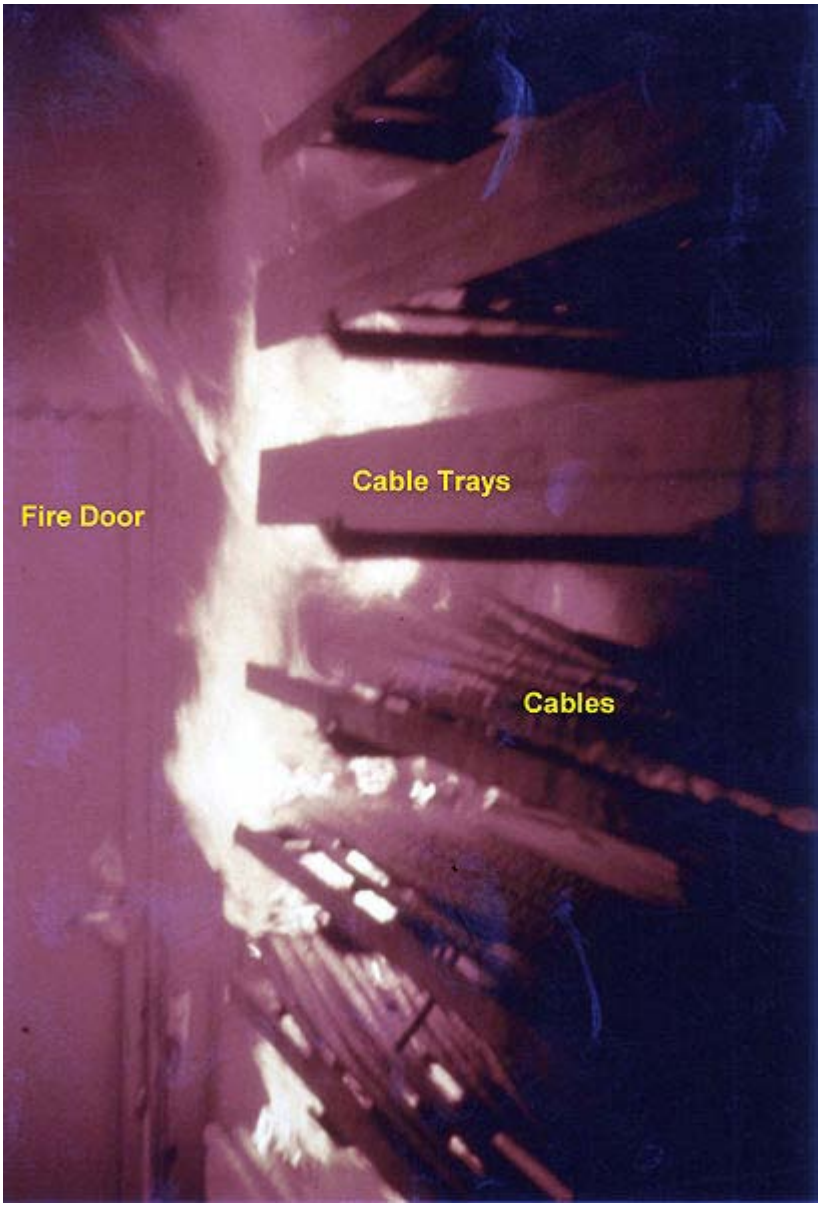


Circuit integrity fireproofing of cable trays.



Instead of cladding: Fire-resistant cables: PVC-sheathed MICC cable. Conductor CSA is 1.5 mm²; overall diameter is 7.2 mm

MI cables fastened into junction box that has not been fireproofed. The circuit is OK until it reaches the box. If the box is exposed to a fire, all the circuits connected to it become inoperable. Even if the electrical room that contains the box has a fire-resistance rating, this is a weak point because fires can break out in electrical rooms.



Fire test in Sweden, showing rapid fire spread through burning of cable jackets from one **cable tray** to another.

Circuit integrity refers to the operability of electrical circuits during a fire. It is a form of fire-resistance rating. Circuit integrity is achieved via passive fire protection means, which are subject to stringent listing and approval use and compliance.

Fireproofing

Providing fireproofing for cables, cable trays, or electrical conduit, is meant to keep cables operational during a specified fire exposure and time. This can be done in two different ways:

- Cable coating is generally considered a fire retardant, which lowers the spread of flame and generation of smoke along the combustible cable jacketing. Some cable coating systems are able to achieve a measure of circuit integrity, which is demonstrated and quantified through certification listing and listing and approval use and compliance.
- An enclosure can be provided. Calcium silicate board can be used, or other methods including boards made of vermiculite, bonded and pressed with sodium silicate, flexible wraps made of ceramic fibre and rockwool, or ceramic fibre wraps treated with endothermic materials. In all cases, the installed configuration must meet the certification listing of the tested system. Alternatively, cables that achieve fire-resistance ratings on their own can be used, such as Mineral-insulated copper-clad cable, or MI cable. Mica insulated cables have also demonstrated a measure of circuit integrity for small cables.

Testing and certification

In Canada, testing is run in accordance with ULC-S101, as required by the local building code. Unfortunately, S101 is ill equipped to deal realistically with circuit integrity, particularly for enclosures. For circuit integrity cables, one simply uses a full scale wall panel test, loops the cables through the fire, energises the cables and quantifies the current carrying capacity of the cables during the fire.

There are two ways of achieving circuit integrity. One may either choose mineral insulated or otherwise fire-resistant (tested for that purpose) cables, or one may use an enclosure that was tested for that purpose. This is where "grandfathered" systems still find acceptance in certain parts in North America. A prime example of this is Canada, where the code indicates that 2" of concrete coverage over or around electrical circuits is sufficient to obtain an unquantified duration of circuit integrity. No testing documentation exists to qualify this measure, according to the Institute for Research in Construction, a part of the National Research Council of Canada. 2" of concrete, regardless of the conductor configuration, percentage fill, etc. is of course a judgment call.

Inherently fire resistive cables can be tested to UL 2196, Tests for Fire Resistive Cables, whereas enclosures for cables that are not inherently fire resistive can be tested to UL 1724 or USNRC Generic Letter 86-10, Supplement 1 in North America, or BS476 in the United Kingdom or DIN4102 in Germany.

The mechanical ducting precedent

The other grandfathered approach is drywall shaftwall systems. Drywall shaftwalls were tested as a flat wall, no corners, no turns. This approach has pretty much been negated for use around ductwork (i.e. pressurisation and grease ducting, which are required to have a fire-resistance rating) since the adoption of the more suitable ISO6944 test regime by ULC as well as Underwriters Laboratories, whereby a duct is suspended from a full scale floor slab and the enclosure is built around the duct (or an inherently fire resistant duct is similarly tested without an enclosure, since it already contains a layer of insulation), for a

more realistic 3D configuration and exposure. Drywall shaftwall systems were entirely grandfathered for this application and ceased to be legally representative of due diligence the instant a properly and purposely tested system with bona fide listings became available. The same thing applies to circuit integrity enclosures.

For the mechanical ductwork, a Canadian entrepreneur got ISO6944 passed by the ULC Standards Council and then performed testing. This made all grandfathered systems legally indefencible.

This has yet to occur in Canada for circuit integrity, but it has long been standard construction work in Europe and also in the US, through work done by UL and other laboratories. Since UL is accredited by the Standards Council of Canada in Canada and its listings are considered public record up all over North America including Canada, one is ill advised to use grandfathered systems for circuit integrity anywhere.

Importantly, drywall shaftwall systems have only been qualified as straight walls in panel furnaces, not 3D enclosures with corners.

Current test methods

Germany has standardised this sort of testing via DIN4102 Part 12, dated January 1991, Fire behaviour of building materials and elements, Fire resistance of electrical cable systems, Requirements and testing. Part 12 encompasses both enclosures for cabling and bus ducts, as well as inherently fire-resistive cables, such as mineral insulated cables. Enclosures for ductwork as well as wiring are a regular part of passive fire protection there. It is also not nearly as expensive as North American qualified approaches. Typically, lightweight mineral boards are used, such as calcium silicate and sodium silicate bonded vermiculite.

The North American state of the art is UL1724 Standard for Tests of Thermal Barrier Systems for Electrical System Components as well as its cousin, UL2196 Standard for Tests of Fire Resistive Cables. UL1724 had its origin with USNRC Generic Letter 86-10 Supplement 1, issued by the Nuclear Regulatory Commission. "Supplement 1" was to address lessons learned from the widely publicised Thermo-lag 330-1 scandal, following disclosures by whistleblower Gerald W. Brown, which resulted on Congressional hearings and a large amount of remedial work.

Supplement 1 is a particularly difficult and expensive test to pass. No testing is done in anything less than a full scale fire test, running easily into 6 figure costs per burn multiplied by all the applications one desires to test. In order to pass, one must test the smallest as well as the largest application (12" and 36" cable tray, 1/2" and 6" conduit). Accordingly, the approved materials are costly, as manufacturers must get a return on the large test investment.

In concept, it is simple to devise systems that will pass the test. As far back as the 1970s, it was apparent that when one uses enough high temperature qualified insulation, such as

ceramic fibre, one is assured of a rating. However, this comes at the price of significant ampacity derating. Also, the concept that more fireproofing is better, was defeated by industry tests of Thermo-lag 330-1 (which is not a fibrous insulation). No matter what was done to this material (used for fireproofing purposes over electrical circuits in full scale fire testing) by various nuclear power plant owners (USNRC licensees) who sponsored extensive testing, where more of the old Thermo-lag was applied onto the older substrate, no satisfactory results were achieved. In order for licensees to come into compliance, other methods, replacements, overlays and MI Cable were used to fix the problem. Also, since the forerunner of this testing was the USNRC, and the commercial version of it (UL1724) has undergone various revisions, the UL systems listed in the UL Building Materials directory are not necessarily qualified to the latest USNRC compliant or the latest UL version. But that does not mean that the older listings are simply discarded or that the manufacturers performed all new tests. Therefore, users must closely review the versions of the tests deemed acceptable in an end-user facility.

Ampacity derating

Ampacity derating refers to the reduction of the ability of a cable to conduct electricity. It can be tested through the use of IEEE 848 Standard Procedure for the Determination of the Ampacity Derating of Fire-Protected Cables. The more one insulates a conductor, the less current it can conduct without damage from overheating. The result of the test referenced herein is quantified in terms of percentage. If a cable is derated by 30%, it can be used to conduct only 70% as much current, thus cable of greater cross sectional area is often needed to conduct a given amount of power. The use of intumescent "windows", which shut in case of a fire, can reduce or negate the effect of ampacity derating, subject to listing and approval use and compliance.

What circuit integrity methods are used where

Ordinarily, small runs of cables are individually run with cables that are fire-resistance rated on their own. Larger bundles and trays full of wiring may be less expensive to clad or wrap on the outside. The concrete cover method is most often used in Canadian construction, as the code and common practice permit this, despite the absence of testing data that gives the required "carte blanche" for all cables and indefinite ratings.

Cladding and wrapping considerations

The added weight of the wrap systems must be included in static and seismic calculations. Fireproofing of the hanging system must also be considered. Regular maintenance must be considered, as cladding and wraps are not load-bearing and can be damaged during normal building or facility operations. Ampacity-derating may be mitigated by the use of purpose-designed intumescent or mechanically/electronically activated "windows" that permit heat venting. Like everything else in passive fire protection, all such methods are subject to stringent listing and approval use and compliance.

Circuit integrity cable considerations

Termination points and junction boxes, in other words the entire circuit, must be completely protected. Often, termination points are left out, providing a weak link. Therefore, some enclosures are needed to be used in conjunction with MI cables. One may run MI cable into a box in an electrical room. However, just because that room may be a "service room" and may be subject to compartmentalization (fire protection), this does not mean one no longer requires a rated box or wrap around the electrical outlet box or junction box where the wiring is terminated because that box may be disabled as a result of a fire within the room. The probability of electrical fires are a strong motivating factor for compartmetalisation to begin with. The cable may thus be operable but the circuit as a whole may be defeated because the junction box would not have been protected. Such omissions are not entirely uncommon in the field.

Chapter 7

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 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.

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.

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.

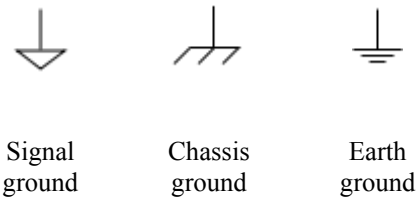
Power transmission

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

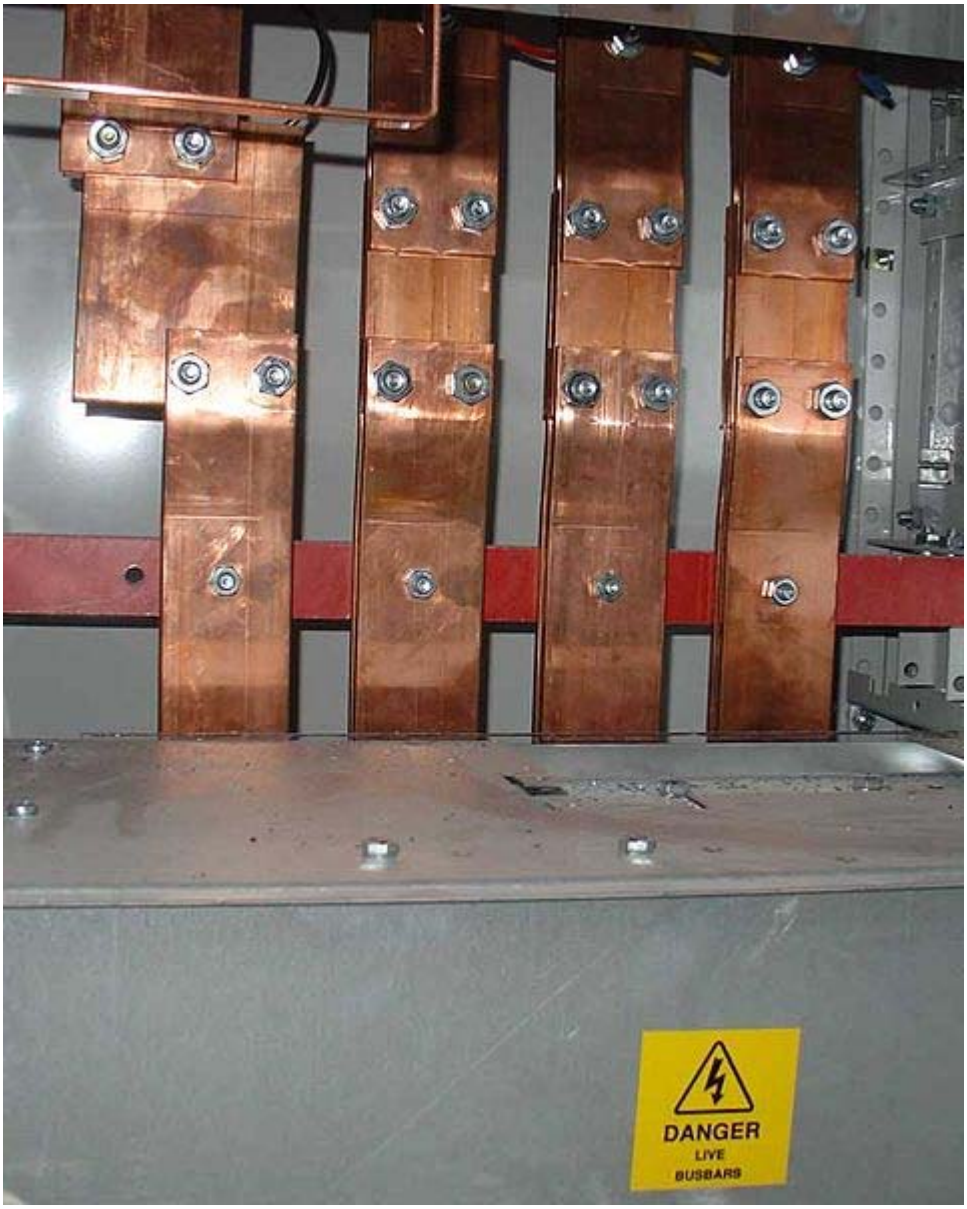
Voltage is a differential quantity. To measure the voltage of a single point, a reference point must be selected to measure against. This common reference point is called "ground" and considered to have zero voltage. This signal ground may not actually be connected to a power ground. A system where the 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 ars 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 8

Ground and Neutral & Extra-Low Voltage

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.

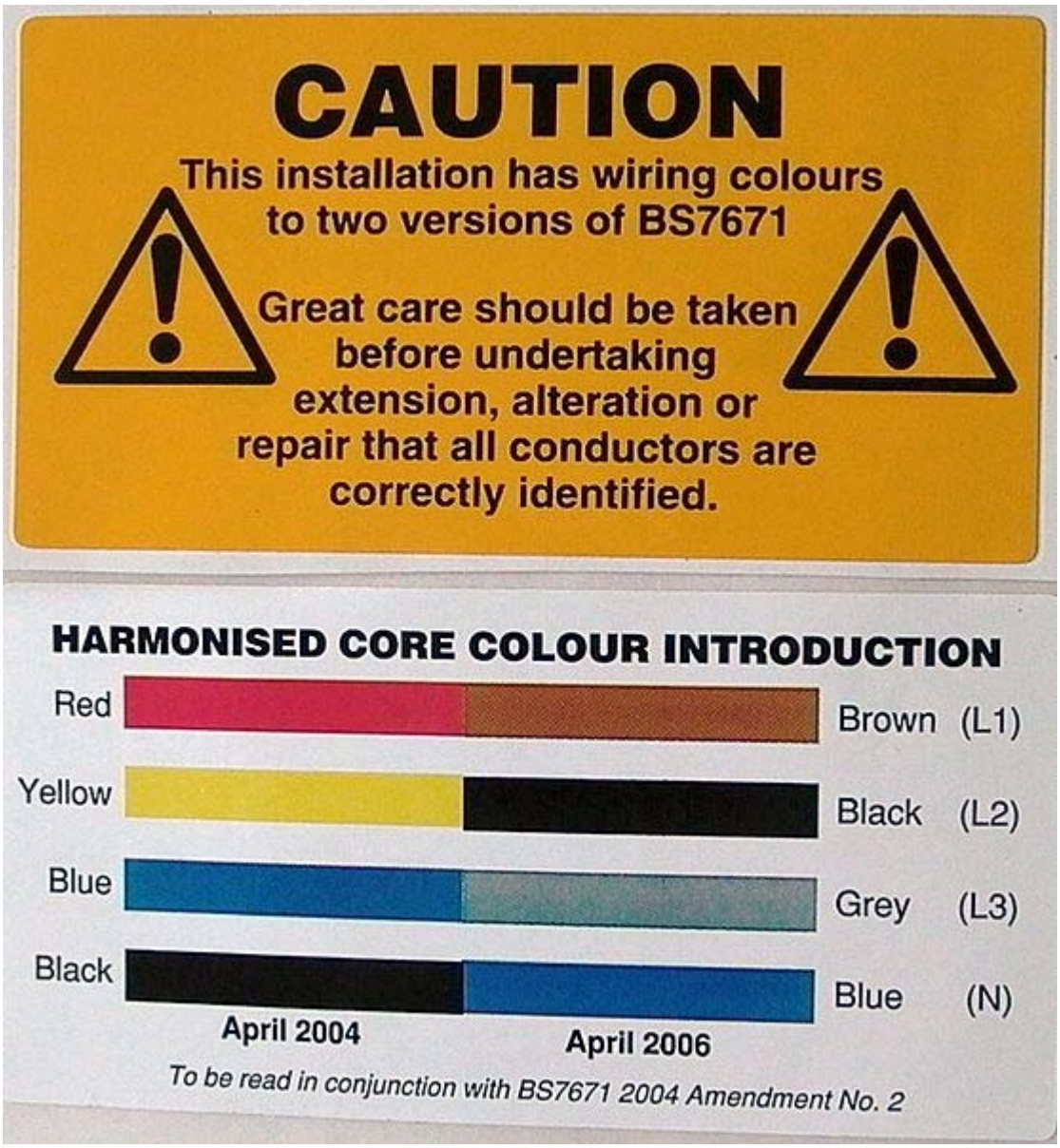
The NEC and Canadian electrical code only define neutral as the first of these. In North American use, the second definition is used in less formal language but not in official specifications. In the UK the IET definition of a neutral conductor is one connected to the supply system neutral point, which 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/wye connected transformers. Other arrangements of polyphase transformers may result in no neutral point, and no neutral conductors.

Wiring colours



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

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.

Extra-Low Voltage

IEC voltage range	AC	DC	defining risk
High voltage	> 1000 V_{rms}	> 1500 V	electrical arcing
Low voltage	25–1000 V_{rms}	60–1500 V	electrical shock
Extra-low voltage	< 25 V_{rms}	< 60 V	low risk

In electricity supply, using **extra-low voltage** (**ELV**) is one of several means to protect against electrical shock. The International Electrotechnical Commission and its member organizations define an ELV circuit as one in which the electrical potential of any conductor against earth (ground) is not more than either 25 volts RMS (35 volts peak) for alternating current, or ripple-free 60 volts for direct current under dry conditions. Lower numbers apply in wet conditions, or when large contact areas are exposed to contact with the human body.

Three types of extra-low-voltage systems are distinguished by their safety properties.

Types

Separated or safety extra-low voltage (SELV)

IEC defines a SELV system as "an electrical system in which the voltage cannot exceed ELV under normal conditions, and under single-fault conditions, *including* earth faults in other circuits".

There exists some confusion regarding the origin of the acronym: "SELV" stands for "*separated* extra-low voltage" in installation standards (e.g., BS 7671) and for "*safety* extra-low voltage" in appliance standards (e.g., BS EN 60335).

A SELV circuit must have:

- protective-separation (i.e., double insulation, reinforced insulation or protective screening) from all circuits other than SELV and PELV (i.e., all circuits that might carry higher voltages)
- simple separation from other SELV systems, from PELV systems and from earth (ground).

The safety of a SELV circuit is provided by

- the extra-low voltage
- the low risk of accidental contact with a higher voltage;
- the lack of a return path through earth (ground) that electric current could take in case of contact with a human body.

The design of a SELV circuit typically involves an isolating transformer, guaranteed minimum distances between conductors and electrical insulation barriers. The electrical connectors of SELV circuits should be designed such that they do not mate with connectors commonly used for non-SELV circuits.

A typical example for a SELV circuit is a Class III battery charger, fed from a Class II power supply.

Protected extra-low voltage (PELV)

IEC 61140 defines a PELV system as "an electrical system in which the voltage cannot exceed ELV under normal conditions, and under single-fault conditions, *except* earth faults in other circuits".

A PELV circuit only requires protective-separation from all circuits other than SELV and PELV (i.e., all circuits that might carry higher voltages), but it may have connections to other PELV systems and earth (ground).

In contrast to a SELV circuit, a PELV circuit can have a protective earth (ground) connection. A PELV circuit, just as with SELV, requires a design that guarantees a low risk of accidental contact with a higher voltage. For a transformer, this can mean that the primary and secondary windings must be separated by an extra insulation barrier, or by a conductive shield with a protective earth connection.

A typical example for a PELV circuit is a computer with a Class I power supply.

Functional extra-low voltage (FELV)

The term functional extra-low voltage (FELV) describes any other extra-low-voltage circuit that does not fulfill the requirements for an SELV or PELV circuit. Although the FELV part of a circuit uses an extra-low voltage, it is not adequately protected from accidental contact with higher voltages in other parts of the circuit. Therefore the protection requirements for the higher voltage have to be applied to the entire circuit.

Examples for FELV circuits include those that generate an extra low voltage through a semiconductor device or a potentiometer.

Stand-alone power systems

Cabling for extra-low voltage systems, such as in remote-area power systems (RAPS), is designed to minimise energy losses while maximising safety. Lower voltages require a higher current for the same power. The higher current results in greater resistive losses in the cabling. Cable sizing must therefore consider maximum demand, voltage drop over the cable, and current-carrying capacity. Voltage drop is usually the main factor considered, but current-carrying capacity is an important when considering short, high-current runs such as between a battery bank and inverter.

Arcing is a risk in DC ELV systems, and some fuse types which can cause undesired arcing include semi-enclosed, rewireable and automotive fuse types. Instead high rupturing capacity fuses and appropriately rated circuit breakers are the recommended type for RAPS. Cable termination and connections must be done properly to avoid arcing also, and soldering is not recommended.

Regulations

Australia and New Zealand

ELV is defined in AS/NZS 3000 *Wiring Rules* with the same voltages as the IEC standard.

In most Australian states (but not all) there are no formal constraints as to who can work on ELV systems. AS 4509.1 *Stand-alone Power Systems: Safety* requires that work be performed by a *"competent person"* that is *"a person who has acquired through training, qualifications, experience, or a combination of these, knowledge and skill enabling that person to correctly perform the task required"*.

ELV wiring in domestic premises must be installed at a minimum distance of 50 mm from low voltage wiring or have a separate insulating barrier such a conduit. ELV cable and wire types include PVC insulated building wire, double insulated Thermo-Plastic Sheath (TPS), and fine stranded multi-strand cable (like automotive cable, although this may only be rated to 32 V DC, and not the full ELV range).

Chapter 9

Electrostatic Discharge

Electrostatic discharge (**ESD**) is the sudden and momentary electric current that flows between two objects at different electrical potentials. The term is usually used in the electronics and other industries to describe momentary unwanted currents that may cause damage to electronic equipment.

ESD is a serious issue in solid state electronics, such as integrated circuits. Integrated circuits are made from semiconductor materials such as silicon and insulating materials such as silicon dioxide. Either of these materials can suffer permanent damage when subjected to high voltages; as a result, there are now a number of antistatic devices that help prevent static build up.

Causes of ESD

One of the causes of ESD events is static electricity. Static electricity is often generated through tribocharging, the separation of electric charges that occurs when two materials are brought into contact and then separated. Examples of tribocharging include walking on a rug, rubbing plastic comb against dry hair, rubbing a balloon against a sweater, ascending from a fabric car seat, or removing some types of plastic packaging. In all these cases, the friction between two materials results in tribocharging, thus creating a difference of electrical potential that can lead to an ESD event.

Another cause of **ESD** damage is through electrostatic induction. This occurs when an electrically charged object is placed near a conductive object isolated from ground. The presence of the charged object creates an electrostatic field that causes electrical charges on the surface of the other object to redistribute. Even though the net electrostatic charge of the object has not changed, it now has regions of excess positive and negative charges. An ESD event may occur when the object comes into contact with a conductive path. For example, charged regions on the surfaces of styrofoam cups or plastic bags can induce

potential on nearby ESD sensitive components via electrostatic induction and an ESD event may occur if the component is touched with a metallic tool.

Types of ESD

The most spectacular form of ESD is the **spark**, which occurs when a strong electric field creates an ionized conductive channel in air. This can cause minor discomfort to people, severe damage to electronic equipment, and fires and explosions if the air contains combustible gases or particles.

However, many ESD events occur without a visible or audible spark. A person carrying a relatively small electric charge may not feel a discharge that is sufficient to damage sensitive electronic components. Some devices may be damaged by discharges as small as 10 V. These invisible forms of ESD can cause device outright failures, or less obvious forms of degradation that may affect the long term reliability and performance of electronic devices. The degradation in some devices may not become evident until well into their service life.

Sparks

A spark is triggered when the electric field strength exceeds approximately 4–30 kV/cm — the dielectric field strength of air. This may cause a very rapid increase in the number of free electrons and ions in the air, temporarily causing the air to abruptly become an electrical conductor in a process called dielectric breakdown.

Lightning over Rymań. Northern Poland.

Perhaps the best known example of a natural spark is a lightning strike. In this case the potential difference between a cloud and ground, or between two clouds, is typically hundreds of millions of volts. The resulting current that flows through the ionized air causes an explosive release of energy. On a much smaller scale, sparks can form in air during electrostatic discharges from charged objects that are charged to as little as 380 V (Paschen's law).

Earth's atmosphere consists of 21% oxygen (O_2) and 78% nitrogen (N_2). During an electrostatic discharge, the intervening atmosphere become electrically overstressed. The diatomic oxygen molecules are split, and then recombine to form ozone (O_3), which is unstable, or reacts with metals and organic matter. If the electrical stress is high enough, nitrogen oxides (NOx) can form. Both products are toxic to animals, and nitrogen oxides are essential for nitrogen fixation. Ozone attacks all organic matter by ozonolysis and is used in water purification.

Sparks can cause serious explosions because of the high temperatures reached in a spark. Methane and coal dust explosions have been caused by electrostatic discharges. The Hindenburg disaster has been attributed to spark discharge igniting flammable panels tainted with thermite, which burned vigorously, violently, and extremely swiftly, which ultimately led to the ignition of hydrogen gas held in or leaking from the airship at the time. The ship had just passed through a thunderstorm and therefore may have acquired a

large charge. Discharge supposedly occurred when mooring ropes were dropped as it came in to land in New Jersey in 1937.

Corona discharge

A corona discharge occurs between a highly curved electrode, for example the tip of a needle or a small diameter wire, and an electrode of low curvature such as a flat plate. The high curvature produces a high potential gradient around one electrode.

Brush discharge

A brush discharge occurs between an electrode with a curvature between 5 mm and 50 mm and a voltage of about 500 kV/m. The resulting discharge paths have the shape of a brush.

Damage prevention in electronics

A portion of a static discharger on an aircraft. Note the two sharp 3/8" metal micropoints and the protective yellow plastic.

Prevention of ESD bases on Electrostatic Protective Area (EPA). EPA can be a small working station or a large manufacturing area. The main principle of an EPA is that there are no highly charging materials in the vicinity of ESD sensitive electronics, all conductive materials are grounded, workers are grounded, and charge build-up on ESD sensitive electronics is prevented. International standards are used to define typical EPA and can be found for example from International Electrotechnical Commission (IEC) or American National Standards Institute (ANSI).

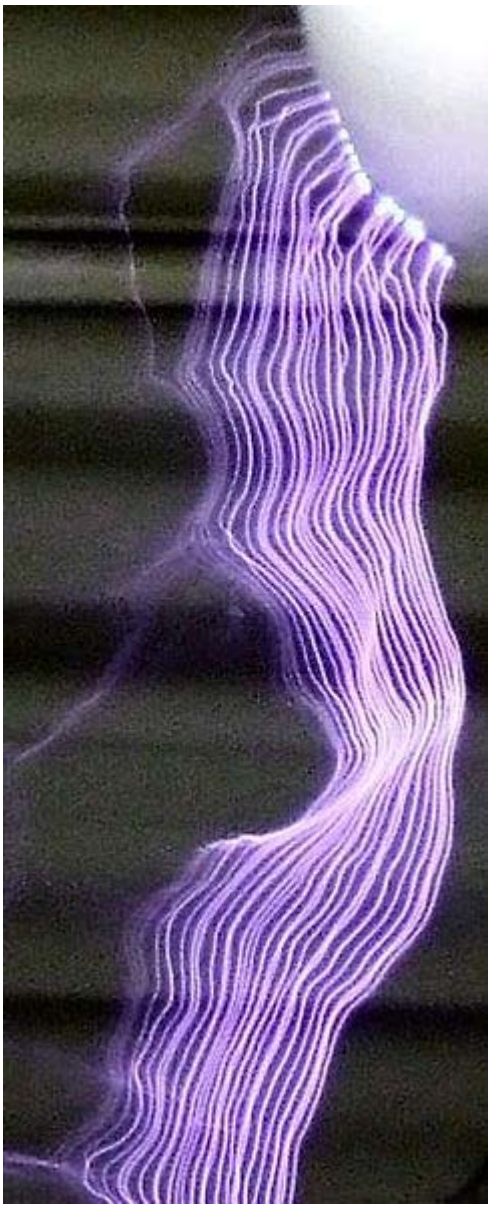
ESD prevention within an EPA may include using appropriate ESD-safe packing material, the use of conductive filaments on garments worn by assembly workers, conducting wrist straps and foot-straps to prevent high voltages from accumulating on workers' bodies, anti-static mats or conductive flooring materials to conduct harmful electric charges away from the work area, and humidity control. Humid conditions prevent electrostatic charge generation because the thin layer of moisture that accumulates on most surfaces serves to dissipate electric charges.

Ion generators are sometimes used to inject ions into the ambient airstream. Ionization systems help to neutralize charged surface regions on insulative or dielectric materials. Insulating materials prone to triboelectric charging should be kept away from sensitive devices to prevent accidental charging of devices through induction. On aircraft, static dischargers are used on the trailing edges of wings and other surfaces.

Manufacturers and users of integrated circuits must take precautions to avoid ESD. ESD prevention can be part of the device itself and include special design techniques for device input and output pins. External protection components can also be used with circuit layout.

Due to dielectric nature of electronics component and assemblies, electrostatic charging can not be completely prevented during handling of devices. Most of ESD sensitive electronic assemblies and components are also so small that manufacturing and handling is made with automated equipment. ESD prevention activities are therefore important with those processes where component is touching on equipment surfaces. In addition, it is important to prevent ESD when electrostatic discharge sensitive component is connected with other conductive parts of the product itself. An efficient way to prevent ESD is to use materials that are not too conductive but will slowly conduct static charges away. These materials are called static dissipative and have resistivity values in the range of 10^5 to 10^{11} ohm-meters. Materials in automated manufacturing which will touch on conductive areas of ESD sensitive electronic should be made of dissipative material, and the dissipative material must be grounded.

Simulation and testing for electronic devices



Electric discharge showing the ribbon-like plasma filaments from multiple discharges from a Tesla coil.

For testing the susceptibility of electronic devices to ESD from human contact, an ESD Simulator with a special output circuit, called the human body model (HBM) is often used. This consists of a capacitor in series with a resistor. The capacitor is charged to a specified high voltage from an external source, and then suddenly discharged through the resistor into an electrical terminal of the device under test. One of the most widely used models is defined in the JEDEC 22-A114-B standard, which specifies a 100 picofarad capacitor and a 1500 ohm resistor. Other similar standards are MIL-STD-883 Method 3015, and the ESD Association's ESD STM5.1. For comportment to European Union

standards for Information Technology Equipment, the IEC-61000-4-2 test specification is used. Guidelines and requirements are given for test cell geometries, generator specifications, test levels, discharge rate and waveform, types and points of discharge on the "victim" product, and functional criteria for gauging product survivability.

A Charged Device Model (CDM) test is used to define the ESD a device can withstand when the device itself has an electrostatic charge and discharges due to metal contact. This discharge type is the most common type of ESD in electronic devices and causes most of the ESD damages in their manufacturing. CDM discharge depends mainly on parasitic parameters of the discharge and is strongly depending on size and type of component package. One of the most widely used CDM simulation test models is defined by the JEDEC.

Other standardized ESD test circuits include the following:

- Machine model (MM)
- Transmission line pulse (TLP)

Chapter 10

Lightning Protection System and Isolation Transformer

Lightning Protection System

A **lightning protection system** is a system designed to protect a structure from damage due to lightning strikes by intercepting such strikes and safely passing their extremely high voltage currents to "ground". Most lightning protection systems include a network of lightning rods, metal conductors, and ground electrodes designed to provide a low resistance path to ground for potential strikes.

Description

Lightning protection systems are used to prevent or lessen damage to structures done by lightning strikes. Lightning protection systems mitigate the fire hazard which lightning strikes pose to structures. A lightning protection system provides a low-impedance path for the lightning current to lessen the heating effect of current flowing through flammable structural materials. If lightning travels through porous and water-saturated materials, these parts of a building may literally explode if their water content is flashed to steam by heat produced from lightning current.

Because of the high energy and current levels associated with lightning (currents can be in excess of 150,000 amps), and the very rapid rise time of a lightning strike, no lightning protection system can guarantee absolute safety from lightning. Lightning current will divide to follow every conductive path to ground, and even the divided current can cause damage. Secondary "side-flashes" can be enough to ignite a fire, blow apart brick, stone, or concrete, or injure occupants within a structure or building. However, the benefits of basic lightning protection systems have been evident for well over a century.

The parts of a lightning protection system are air terminals (lightning rods or strike termination devices), bonding conductors, ground terminals (ground or "earthing" rods, plates, or mesh), and all of the connectors and supports to complete the system. The air terminals are typically arranged at or along the upper points of a roof structure, and are

electrically bonded together by bonding conductors (called "down conductors" or "downleads"), which are connected by the most direct route to one or more grounding or earthing terminals. Connections to the earth electrodes must not only have low resistance, but must have low self-inductance.

An example of a structure vulnerable to lightning is a wooden barn. When lightning strikes the barn, the wooden structure and its contents, may be ignited by the heat generated by lightning current conducted through parts of the structure. A basic lightning protection system would provide a conductive path between an air terminal and earth, so that most of the lightning's current will follow the path of the lightning protection system, with substantially less current traveling through flammable materials.

Originally, scientists believed that such a lightning protection system of air terminals and "downleads" directed the current of the lightning down into the earth to be "dissipated". However, high speed photography has clearly demonstrated that lightning is actually composed of both a cloud component and an oppositely charged ground component. During "cloud-to-ground" lightning, these oppositely charged components usually "meet" somewhere in the atmosphere well above the earth to equalize previously unbalanced charges. The heat generated as this electrical current flows through flammable materials is the hazard which lightning protection systems attempt to mitigate by providing a low-resistance path for the lightning circuit. No lightning protection system can be relied upon to "contain" or "control" lightning completely (nor thus far, to prevent lightning strikes), but they do seem to help immensely on most occasions of lightning strikes.

Steel framed structures can bond the structural members to earth to provide lighting protection. A metal flagpole with its foundation in the earth is its own extremely simple lightning protection system. However, the flag(s) flying from the pole during a lightning strike may be completely incinerated.

In overhead transmission lines, a ground conductor may also be the top most wire on pylons, poles, or towers. This ground conductor is intended to protect the power conductors from lightning strikes. These conductors are connected to earth either through the metal structure of a pole or tower, or by additional ground electrodes installed at regular intervals along the line. As a general rule, overhead power lines with voltages below 50 kV do not have a ground conductor, but most lines carrying more than 50 kV do. An over head transmission line may have two overhead ground conductors. The ground conductor cable may also support fibreoptic cables for data transmission.

The majority of lightning protection systems in use today are of the traditional Franklin design. The fundamental principle used in Franklin-type lightning protections systems is to provide a sufficiently low impedance path for the lightning to travel through to reach ground without damaging the building. This is accomplished by surrounding the building in a kind of Faraday cage. A system of lightning protection conductors and lightning rods are installed on the roof of the building to intercept any lightning before it strikes the building.

Non-traditional systems aim to provide the same or similar protection with fewer components. This category can be further divided into improved lightning rods that claim an increased zone of protection (and are otherwise similar to a Franklin-type system), and systems that claim to eliminate lightning strikes altogether. The first subcategory includes early streamer emission (ESE) systems, radioactive rod systems, and laser induced systems. An example of a system that claims to eliminate lightning strikes is the charge transfer system (CTS).

Risk assessment

Some structures are inherently more or less at risk of being struck by lightning. The risk for a structure is a function of the size (area) of a structure, the height, and the number of lightning strikes per year per mi^2 for the region. For example, a small building will be less likely to be struck than a large one, and a building in an area with a high density of lightning strikes will be more likely to be struck than one in an area with a low density of lightning strikes. The National Fire Protection Agency provides a risk assessment worksheet in their lightning protection standard.

Isolation Transformer

A 230V isolation transformer

An **isolation transformer** is a transformer used to transfer electrical power from a source of alternating current (AC) power to some equipment or device while isolating the powered device from the power source, usually for safety. Isolation transformers provide galvanic isolation and are used to protect against electric shock, to suppress electrical noise in sensitive devices, or to transfer power between two circuits which must not be connected together.

Suitably designed isolation transformers block interference caused by ground loops. Isolation transformers with electrostatic shields are used for power supplies for sensitive equipment such as computers or laboratory instruments.

Strictly speaking *any* true transformer, whether used to transfer signals or power, is isolating, as the primary and secondary are not connected by conductors but only by induction.

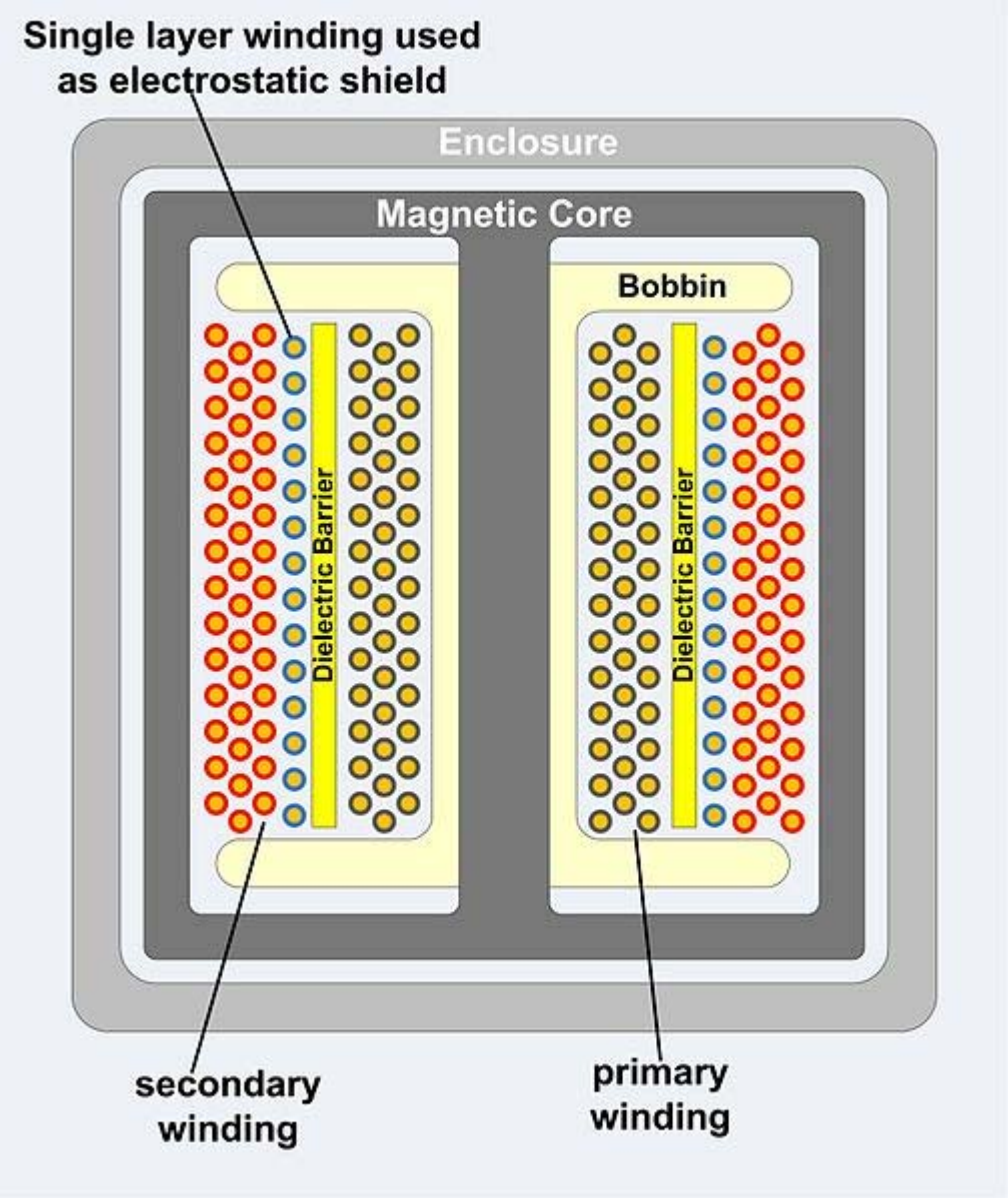
However, only transformers whose *primary* purpose is to isolate circuits (opposed to the more common transformer function of voltage conversion), are routinely described as isolation transformers.

Given this function, a transformer sold for isolation is often built with special insulation between primary and secondary, and is tested, specified, and marked to withstand a high voltage between windings, typically in the 1000 to 4000 volt range.

Sometimes the term is exceptionally used to clarify that some transformer, although not primarily intended for isolation, is a true transformer rather than an autotransformer (whose primary and secondary are not isolated from each other). Even step-down power transformers required, amongst other things, to protect low-voltage equipment from mains voltage by isolating the secondary and primary such as are used in older "wall warts", are not usually described specifically as "isolation transformers".

Some very small transformers—e.g. 4 transformers in one tiny dual in-line (DIL) chip package—used to isolate high-frequency low-voltage (logic) pulse circuits (e.g., 500V RMS primary–secondary for one second), are described as isolation transformers

Isolation transformers are commonly designed with careful attention to capacitive coupling between the two windings. The capacitance between primary and secondary windings would also couple AC current from the primary to the secondary. A grounded Faraday shield between the primary and the secondary greatly reduces the coupling of common-mode noise. This may be another winding or a metal strip surrounding a winding.



A simple 1:1 isolation transformer with an extra dielectric barrier and an electrostatic shield between primary and secondary. The grounded shield prevents capacitive coupling between primary and secondary windings.

Differential noise can magnetically couple from the primary to the secondary of an isolation transformer, and must be filtered out if a problem.

Sometimes a balanced secondary with an earthed center is used. This can reduce earth leakage in equipment used in wet locations. The maximum voltage above earth is halved, reducing the risk of shock if anything live is touched.

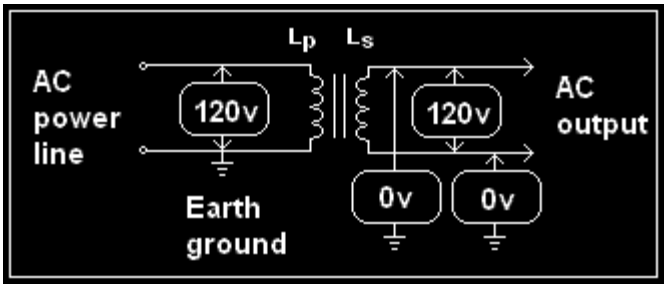
Applications

In electronics testing and servicing an isolation transformer is a 1:1 (under load) power transformer used for safety. Without it, exposed live metal in a device under test is at a hazardous voltage relative to grounded objects such as a heating radiator or oscilloscope ground lead (a particular hazard with some old vacuum-tube equipment with live chassis). With the transformer, as there is no conductive connection between transformer secondary and earth, there is no danger in touching a live part of the circuit while another part of the body is earthed.

Electrical isolation is considered to be particularly important on medical equipment, and special standards apply. Often the system must additionally be designed so that fault conditions do not interrupt power, but generate a warning.

Isolation transformers are also used for the power supply of devices not at ground potential. An example is the Austin transformer for the power supply of air-traffic obstacle warning lamps on radio antenna masts. Without the isolation transformer, the lighting circuits on the mast would conduct radio-frequency energy to ground through the power supply.

Metal boats are subject to corrosion if they use earthed power from shore when moored, due to galvanic currents that flow through the water between shore earth and the hull. This can be avoided by using an isolation transformer with the primary and case connected to shore earth, and the secondary "floating". A metal safety screen between primary and secondary is connected to shore earth; in the event of a fault current in the primary (due, e.g., to insulation breakdown) it will cause the fault current to return and trip a shore-based circuit breaker rather than making the hull live.



Chapter 11

Live-Line Working

A lineman wearing equipment for hot glove work

In electrical engineering, **live-line working** is the maintenance of electrical equipment, often operating at high voltage, while still energised. The first techniques for live-line working were developed in the early years of the twentieth century, and both equipment and work methods were later refined to deal with increasingly higher voltages. In the 1960s, methods were developed in the laboratory to enable field workers to come into

direct contact with high voltage lines. Such methods can be applied to enable safe work at the very highest transmission voltages.

Background

Electrical hazards

Electricity is hazardous: an electric shock from a current as low as 35 milliamps is sufficient to cause fibrillation of the heart in vulnerable individuals. Even a healthy individual is at risk of falling from a high structure due to loss of muscle control. Higher currents can cause respiratory failure and result in extensive and life-threatening burns. The first such human fatality occurred in 1879 and was of a stage carpenter in Lyons, France, who touched a 250 volt wire. The lack of any visible sign that a conductor is energised, even at high voltages, makes electricity a particular hazard.

At high voltages, it is unnecessary to come into direct contact with charged equipment to be shocked. An electric field surrounds all charged devices. Bringing a conducting object such as a human body into that field can intensify the field enough for electrical breakdown of the air and an arc to jump from the equipment to earth via that person. Operating clearances are thus specified in order to maintain a minimum safe distance from conductors. Solid materials such as rubber, while excellent insulators at low voltages, are also subject to electrical failure if subjected to a high enough field.

Avoiding loss of supply

Electricity utilities wish to avoid loss of supply, for which they receive customer complaints or are financially penalised. At the same time they are obligated to maintain and replace their electrical equipment on a regular basis. Due to the hazard of high voltage, it is normally necessary for equipment to be isolated from the supply before being worked upon, termed a *planned outage*.

In a radially-supplied system, a plant outage necessarily results in the loss of supply to all more remote parts of the system, unless equipment is connected in parallel, back up supplies are available or the grid reswitched to transfer the electrical load elsewhere. An interconnected grid results in no loss of power, but security of supply is compromised, and out-of-merit generation may need to be ordered to maintain system security, which can be very expensive.

Methods

There thus can be an economic advantage to live-line working, but this comes with considerable hazards unless the proper precautions are strictly followed to ensure workers' safety.

In general, there are three methods of live-line working:

Hot stick

The work is carried out with insulated tools, such as long insulating poles.

Hot glove

The worker is protected by thick rubber gloves, often extending all the way up his arms, and sometimes wears a rubber apron as well.

Hot hand

The worker is transferred to an isolated platform, such as a heavily insulated cherry picker, or suspended from a helicopter, and brought into contact with the equipment.

Some organisations additionally consider working on unearthed de-energised equipment to be another form of live-line working. This is because the line might become inadvertently charged (e.g. through a back-charged transformer), or inductively coupled from an adjacent in-service line. To prevent this, the line is first grounded via a clamp known as a bond or drain earth. Once this is in place, further work is not considered to be live-line working.

Hot stick

Hot-stick working appeared in the second decade of the twentieth century, when insulating poles made from baked wood were used for tasks such as replacing fuses, swapping out post insulators, and transferring lines onto temporary supports. The sticks enabled the linemen to carry out the work without infringing minimum clearance distances from live equipment. As experience with the techniques developed, then the operating voltages at which the work was performed increased. With the advent of fibreglass poles in the late 1950s, which neither split nor soaked up rainwater, utilities were prepared to carry out hot-stick working to their highest operating voltages, perhaps 765 kV.

Tools, such as hooks or socket wrenches can be mounted at the end of the pole. More sophisticated poles can accept pneumatically- or hydraulically-driven power tools which allow, for example, bolts to be unscrewed remotely. A rotary wire brush allows a terminal to be scoured clean before a connection is made. However, a worker's dexterity is naturally reduced when operating tools at the end of a pole that is several metres long.

Hot glove

For low or medium voltages, work can be carried out if a worker wears insulating gloves of an adequate standard. The gloves often extend all the way to the shoulder to protect the worker's arms. Additional protection can be provided by a rubberised apron. To reduce the length of exposed conductor, insulating blankets and hoses can be draped over the equipment not being worked upon. An additional layer of protection can be provided by

the use of insulated tools such as pliers. Linemen often work from an insulated platform or non-conducting ladder, however the primary protection is deemed to come from the gloves. This provides an ultimate limit on voltage for hot-glove working, perhaps 60 kV.

Hot hand

Hot-hand (also known as bare-hand, or contact) working involves placing the worker in direct electrical contact with an energised overhead line. He might work alongside the lines, from a platform that is suspended from them, or even sit or stand directly on the line itself. In all cases, the worker's body is maintained at exactly the same voltage as the line. It is imperative that no earthed equipment be brought within range, else a flashover would occur.

The first procedures for hot-hand working were developed in 1960 by Harold L. Rorden, a high-voltage engineer for American Electric Power. Techniques were further refined following field and laboratory tests.

There are three general means of getting the worker to the line:

- The worker is placed in a heavily insulated platform, and raised to the line.
- He is lowered from a helicopter and transfers himself to the line.
- He is brought alongside the wire in a hovering helicopter and works from that position.

As the lineman approaches the wire, an arc will form between them as his body is charged. Although this arc carries no more than a few microamps, it is debilitating, and the worker must immediately bond himself electrically to the line to prevent further arcing. He may use a conducting wand during the approach to first make the connection. Once on the line, he is safe from shock as both the lineman and the wire are at the same electric potential and no current passes through his body. This is the same principle that allows birds to safely alight on power lines.

When the work is completed, the process is reversed to remove him safely from the wire. Hot-hand working provides the lineman with greater dexterity than the hot stick method, and may be the preferred option if conditions permit it. With this technique, insulator strings, conductor spacers and vibration dampers can be replaced, or lines spliced, without any loss of supply.

The strong electric field surrounding charged equipment is enough to drive a current of approximately 15 μA for each $kV \cdot m^{-1}$ through a human body. To prevent this, hot-hand workers are usually required to wear a Faraday suit. This is a set of overalls made from or woven throughout with conducting fibres. The suit is in effect a wearable Faraday cage, which equalises the potential over the body, and ensures there is no through-tissue current. Conducting gloves, even conducting socks, are also necessary, leaving only the face uncovered.

There is little practical upper voltage limit for hot-hand working, and it has been successfully performed at some of the highest transmission operating voltages in the world, such as the Russian 1150 kV system.

General precautions

Transmission systems are often fitted with coordinated protection devices called autoreclosers, which are circuit breakers that automatically attempt to remake a circuit after a fault. In the event that a fault did occur, shocking a worker, it would be most undesirable for the autorecloser to re-energise the circuit, shocking him again, perhaps repeatedly. Hence if reclosing equipment is fitted, it is normally switched out of service during live-line working. Additional protection against unplanned overvoltage events (such as switching surges) can be provided by means of a surge diverter known as portable protective air gap.

An electric arc is extremely bright, including in the ultraviolet, and can cause arc eye, a painful and potentially blinding condition. Workers may be issued with appropriately tinted goggles that both protect their vision in the event of a flash and provide defence against debris ejected by an arc.

Regulations for live working are strict, and rigid adherence to protocols is essential. For example, it is usually required that more than one worker be present on site when working on live equipment above a specified voltage. The work may be postponed if adverse weather conditions such as lightning or rainfall are anticipated.

Chapter 12

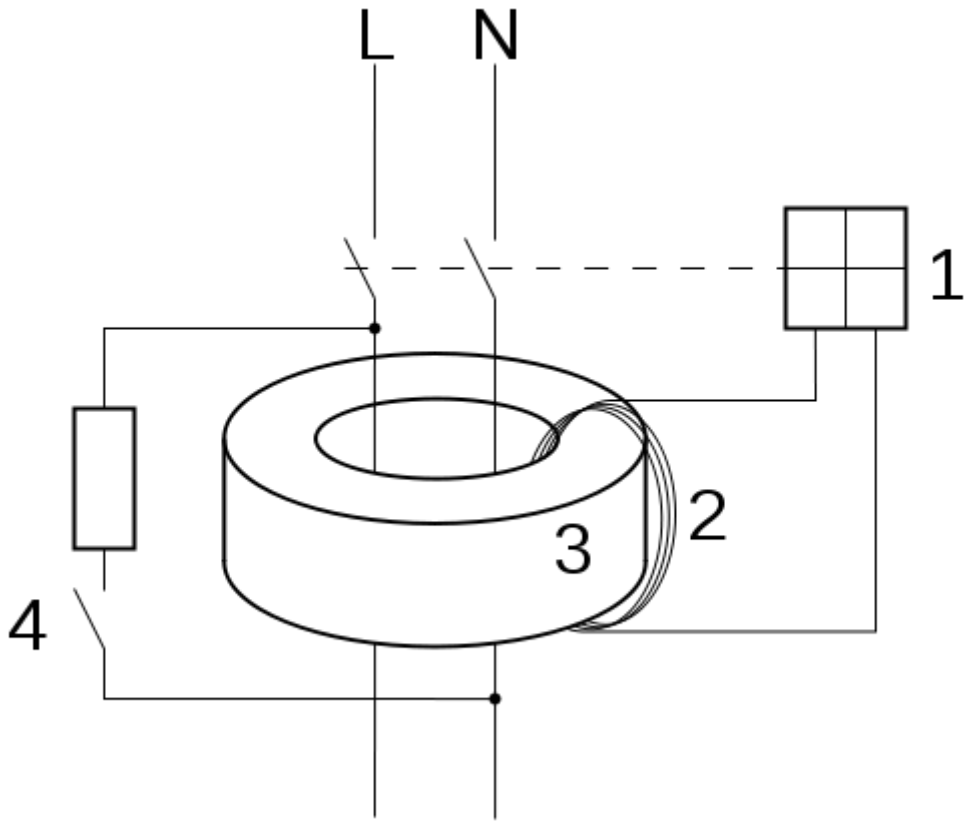
Residual-Current Device

A two-pole residual current device

A **residual-current device** (**RCD**), similar to a **residual current circuit breaker** (**RCCB**), (formerly known as an Earth leakage circuit breaker or ELCB) is an electrical wiring device that disconnects a circuit whenever it detects that the electric current is not balanced between the energized conductor and the return neutral conductor. Such an imbalance is sometimes caused by current leakage through the body of a person who is grounded and accidentally touching the energized part of the circuit. A lethal shock can result from these conditions. RCDs are designed to disconnect quickly enough to mitigate the harm caused by such shocks although they are not intended to provide protection against overload or short-circuit conditions.

In the United States and Canada, a residual current device is also known as a **ground fault circuit interrupter** (**GFCI**), **ground fault interrupter** (**GFI**) or an **appliance leakage current interrupter** (**ALCI**). In Australia they are sometimes known as "safety switches" or simply "RCD" and in the United Kingdom, along with circuit breakers, they can be referred to as "trips" or "trip switches". In the previous edition of the IEE Electrical Wiring Regulations (16th Edition) they were used to add extra fault protection to socket outlets. The current edition (17th Edition) of the regulations state that all new installations, as well as a change of distribution board or the installation of new circuits in a property wired to any previous installation, must have a split load distribution board with two RCDs covering the installation, with upstairs and downstairs lighting and power circuits spread across both RCDs in case of a fault on one RCD, therefore leaving power to at least one lighting and power circuit.

Purpose and operation



Principle of operation.
1. Electromagnet with help electronics
2. Current transformer secondary winding
3. Transformer core
4. Test switch
L live conductor
N neutral conductor.

RCDs are designed to prevent electrocution by detecting the leakage current, which can be far smaller (typically 5–30 milliamperes) than the currents needed to operate conventional circuit breakers or fuses (several amperes). RCDs are intended to operate within 25-40 milliseconds, before electric shock can drive the heart into ventricular fibrillation, the most common cause of death through electric shock.

In the United States, the National Electrical Code requires GFCI devices intended to protect people to interrupt the circuit if the leakage current exceeds a range of 4–6 mA of current (the trip setting is typically 5 mA) within 25 ms. A GFCI device which protects equipment (not people) is allowed to trip as high as 30 mA of current; this is known as an

Equipment Protective Device (EPD). In Europe, the commonly used RCDs have trip currents of 10–300 mA.

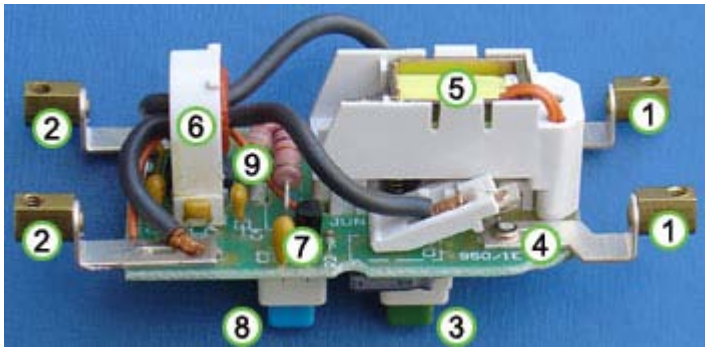
RCDs operate by measuring the current balance between two conductors using a differential current transformer. This measures the difference between the current flowing out the live conductor and that returning through the neutral conductor. If these do not sum to zero, there is a leakage of current to somewhere else (to earth/ground, or to another circuit), and the device will open its contacts.

Residual current detection is complementary to over-current detection. Residual current detection cannot provide protection for overload or short-circuit currents.

RCDs with trip currents as high as 500 mA are sometimes deployed in environments (such as computing centers) where a lower threshold would carry an unacceptable risk of accidental trips. These high-current RCDs serve more as an additional fire-safety protection than as an effective protection against the risks of electrical shocks.

In some countries, two-wire (ungrounded) outlets may be replaced with three-wire GFCIs to protect against electrocution, and a grounding wire does not need to be supplied to that GFCI, but the outlet must be labeled as such. The GFCI manufacturers provide tags for the appropriate installation description.

Example



Internal mechanism of RCD

The photograph depicts the internal mechanism of a residual current device (RCD). The device pictured is designed to be wired in-line in an appliance power cord. It is rated to carry a maximum current of 13 amperes and is designed to trip on a leakage current of 30 mA. This is an active RCD; that is, it doesn't latch mechanically and therefore trips on power failure, a useful feature for equipment that could be dangerous on unexpected re-energisation.

The incoming supply and the neutral conductors are connected to the terminals at (1) and the outgoing load conductors are connected to the terminals at (2). The earth conductor (not shown) is connected through from supply to load uninterrupted.

When the reset button (3) is pressed the contacts ((4) and hidden behind (5)) close, allowing current to pass. The solenoid (5) keeps the contacts closed when the reset button is released.

The sense coil (6) is a differential current transformer which surrounds (but is not electrically connected to) the live and neutral conductors. In normal operation, all the current down the live conductor returns up the neutral conductor. The currents in the two conductors are therefore equal and opposite and cancel each other out.

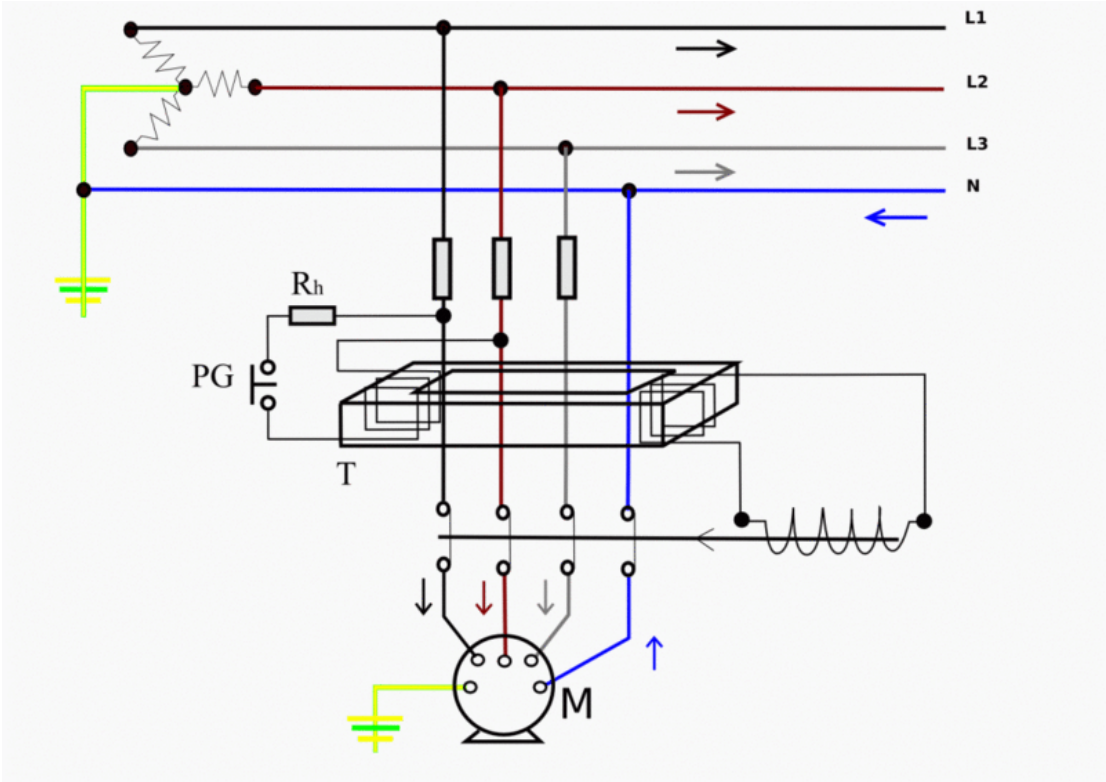
Any fault to earth (for example caused by a person touching a live component in the attached appliance) causes some of the current to take a different return path which means there is an imbalance (difference) in the current in the two conductors (single phase case), or, more generally, a nonzero sum of currents from among various conductors (for example, three phase conductors and one neutral conductor).

This difference causes a current in the sense coil (6) which is picked up by the sense circuitry (7). The sense circuitry then removes power from the solenoid (5) and the contacts (4) are forced apart by a spring, cutting off the electricity supply to the appliance.

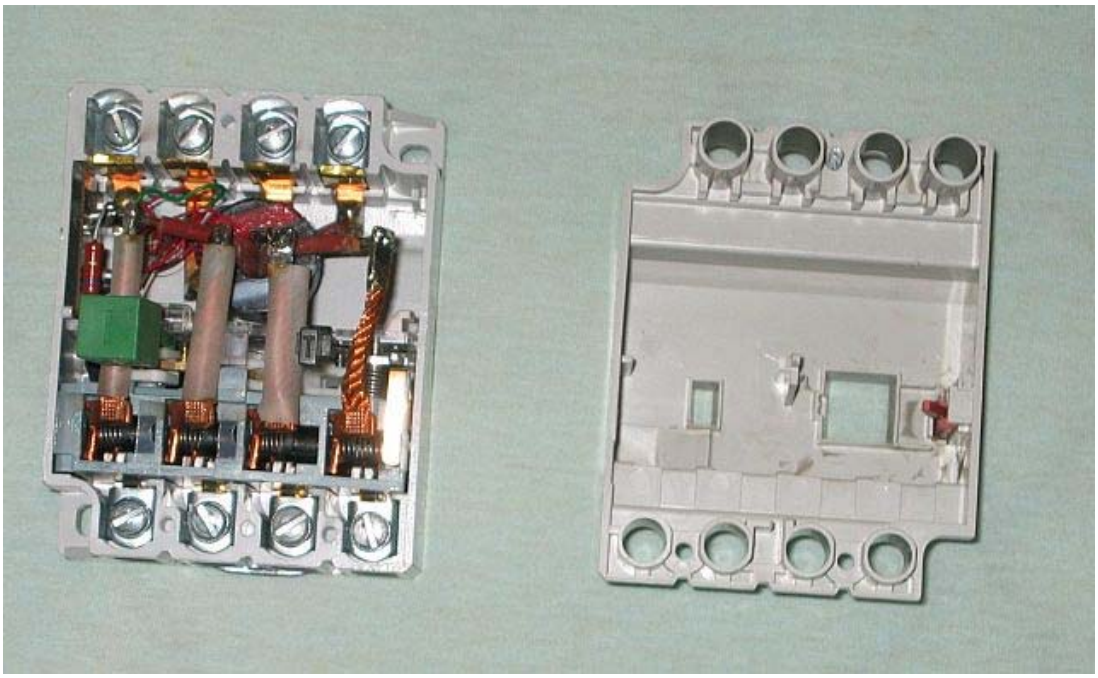
The device is designed so that the current is interrupted in a fraction of a second, greatly reducing the chances of a dangerous electric shock being received.

The test button (8) allows the correct operation of the device to be verified by passing a small current through the orange test wire (9). This simulates a fault by creating an imbalance in the sense coil. If the RCD does not trip when this button is pressed then the device must be replaced.

Three-phase example



3-phase RCD schematic.



Opened residual current device

For a three-phase variant all live conductors and the neutral must pass through the current transformer.

Rules and regulations

Rules and regulations differ widely from country to country. In Europe, the UK has only mandated the use of RCDs in new installations since July 2008. In contrast, Germany requires the use of RCDs on sockets up to 20A which are for general use. This rule was introduced in June 2007 (DIN VDE 0100-410 Nr. 411.3.3). In Norway, it has been required in all new homes since 2002, and on all new sockets since 2006. In Australia, they have been mandatory in all new houses since 1991 on all power and lighting circuits. In the U.S., the National Electrical Code requires GFCIs for underwater swimming pool lights (1968); construction sites (1974); bathrooms and outdoor areas (1975); garages (1978); near hot tubs or spas (1981); hotel bathrooms (1984); kitchen counter receptacles (1987, revised 1996 and specifically excluding the refrigerator outlet, which is usually on a dedicated circuit); crawl spaces and unfinished basements (1990); wet bar sinks (1993); laundry sinks (2005).

Use and placement

In most countries, not all circuits in a home are protected by RCDs. If a single RCD is installed for an entire electrical installation, any fault will cut all power to the premises. Normal practice in domestic installations in the UK was to use a single RCD for all RCD protected circuits but to have some circuits that are not protected at all (sockets usually are on the RCD; lamp holders usually aren't; other circuits vary by who installed the system). Regulation introduced in 2008 dictate that on all new electrical installations in the UK, all circuits must be protected by an RCD however, this does not affect existing installations.

GFI receptacles in the USA have connections to protect downstream receptacles so that all outlets on a circuit may be protected by one GFI outlet.

Combined residual current and over current (GFCI/RCBO) devices

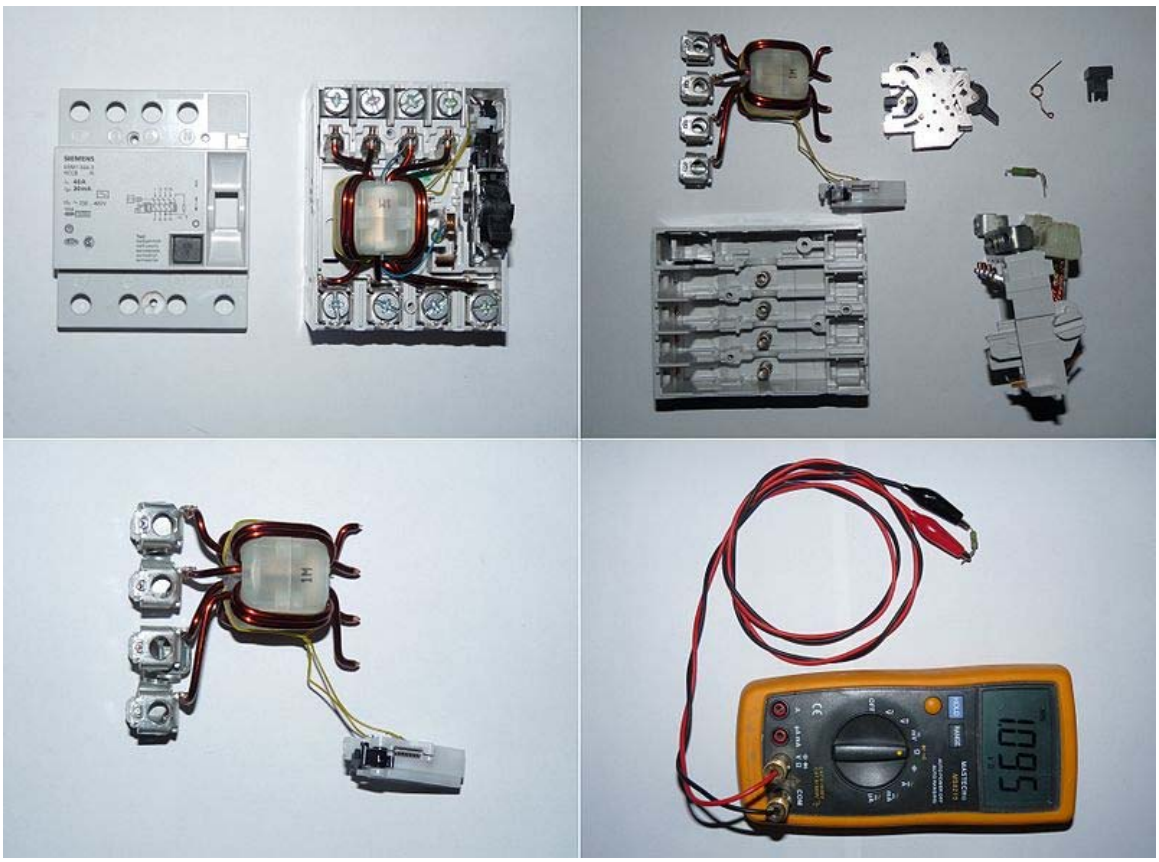
RCBO

Residual current and overcurrent protection may be combined in one device for installation into the service panel; this device is known as a GFCI breaker (Ground Fault Circuit Interrupter) in USA/Canada and as an RCBO (Residual current circuit breaker with overload protection) in Europe. In the US, RCBOs are more expensive than RCD outlets.

As well as requiring both line and neutral (or 3-phase) input and output, GFCI/RCBO devices require a functional earth (FE) connection. For reasons of space some devices use flying leads rather than screw terminals, especially for the neutral input and FE connections.

More than one RCD feeding another is unnecessary, provided they have been wired properly. One exception is the case of a TT earthing system where the earth loop impedance may be high, meaning that a ground fault might not cause sufficient current to trip an ordinary circuit breaker or fuse. In this case a special 100 mA (or greater) trip current time-delayed RCD is installed covering the whole installation and then more sensitive RCDs should be installed downstream of it for sockets and other circuits which are considered high risk.

Testing



This RCD contains a resistor with an improper value in the test circuit, which given incorrect results in testing. Under certain circumstances it may prove lethal because it will not trip when expected. That is why RCDs should be tested by the socket tester with calibrated leakage.

RCDs can be tested with the built-in test button to confirm functionality on a regular basis. RCDs if wired improperly may not operate correctly and are generally tested by the

installer to verify correct operation. Use of a solenoid voltmeter from live to earth provides an external path and can test the wiring to the RCD. Such a test may be performed on installation of the device and at any "downstream" outlet.

Limitations

A residual current circuit breaker cannot remove all risk of electric shock or fire. In particular, an RCD alone will not detect overload conditions, phase to neutral short circuits or phase-to-phase short circuits. Over-current protection (fuse or circuit breaker) must be provided. Circuit breakers that combine the functions of an RCD with overcurrent protection respond to both types of fault. These are known as RCBOs, and are available in 1, 2, 3 and 4 pole configurations. RCBOs will typically have separate circuits for detecting current imbalance and for overload current but will have a common interrupting mechanism.

An RCD will help to protect against electric shock where current flows through a person from a phase (live / line / hot) to earth. It cannot protect against electric shock where current flows through a person from phase to neutral or phase to phase, for example where a finger touches both live and neutral contacts in a light fitting; a device can not differentiate between current flow through an intended load from flow through a person.

Whole installations on a single RCD, common in the UK, are prone to nuisance trips that can cause safety problems with loss of lighting and defrosting of food. RCDs also cause nuisance trips with appliances where earth leakage is common and not a cause of injury or mortality, such as water heaters.

A dangerous condition can arise if the neutral wire is broken or switched off before the RCD while its live wire is not interrupted. In this situation the tripping circuitry of the RCD that needs power to be supplied will cease to work. The circuit will look like it is switched off, but if someone touches the live wire thinking that it is de-energized, the RCD will not trip. For this reason circuit breakers must be installed in a way that ensures that the neutral wire is turned off only at the moment when the live wire is also turned off. Separate single-pole circuit breakers must never be used for live and neutral, only two or four pole breakers must be used in cases there is a need for switching off the neutral wire.

History and nomenclature

The world’s first high-sensitivity earth leakage protection system (ie. a system capable of protecting people from the hazards of direct contact between a live conductor and earth), was a second-harmonic magnetic amplifier core-balance system, known as the magamp, developed in South Africa by Henri Rubin. Electrical hazards were of great concern in South African gold mines, and Rubin, an engineer at the company F.W.J. Electrical Industries, initially developed a cold-cathode system in 1955 which operated at 525 V and had a tripping sensitivity of 250 mA. Prior to this, core balance earth leakage protection systems operated at sensitivities of about 10 A.

The cold cathode system was installed in a number of gold mines and worked reliably. However, Rubin began working on a completely novel system with greatly improved sensitivity, and by early 1956, he had produced a prototype second-harmonic magnetic amplifier-type core balance system (South African Patent No. 2268/56 and Australian Patent No. 218360). The prototype magamp was rated at 220V 60A and had an internally adjustable tripping sensitivity of 12.5 to 17.5 mA. Very rapid tripping times were achieved through a novel design, and this combined with the high sensitivity was well within the safe current-time envelope for ventricular fibrillation determined by Charles Dalziel of the University of California, Berkeley, USA, who had estimated electrical shock hazards in humans. This system, with its associated circuit breaker, included overcurrent and short-circuit protection. In addition, the original prototype was able to trip at a lower sensitivity in the presence of an interrupted neutral, thus protecting against an important cause of electrical fire.

Following the accidental electrocution of a woman in a domestic accident at the Stilfontein gold mining village near Johannesburg, a few hundred F.W.J. 20 mA magamp earth leakage protection units were installed in the homes of the mining village during 1957 and 1958. F.W.J. Electrical Industries, which later changed its name to FW Electrical Industries, continued to manufacture 20 mA single phase and three phase magamp units.

At the time that he worked on the magamp, Rubin also considered using transistors in this application, but concluded that the early transistors then available were too unreliable. However, with the advent of improved transistors, the company that he worked for and other companies later produced transistorized versions of earth leakage protection.

In 1961, Charles F. Dalziel, working with Rucker Manufacturing Co., developed a transistorized device for earth leakage protection which became known as a Ground Fault Circuit Interrupter (GFCI), sometimes colloquially shortened to Ground Fault Interrupter (GFI). This name for high-sensitivity earth leakage protection is still in common use in the U.S.A.

In the early 1970s most GFCI devices were of the circuit breaker type. However the most commonly used in the USA since the early 1980s are built into outlet receptacles. The problem with those of the circuit breaker type was that of many false trips due to the poor alternating current characteristics of 120 volt insulations, especially in circuits having longer cable lengths. So much current leaked along the length of the conductors' insulation that the breaker might trip with the slightest increase of current imbalance.

Types

Ground Fault Circuit Interrupter (GFCI in USA) and Residual Current Breaker with Overload (RCBO in Europe) are devices which combines Residual Current Device (RCD) with a Circuit Breaker or miniature circuit breaker (MCB) which both detects supply imbalance and limits the current that may supplied.

In Europe RCDs can fit on the same DIN rail as the MCBs, however the busbar arrangements in consumer units and distribution boards can make it awkward to use them in this way. If it is desired to protect an individual circuit an RCBO (Residual-current Circuit Breaker with Overcurrent protection) can be used. This incorporates an RCD and a miniature circuit breaker in one device.

It is common to install an RCD in a consumer unit in what is known as a split load configuration where one group of circuits is just on the main switch (or time delay RCD in the case of a TT earth) and another group is on the RCD.

Electrical plugs which incorporate an RCD are sometimes installed on appliances which might be considered to pose a particular safety hazard, for example long extension leads which might be used outdoors or garden equipment or hair dryers which may be used near a tub or sink. Occasionally an in-line RCD may be used to serve a similar function to one in a plug. By putting the RCD in the extension lead you provide protection at whatever outlet is used even if the building has old wiring.

Electrical sockets with included RCDs are becoming common. In the U.S. these are required by law in wet areas.

In North America, RCD ("GFCI") sockets are usually of the **decora** size (a size that harmonizes outlets and switches, so that there is no difference in size between an outlet cover and a switch cover). For example, using the decora size outlets, RCD outlets can be mixed with regular outlets or with switches in a multigang box with a standard cover plate.

Active/passive latching/non-latching

RCDs may be obtained that have different behaviours if the circuit they are protecting is de-energised.

- One type will trip on power failure and not re-make the circuit when the circuit is re-energised. This type is known as *non-latching*.

- Another type will maintain the circuit after power is restored. This type is known as *latching* or *active*.

The first type is used when the power-drawing equipment is regarded as a safety hazard if it is unexpectedly re-energised after a power failure e.g. lawn-mowers and hedge trimmers.

The second type may be used on equipment where unexpected re-energisation after a power failure is not a hazard. An example may be the use of an RCD on a circuit providing power to a food freezer, where having to reset an RCD after a power failure may be inconvenient.

Main characteristics

Number of poles

RCDs may comprise two poles for use on single phase supplies (two current paths), three poles for use on three phase supplies (three current paths) or four poles for use on three phase & neutral supplies (four current paths).

Rated current

The rated current of an RCD is chosen according to the maximum sustained load current it will carry (if the RCD is connected in series with, and downstream of a circuit-breaker, the rated current of both items shall be the same).

Sensitivity

RCD sensitivity is expressed as the rated residual operating current, noted **IΔn**. Preferred values have been defined by the IEC, thus making it possible to divide RCDs into three groups according to their IΔn value.

- High sensitivity (**HS**): 6 – 10 – 30 mA (for direct-contact / life injury protection)
- Medium sensitivity (**MS**): 100 – 300 – 500 – 1000 mA (for fire protection)
- Low sensitivity (**LS**): 3 – 10 – 30 A (typically for protection of machine)

Type

Standard IEC 60755 (General requirements for residual current operated protective devices) defines three types of RCD depending on the characteristics of the fault current.

- Type **AC**: RCD for which tripping is ensured for residual sinusoidal alternating currents
- Type **A**: RCD for which tripping is ensured
  - for residual sinusoidal alternating currents
  - for residual pulsating direct currents
  - for residual pulsating direct currents superimposed by a smooth direct current of 0.006 A, with or without phase-angle control, independent of the polarity
- Type **B**: RCD for which tripping is ensured
  - as for type A
  - for residual sinusoidal currents up to 1000 Hz
  - for residual sinusoidal currents superposed by a pure direct current
  - for pulsating direct currents superposed by a pure direct current
  - for residual currents which may result from rectifying circuits
    - three pulse star connection or six pulse bridge connection
    - two pulse bridge connection line-to-line with or without phase-angle monitoring, independently of the polarity

Break time

There are two groups of devices:

- **G** (general use) for **instantaneous** RCDs (i.e. without a time delay)
  - Minimum break time: immediate
  - Maximum break time: 200 ms for 1x IΔn, 150 ms for 2x IΔn, and 40 ms for 5x IΔn
- **S** (selective) or **T** (time delayed) for RCDs with a short time **delay** (typically used in circuits containing surge suppressors)
  - Minimum break time: 130 ms for 1x IΔn, 60 ms for 2x IΔn, and 50 ms for 5x IΔn
  - Maximum break time: 500 ms for 1x IΔn, 200 ms for 2x IΔn, and 150 ms for 5x IΔn

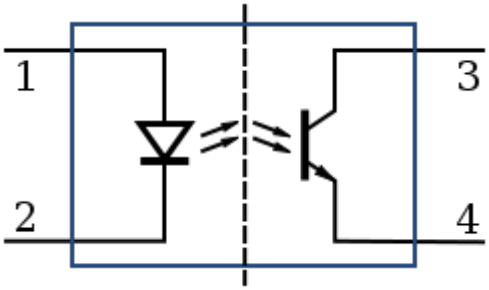
Surge current resistance

The surge current refers to the peak current an RCD is designed to withstand using a test impulse of specified characteristics (an 8/20 μs impulse, named after the time constants of the rise and fall of current).

The IEC 61008 and IEC 61009 standards impose the use of a 0.5 μs/ 100 kHz damped oscillator wave (ring wave) to test the ability of residual current protection devices to withstand operational discharges with a peak current equal to **200 A**. With regard to atmospheric discharges, IEC 61008 and 61009 standards establish the 8/20 μs surge current test with **3000 A** peak current but limit the requirement to RCDs classified as Selective.

Chapter 13

Opto-Isolator



Schematic diagram of an opto-isolator showing source of light (LED) on the left, dielectric barrier in the center, and sensor (phototransistor) on the right.

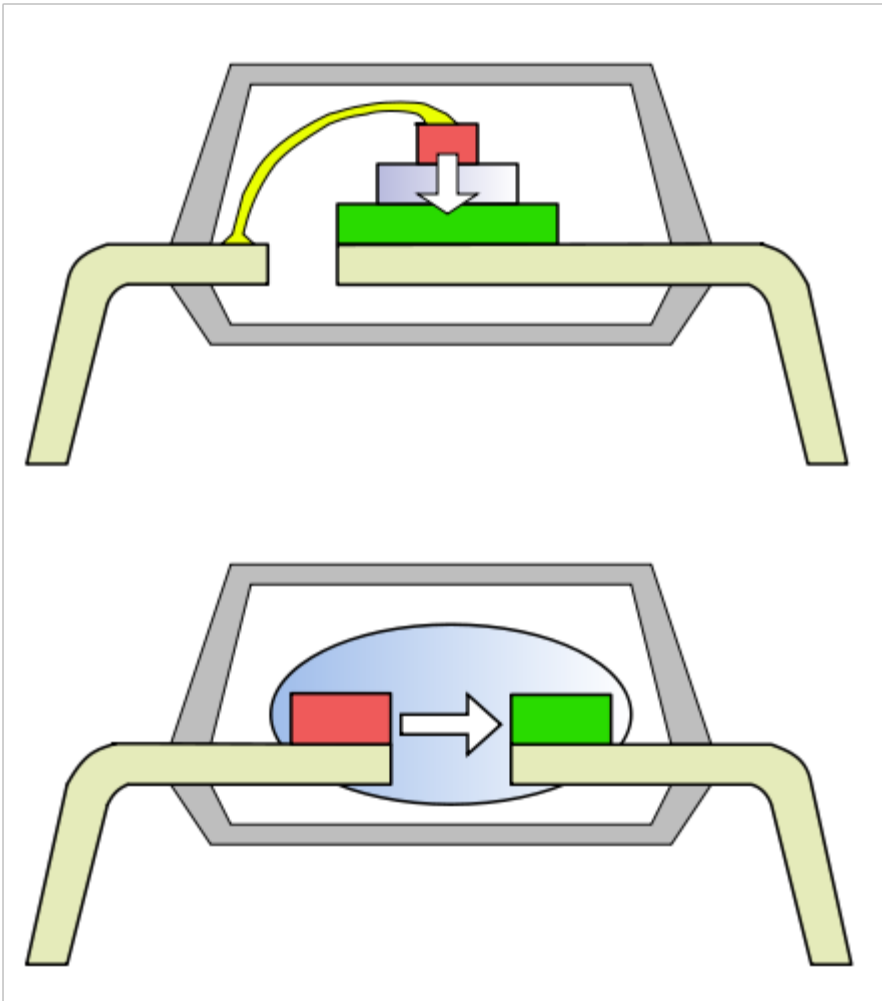
In electronics, an **opto-isolator**, also called an **optocoupler**, **photocoupler**, or **optical isolator**, is "an electronic device designed to transfer electrical signals by utilizing light waves to provide coupling with electrical isolation between its input and output". The main purpose of an opto-isolator is "to prevent high voltages or rapidly changing voltages on one side of the circuit from damaging components or distorting transmissions on the other side." Commercially available opto-isolators withstand input-to-output voltages up to 10 kV and voltage transients with speeds up to 10 kV/μs.

An opto-isolator contains a source (emitter) of light, almost always a near infrared light-emitting diode (LED), that converts electrical input signal into light, a closed optical channel (also called dielectrical channel), and a photosensor, which detects incoming light and either generates electric energy directly, or modulates electric current flowing from an external power supply. The sensor can be a photoresistor, a photodiode, a phototransistor, a silicon-controlled rectifier (SCR) or a triac. Because LEDs can sense light in addition to emitting it, construction of symmetrical, bidirectional opto-isolators is possible. An optocoupled solid state relay contains a photodiode opto-isolator which drives a power switch, usually a complementary pair of MOSFET transistors. A slotted optical switch contains a source of light and a sensor, but its optical channel is open,

allowing modulation of light by external objects obstructing the path of light or reflecting light into the sensor.

Photoresistor-based opto-isolators were introduced in the 1960s. They are the slowest, but also the most linear isolators and still retain a niche market in audio and music industry. Commercialization of LED technology in 1968–1970 caused a boom in optoelectronics, and by the end of the 1970s the industry developed all principal types of opto-isolators. The majority of opto-isolators on the market use bipolar silicon phototransistor sensors. They attain medium data transfer speed, sufficient for applications like electroencephalography. The fastest opto-isolators use PIN diodes in photoconductive mode and contain electronic circuitry for amplification, shaping and interfacing of the signal detected by the sensor, and can attain data transfer rates of 50 MBd. Their role in computing and communications is being challenged by new integrated isolation devices based on microminiature transformers, capacitive coupling or spin valves.

Electric isolation



Planar (top) and silicone dome (bottom) layouts - cross-section through a standard dual in-line package. Relative sizes of LED (red) and sensor (green) are exaggerated.

Electronic equipment and signal and power transmission lines can be subjected to voltage surges induced by lightning, electrostatic discharge, radio frequency transmissions, switching pulses (spikes) and perturbations in power supply. Remote lightning strikes can induce surges up to 10 kV, one thousand times more than the voltage limits of many electronic components. A circuit can also incorporate high voltages by design, in which case it needs safe, reliable means of interfacing its high-voltage components with low-voltage ones.

The main function of an opto-isolator is to block such high voltages and voltage transients, so that a surge in one part of the system will not disrupt or destroy the other parts. Or, according to the authors of *The Art of Electronics*, "in a nutshell, opto-couplers let you send digital (and sometimes analog) signals between circuits with separate grounds." Historically, this function was delegated to isolation transformers, which use inductive coupling between galvanically isolated input and output sides. Transformers and opto-isolators are the only two classes of electronic devices that offer *reinforced protection* — they protect both the equipment *and* the human user operating this equipment. They contain a single physical isolation barrier, but provide protection equivalent to double isolation. Safety, testing and approval of opto-couplers are regulated by national and international standards: IEC 60747-5-2, EN (CENELEC) 60747-5-2, UL 1577, CSA Component Acceptance Notice #5, etc. Opto-isolator specifications published by manufacturers always follow at least one of these regulatory frameworks.

An opto-isolator connects input and output sides with a beam of light modulated by input current. It transforms useful input signal into light, sends it across the dielectric channel, captures light on the output side and transforms it back into electric signal. Unlike transformers, which pass energy in both directions with very low losses, opto-isolators are unidirectional and they cannot transmit *power*. Typical opto-isolators can only modulate the flow of energy already present on the output side. Unlike transformers, opto-isolators can pass DC or slow-moving signals and do not require matching impedances between input and output sides. Both transformers and opto-isolators are effective in breaking ground loops, common in industrial and stage equipment, caused by high or noisy return currents in ground wires.

The physical layout of an opto-isolator depends primarily on the desired isolation voltage. Devices rated for less than a few kV have planar (or sandwich) construction. The sensor die is mounted directly on the lead frame of its package (usually, a six-pin or a four-pin dual in-line package). The sensor is covered with a sheet of glass or clear plastic, which is topped with the LED die. The LED beam fires downward. To minimize losses of light, the useful absorption spectrum of the sensor must match the output spectrum of the LED, which almost invariably lies in the near infrared. The optical channel is made as thin as possible for a desired breakdown voltage. For example, to be rated for short-term voltages of 3.75 kV and transients of 1 kV/μs, the clear polyimide sheet in the Avago ASSR-300 series is only 0.08 mm thick. Breakdown voltages of planar assemblies depend on the thickness of the transparent sheet and the configuration of bonding wires that connect the dies with external pins. Real in-circuit isolation voltage is further reduced by creepage over the PCB and the surface of the package. Safe design rules

require a minimal clearance of 25 mm/kV for bare metal conductors or 8.3 mm/kV for coated conductors.

Opto-isolators rated for 2.5 to 6 kV employ a different layout called *silicone (sic) dome*. Here, the LED and sensor dies are placed on the opposite sides of the package; the LED fires into the sensor horizontally. The LED, the sensor and the gap between them are encapsulated in a blob, or dome, of transparent silicone. The dome acts as a reflector, retaining all stray light and reflecting it onto the surface of the sensor, minimizing losses in a relatively long optical channel. In *double mold* designs the space between the silicone blob ("inner mold") and the outer shell ("outer mold") is filled with dark dielectric compound with a matched coefficient of thermal expansion.

Types of opto-isolators

Device type	Source of light	Sensor type	Speed	Current transfer ratio
Resistive opto-isolator (Vactrol)	Incandescent light bulb	CdS or CdSe photoresistor (LDR)	Very low	<100%
	Neon lamp		Low	
	GaAs infrared LED		Low	
Diode opto-isolator	GaAs infrared LED	Silicon photodiode	Highest	0.1% - 0.2%
Transistor opto-isolator	GaAs infrared LED	Bipolar silicon phototransistor	Medium	2% - 120%
		Darlington phototransistor	Medium	100% - 600%
Opto-isolated SCR	GaAs infrared LED	Silicon-controlled rectifier	Low to medium	>100%
Opto-isolated triac	GaAs infrared LED	TRIAC	Low to medium	Very high
Opto-isolated maus	DoNs infrared LED	TRIAC	Low to high	Extremely high
Solid-state relay	Stack of GaAs infrared LEDs	Stack of photodiodes driving a pair of MOSFETs or an IGBT	Low to high	Practically unlimited

Resistive opto-isolators

The earliest opto-isolators, originally marketed as *light cells*, emerged in the 1960s. They employed miniature incandescent light bulbs as sources of light, and cadmium sulfide (CdS) or cadmium selenide (CdSe) photoresistors (also called light-dependent resistors, LDRs) as receivers. In applications where control linearity was not important, or where available current was too low for driving an incandescent bulb (as was the case in vacuum tube amplifiers), it was replaced with a neon lamp. These devices (or just their

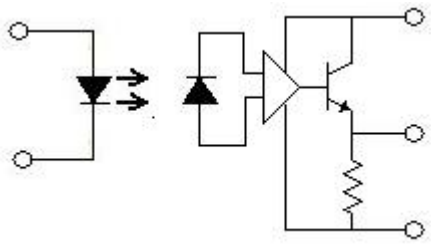
LDR component) were commonly named *Vactrols*, after a trademark of Vactec, Inc. The trademark has since been genericized, but the original Vactrols are still being manufactured by PerkinElmer.

The turn-on and turn-off lag of an incandescent bulb lies in hundreds of milliseconds range, which makes the bulb an effective low-pass filter and rectifier but limits the practical modulation frequency range to a few Hertz. With the introduction of light-emitting diodes (LEDs) in 1968–1970, the manufacturers replaced incandescent and neon lamps with LEDs and achieved response times of 5 milliseconds and modulation frequencies up to 250 Hz. The name *Vactrol* was carried over on LED-based devices which are, as of 2010, still produced in small quantities.

Photoresistors used in opto-isolators rely on bulk effects in a uniform film of semiconductor; there are no p-n junctions. Uniquely among photosensors, photoresistors are non-polar devices suited for either AC or DC circuits. Their resistance drops in reverse proportion to the intensity of incoming light, from virtually infinity to a residual floor that may be as low as less than a hundred Ohms. These properties made the original Vactrol a convenient and cheap automatic gain control and compressor for telephone networks. The photoresistors easily withstood voltages up to 400 Volts, which made them ideal for driving vacuum fluorescent displays. Other industrial applications included photocopiers, industrial automation, professional light measurement instruments and auto-exposure meters. Most of these applications are now obsolete, but resistive opto-isolators retained a niche in audio, in particular guitar amplifier, markets.

American guitar and organ manufacturers of the 1960s embraced the resistive opto-isolator as a convenient and cheap tremolo modulator. Fender's early tremolo effects used two vacuum tubes; after 1964 one of these tubes was replaced by an optocouple made of a LDR and a neon lamp. To date, Vactrols activated by pressing the stompbox pedal are ubiquitous in the music industry. Shortages of genuine PerkinElmer Vactrols forced the DIY guitar community to "roll their own" resistive opto-isolators. Guitarists to date prefer opto-isolated effects because their superior separation of audio and control grounds results in "inherently high quality of the sound". However, the distortion introduced by a photoresistor at line level signal is higher than that of a professional electrically-coupled voltage-controlled amplifier. Performance is further compromised by slow fluctuations of resistance owing to light history, a memory effect inherent in cadmium compounds. Such fluctuations take hours to settle and can be only partially offset with feedback in the control circuit.

Photodiode opto-isolators



A fast photodiode opto-isolator with an output-side amplifier circuit.

Diode opto-isolators employ LEDs as sources of light and silicon photodiodes as sensors. When the photodiode is reverse-biased with an external voltage source, incoming light increases the reverse current flowing through the diode. The diode itself does not generate energy; it modulates the flow of energy from an external source. This mode of operation is called photoconductive mode. Alternatively, in the absence of external bias the diode converts the energy of light into electric energy by charging its terminals to a voltage of up to 0.7 V. The rate of charge is proportional to the intensity of incoming light. The energy is harvested by draining the charge through an external high-impedance path; the ratio of current transfer can reach 0.2%. This mode of operation is called photovoltaic mode.

The fastest opto-isolators employ PIN diodes in photoconductive mode. The response times of PIN diodes lie in the subnanosecond range; overall system speed is limited by delays in LED output and in biasing circuitry. To minimize these delays, fast digital opto-isolators contain their own LED drivers and output amplifiers optimized for speed. These devices are called *full logic opto-isolators*: their LEDs and sensors are fully encapsulated within a digital logic circuit. The Hewlett-Packard 6N137/HPCL2601 family of devices equipped with internal output amplifiers was introduced in the late 1970s and attained 10 MBd data transfer speeds. It remained an industry standard until the introduction of the 50 MBd Agilent Technologies 7723/0723 family in 2002. The 7723/0723 series opto-isolators contain CMOS LED drivers and a CMOS buffered amplifiers, which require two independent external power supplies of 5 V each.

Photodiode opto-isolators can be used for interfacing analog signals, although their non-linearity invariably distorts the signal. A special class of analog opto-isolators introduced by Burr-Brown uses *two* photodiodes and an input-side operational amplifier to compensate for diode non-linearity. One of two identical diodes is wired into the feedback loop of the amplifier, which maintains overall current transfer ratio at a constant level regardless of the non-linearity in the second (output) diode.

Solid-state relays built around MOSFET switches usually employ a photodiode opto-isolator to drive the switch. The gate of a MOSFET requires relatively small total charge to turn on and its leakage current in steady state is very low. A photodiode in photovoltaic mode can generate turn-on *charge* in a reasonably short time but it's output

voltage is many times less than the MOSFET's threshold voltage. To reach the required threshold, solid-state relays contain stacks of up to thirty photodiodes wired in series.

Phototransistor opto-isolators

Phototransistors are inherently slower than photodiodes. The earliest and the slowest but still common 4N35 opto-isolator, for example, has rise and fall times of 5 μs into a 100 Ohm load and its bandwidth is limited at around 10 kiloHertz - sufficient for applications like electroencephalography or pulse-width motor control. Devices like PC-900 or 6N138 recommended in the original 1983 Musical Instrument Digital Interface specification allow digital data transfer speeds of tens of kiloBauds. Phototransistors must be properly biased and loaded to achieve their maximum speeds, for example, the 4N28 operates at up to 50 kHz with optimum bias and less than 4 kHz without it.

Design with transistor opto-isolators requires generous allowances for wide fluctuations of parameters found in commercially available devices. Such fluctuations may be destructive, for example, when an opto-isolator in the feedback loop of a DC-to-DC converter changes its transfer function and causes spurious oscillations, or when unexpected delays in opto-isolators cause a short circuit through one side of an H-bridge. Manufacturers' datasheets typically list only worst-case values for critical parameters; actual devices surpass these worst-case estimates in an unpredictable fashion. Bob Pease observed that current transfer ratio in a batch of 4N28's can vary from 15% to more than 100%; the datasheet specified only a minimum of 10%. Transistor beta in the same batch can vary from 300 to 3000, resulting in 10:1 variance in bandwidth.

Opto-isolators using field-effect transistors (FETs) as sensors are rare and, like vactrols, can be used as remote-controlled analog potentiometers provided that the voltage across the FET's output terminal does not exceed a few hundred mV. Opto-FETs turn on without injecting switching charge in the output circuit, which is particularly useful in sample and hold circuits.

Bidirectional opto-isolators

All opto-isolators described so far are uni-directional. Optical channel always works one way, from the source (LED) to the sensor. The sensors, be it photoresistors, photodiodes or phototransistors, cannot emit light. But LEDs, like all semiconductor diodes, are capable of detecting incoming light, which makes possible construction of a two-way opto-isolator from a pair of LEDs. The simplest bidirectional opto-isolator is merely a pair of LEDs placed face to face and held together with heat-shrink tubing. If necessary, the gap between two LEDs can be extended with a glass fiber insert.

Visible spectrum LEDs have relatively poor transfer efficiency, thus near infrared spectrum GaAs, GaAs:Si and AlGaAs:Si LEDs are the preferred choice for bidirectional devices. Bidirectional opto-isolators built around pairs of GaAs:Si LEDs have current transfer ratio of around 0.06% in either photovoltaic or photoconductive mode — less than photodiode-based isolators, but sufficiently practical for real-world applications.

Alternatives

Opto-isolators can be too slow and bulky for modern digital applications. Since the 1990s, researchers have examined and perfected alternative, faster and more compact isolation technologies. Two of these technologies, magnetic isolators and capacitor-coupled isolators, reached the mass market in the 2000s. The third alternative, based on giant magnetoresistance, has been present on the market since 2002 in limited quantities. As of 2010, production models of all three types allow data transfer speeds of 150 MBit/s and resist voltage transients of up to 25 kV/μs, compared to 10 kV/μs for opto-isolators. Unlike opto-isolators, which are stacks of discrete LEDs and sensors, the new devices are monolithic integrated circuits, and are easily scalable into multi-bit data bus isolators.

- In 2000 Analog Devices introduced integrated magnetic isolators — electrically-decoupled 100 MBit/s, 2.5 kV isolation circuits employing air core transformers micromachined on the surface of silicon integrated circuits. They featured lesser power consumption, lesser cost and were four times faster than the fastest contemporary opto-isolators. In 2010, Analog increased the speed of their magnetic isolators to 150 MBit/s and offered isolation up to 5 kV. Microtransformer-based isolators can work as dc-dc converters, passing both signal *and* power. Commercially available ICs can carry up to four isolated digital channels and a 2 W isolated power channel in miniature 20-pin packages. According to Analog Devices, by October 2010 the company has more "than 450 million [magnetic isolator] channels deployed". In the same year NEC and Renesas announced transformer-based CMOS devices with transfer rates of 250 MBit/s.
- High-speed capacitive-coupled isolators were introduced in 2000 by Silicon Laboratories and commercialized by Texas Instruments. These devices convert an incoming data stream into an amplitude-modulated UHF signal, pass it through a silicon dioxide isolation layer, and demodulate the received signal. The spectra of spurious voltage transients, which can pass through the capacitive barrier and disrupt operation, lie far below the modulation frequency and can be effectively blocked. As of 2010, capacitive-coupled isolators offer data transfer speeds of 150 MBit/s and voltage isolation of 560 V continuous and 4 kV peak across the barrier.
- NVE Corporation, the pioneer of magnetoresistive random access memory, markets an alternative type of isolator based on giant magnetoresistance (GMR) effect (*Spintronic* and *IsoLoop* trademarks). Each isolation cell of these devices is formed by a flat square coil which is micromachined above four spin valve sensors buried in the silicon wafer. These sensors, wired into a Wheatstone bridge circuit, generate binary on/off output signals. At the time of their introduction in 2002, NVE advertised speeds 5 to 10 times higher than the fastest opto-isolators; and in March 2008 commercial devices marketed by NVE were rated for speeds up to 150 MBit/s.