Application Note
Design for Electrical Safety

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Summary

The intent of this Application Note on design for electric safety is to present an overview of the subject. It also gives general insight into why and how design solutions contribute to safety.

The first section presents the most important and common hazards associated with the use of electricity, along with some basic concepts on hazard, risk, and risk reduction.

The second section gives an overview of common and standard design solutions, with a focus on the safety aspects of the particular techniques cited.

INTRODUCTION

It is difficult to imagine a modern society that does not rely upon the use of electricity.

Electricity is used in a vast variety of forms, including conveying energy in its purest form, processing and transmitting information at dazzling speeds, and the control of machinery and various real world systems. Electrical engineering brings together both the energy transmission and information processing characteristics.

Unleashing the limitless possibilities of electricity in technological applications, however, requires proper caution and care. Handling vast amounts of energy—in any form—comes with significant hazards. When energy is released in an undesired way, the results can be devastating. One only needs to consider some manifestations of unwanted energy release in nature such as lightning strikes or earthquakes, to realize that handling energy requires due care.

Fortunately, the manifestation of energy in the form of electricity can be controlled—and thus can be made safe—relatively easily. Since its discovery, numerous methods and systems have been developed for harnessing electricity. This has enabled the benefits of electricity in everyday use and avoided its hazards.

The first section of this Application Note provides a synopsis of the most important hazards associated with the use of electricity, resulting in a clear definition of the problem. An overview of the methods and systems available in electrical engineering to reduce and mitigate these risks to acceptable safe levels is given in the sections that follow.

HAZARDS ASSOCIATED WITH THE USE OF ELECTRICITY

Various hazards can occur with electricity. These hazards originate from a number of mechanisms related to thermal effects, direct effects of electric current on living organisms (and the human body in particular), electromagnetic fields, electromagnetic radiation, and non-electrical hazards induced by the use of electricity.

To design a safe product, installation, or application requires a firm understanding of what constitutes safety. Communications concerning safety requires clear and unambiguous definitions of a number of concepts and terms. Table 1 gives an overview of some essential terms when discussing electrical safety.

Term	Definition
Safety	Freedom from unacceptable risk
Risk	Combination of the probability of occurrence of a hazard and the severity of that hazard
Hazard	Potential source of harm
Tolerable risk	Risk which is accepted in a given context based on the current values of society
Residual risk	Risk remaining after protective measures have been taken
Electrical hazard	Potential source of harm when electric energy is present in an electrical installation

Table 1 – Terms and definitions in the domain of electrical safety (source IEC 60050)

The distinction between risk and hazard is of particular importance in the context of electrical safety.

The hazard associated with a person coming into contact with an electrical supply, either directly or indirectly, is clear and very severe: potential death through electrocution. This hazard is governed by the rules of physics and cannot be removed (although, in exceptional cases, replacing the power source by an extra low voltage source can be an option).

The probability of a person coming into contact with the electrically energized parts of a system can be substantially influenced by appropriate design.

Thus, the risk associated with the electric power system is made greater or smaller through design and construction.

What level of risk is tolerable or acceptable is a notoriously difficult question, in every engineering domain. For the electrical engineering domain, most national authorities have established specific sets of rules governing electrical safety. In such a context, it can be assumed that an electrical system that meets the legal requirements is sufficiently safe. Country specific differences do exist between the various rules and regulations. The general approach is however quite similar for the vast majority of countries. The level and method of enforcement of the governing rules is a noteworthy exception to this general observation.

FIRE AND IGNITION

Electric energy can be converted to heat energy. Examples of useful applications are electric heating systems and furnaces. Electric current flowing through cabling systems is partially converted to heat. This is generally referred to as conductive losses and is scientifically explained by the Joule effect.

The heat generated in the cabling system is balanced by the heat dissipated into the environment, and will result in a temperature rise. Since the amount of heat generated evolves quadratically to the current intensity, the resulting temperature rise will be more significant during circuit overload, and can be very dramatic in short circuit conditions.

Depending on the environmental conditions and the materials in contact with the cabling system, such elevated temperatures can act as an ignition source causing fire.

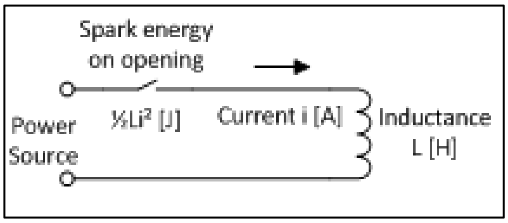

Figure 1 – Inductive Spark generation

The operation of electrical circuits—and in particular switching elements in these circuits—can cause electric sparks. This is explained by the inductive properties of the circuit that cause the current to continue to flow for a period of time after the opening of the switch contacts.

When a flammable or explosive atmosphere is present, such sparks can act as an ignition source causing fire and explosions.

Another electric phenomenon that can act as ignition source for flammable atmospheres is electrostatic discharge. Although this is not directly associated to the use of electricity, it needs to be noted. When non-conductive objects (or isolated conductive objects) become electrostatically charged, this can result in a discharge through sparks of significant energy levels, resulting in the ignition of a flammable or explosive atmosphere.

OTHER THERMAL HAZARDS

Certain hazards still need to be considered, even in environmental conditions where the temperature rise of parts of the electric circuit do not result in a fire hazard:

- Hot surfaces can cause burns and scalds
- Electric arcs—such as occur during electric arc welding operations, or such as arc flashes during (severe) short circuit conditions—radiate vast amounts of heat, with the potential for causing severe burns or ignite a fire

The huge amount of energy involved in electric arcs is at the origin of the high hazards associated with arc flash incidents. Depending upon arc current and the duration of the radiated heat, pressure waves due to rapid expanding air, projection of shrapnel, emission of vaporized material as a plasma cloud, and intense (ultraviolet) light are some of the phenomena to be expected. Arc faults can also initiate fires in electrical installations. This risk arises, for instance, where arcs occur between active conductors which have insulation defects or loose terminal connections.

The thermal effects can also cause damage to installations, buildings and property in general. While these are not considered in this document, it must be noted that malfunctioning of damaged installations can lead to a safety hazard.

ELECTRIC SHOCK AND ELECTROCUTION

The term "electric shock" (of a person or other living organisms such as livestock) is used to describe an event where a person is subjected to electrical current either accidentally or as a resolute act. The term "electrocution" refers to an electric shock with *lethal* consequences.

The effects a person experiences are not directly related to the voltage, but rather are associated with the current passing through the body. Basic application of Ohm's law reveals the link between voltage applied, current flowing, and resistance of the circuit. During electric shock, the resistance of the person's body is part of the circuit.

The effects of the current passing through a human body depend on numerous factors. For instance, the path of the current through the body has an important effect: current passing from one finger to another finger of the same hand is less likely to affect vital functions, than current passing from hand to hand through the rib cage. The severity of the effects is directly related to the length of time the current flows through the body. Direct current and alternating current of various frequencies have significantly different effects as well. **Error! Reference source not found.** gives an overview of the effects of common industrial power frequencies (50Hz and 60Hz).

Slight differences can exist between persons, as well as between the results of various studies, but the general tendencies are quite consistent.

Indicative effects of electrical current on the human body (industrial frequency – for 10 s)	
Current	Effects
Up to 0.5 mA	Generally not perceptible
Up to 5 mA	Perception and involuntary muscle contractions likely, but usually no harmful electrical physiological effects
Up to 30 mA	Strong involuntary muscular contractions. Difficulty in breathing. Reversible disturbances of heart function. Immobilization may occur. Effects increasing with current magnitude. Usually no organic damage is to be expected.
> 30 mA	Patho-physiological effects may occur such as cardiac arrest, breathing arrest and burns, or other cellular damage. Probability of ventricular fibrillation increasing with current magnitude and time. **Cardiac arrest**, **severe burns**, **Death is probable**.

Table 2 -- Indicative effects of electrical current on the human body (elaborated from IEC 60479-1)

It is immediately clear from Table 2 that allowing currents of over 30 mA to travel through a person cannot be considered safe, and depending on circumstances even currents as low as 5 mA can constitute a hazard to persons.

An electric shock can occur due to either of the following:

- Direct contact: electrical contact of persons or animals with live parts (e.g. bare copper bus bars, damaged power cables with exposed conductor cores, or power outlets with missing protective covers, etc.)
- Indirect contact: electrical contact of persons or animals with exposed conductive parts which have become live under fault conditions (e.g. the metal housing of a machine with faulty insulation, or steel structural elements incidentally contacting a conductor, etc.)

However, according to IEC Guide 104, IEC EN 61140, IEC 60364-4-41 and HD 60364-4-41, this use of direct contact and indirect contact terminology is obsolete. International and European standards now use the following terminology:

- Protection under normal conditions, also called basic protection (= protection against direct contact)
- Protection under fault conditions, also called fault protection (= protection against indirect contact)

The concept has not changed, only the terminology. The protection principle is that hazardous-live-parts must be inaccessible, and accessible conductive parts may never become hazardous-live, in either of the following circumstances:

- Under normal conditions (operation as intended, see 3.13 of ISO/IEC Guide 51, and in the absence of a fault)
- Under single-fault conditions (see also 2.8 of IEC Guide 104)

A special state of hazard can occur in some earth fault conditions where, due to current flowing into the ground, a significant potential gradient exists between two different points of the soil. This is usually associated with high voltage earth faults and lightning strike incidents.

In special circumstances, the phenomenon of electrostatic discharge, indicated above as a potential ignition source, can pose a risk to persons as well.

Electromagnetic fields and radiation

In recent years, a substantial controversy has grown over the possible effects of exposure to electromagnetic fields and radiation. Given that even renowned scientific institutions tend to disagree on the possible effects of various exposure scenarios, it is not the intention of this Application Note to address this question. However, a few particular cases must be noted.

High-power, high frequency electromagnetic fields, and radiation encountered in industrial radio frequency and microwave heating applications present a potential hazard. Persons entering the effective area or radiation escaping the technical installation due to faulty shielding can lead to localized internal and/or superficial overheating of tissue, resulting in specific types of burns and scalds, with potentially very severe impact.

An electric arc—whether from welding or arc flash fault conditions—will, in addition to the significant amount of heat, emit a broad spectrum of electromagnetic radiation. The emitted spectrum encompasses the visual and ultraviolet light ranges. This intense radiation can affect a person’s health and safety through effects on the eyes (actinic conjunctivitis) and skin (similar to sunburn).

Other non-electrical effects of electricity

In many applications, the use of electricity can introduce specific non-electrical hazards. This is not, as such, a property of electricity. Any other source of energy to power the application (compressed air, steam, combustion engines, et cetera) can introduce the same or similar hazards. A few examples of such hazards are:

- Moving parts and mechanical forces resulting from them, especially in case of unexpected start-up
- Malfunction of apparatus, machinery, or control systems due to, for instance, over or under voltage, EMI/EMC issues, or static discharges, leading to unintended actions.
- Failure of critical systems due to power outage, e.g. life support systems or critical safety systems

Risk reduction by design

Proper design of an electrical system can reduce the risk associated with the use of electricity to an acceptable level.

To achieve the goal of a safe electrical system, the design effort needs to identify and account for all of the existing hazards. Design strategies should aim to either reduce the possible consequences or reduce the probability of occurrence of hot surfaces, incendiary sparks, electric shock of persons by direct or indirect contact, et cetera.

Various risk reduction strategies can be envisaged:

- Reduction of voltage levels
- Avoidance of direct contact with dangerous parts
- Conductor sizing to limit temperature during normal operation
- Detection and elimination of fault conditions
- Limiting exposure by decreasing the time the hazardous conditions remain present
- Other strategies

A wide array of standard design solutions for electrical systems has evolved over time. Virtually all of these standard solutions incorporate elements of one or more of these risk reduction strategies.

International Standard IEC 60364 prescribes minimum design solutions for low voltage electrical system safety.

Common and standard design solutions for electricity

In this section, a number of widely used technical design solutions are discussed. The main angle of approach is how design contributes to electrical safety. Where appropriate, indications of specific benefits and possible limitations and trade-offs linked to appropriate design solutions are given.

Short circuit and overload protection

Short circuit and overload protection of electrical circuits plays an important role in risk reduction as it relates to thermal hazards. Additionally, short circuit protection limits the consequences of high mechanical forces occurring due to magnetic effects in short circuit conditions. Short circuit protection furthermore reduces risks of indirect touch in TN type networks.

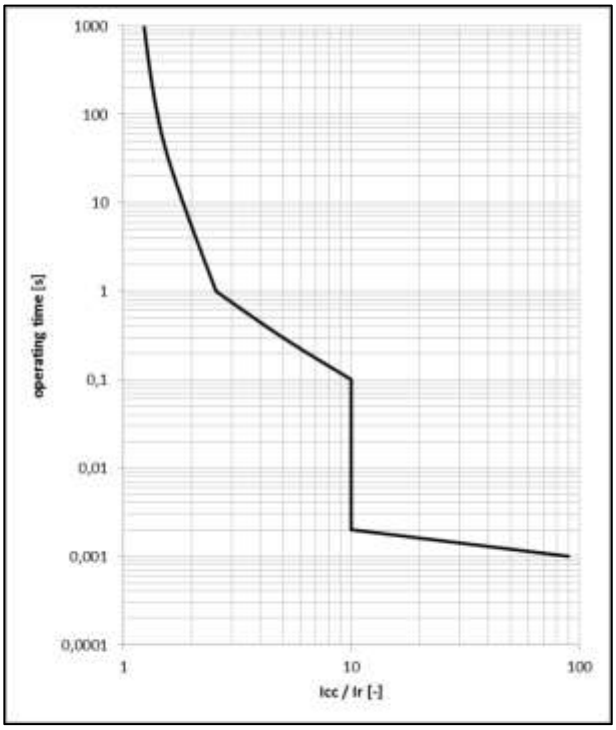

Figure 2 – Typical circuit breaker characteristic

The heat generated in a cable is proportional to square of the current flowing through the cable($Q = R_{cable} \times I^2$). During overload conditions, the additional heat generation results in elevated temperature, resulting in risk of damage to the cable insulation and a fire hazard. (For example, at 10% overload, heat generation rises 21%; at 100% overload, heat generation rises to 400%) The temperature rise is not instantaneous, due to the heat capacitance of both cable and surrounding materials. Thus, the overload protection does not have to react instantaneously. Virtually all overload protective systems (fuses, thermal relays, et cetera) are engineered with a declining reaction time as a function of the overload ratio. Common operating times range from tens of seconds to a few hours.

The rise in heat generation during short circuit condition is dramatically higher compared to overload. In common applications, short circuit current to nominal current ratios are in the range of 10 to 1,000. This results in an increase of instantaneous heat generation of 2 to 6 orders of magnitude.

Mechanical forces generated between current carrying conductors also evolve proportional to the square of the current. In most applications, these are negligible at nominal current, but become a major design issue at short circuit current.

It is immediately clear that for a technical component (cable, bus bar, switch gear, or other device) to survive such a heat surge and the related mechanical stress, the time required for switching off the current needs to be very short. Common operating times range from a few milliseconds (about a quarter cycle of the AC waveform) up to a few seconds.

ARC FLASH PROTECTION

The previous sections focus on prevention of electric shock by contact with current carrying parts, or prevention of the effects of heating of current carrying parts. Standards addressing electric shock and fire prevention have existed for over a century. Scientific and experimental work underpinning these standards dates back to the discovery of electricity.

As the power levels and current magnitudes have increased over time, arc flash became "that other electrical hazard". Some early scientific work on the subject was conducted in the 1960s and 1970s. Widespread industrial interest in the subject only emerged in the mid-nineties, and was mainly due to the publication of the fifth edition of NFPA70E (*Standard for Electrical Safety in the Workplace*) in 1995 which introduced the concept of arc flash hazard. The interest in the subject, and development of mitigating strategies in the US was further encouraged by the publication of IEEE1584 *Guide for Performing Arc Flash Calculations* in 2000.

In the residential sector, interest in protection against electric arcs arose initially in the US because of building technologies based on wood, but it has more recently become an international concern.

At international level, IEC standards concerning arc flash have been published in recent years. These include requirements and test methods for protective clothing (IEC 61482-1) and requirements for arc fault detection devices (AFDD).

Clause 421.7 and annex B of standard IEC 60364-4-42 recommend that special measures be taken to protect against the effects of arc faults in final circuits. This recommended protection, according to IEC 62606, will be provided by arc fault detection devices.

Experience of arc flash standardization is rather limited (no more than two decades) compared to electric shock prevention. It is clear that methods and techniques for arc flash protection have not yet reached the same level of maturity and general acceptance as electrocution and fire prevention.

The current state of the art in arc flash protection consists in a combined approach.

The first step is a risk analysis, in particular conducting an arc flash study of the electric network. The aim of such a study is to determine the amount of incident energy that could be released for each busbar in the network, taking into account all relevant switching scenarios. This comes down to calculation of the arc fault current for each busbar in every selected switching scenario. The calculations at first sight resemble classic short circuit calculations (often designated as bolted fault). There is, however, an important difference: the arc itself has impedance. The arc impedance is difficult to predict. At best, estimates of minimal and maximal value can be obtained in real life situations. The impact of the arc impedance can be significant, especially in low voltage distribution systems. Low voltage system arc fault currents are often only about half the bolted short circuit current. In many cases, this renders the ordinary short circuit protection devices totally inadequate, since reaction times increase with lower fault currents. The minimum fault value is required to develop a protection system able to detect arc faults reliably. The maximum fault value is required for construction of equipment able to withstand the consequences.

A protection strategy is developed based on the information from the arc flash study. Generally, the strategy will encompass a number of techniques such as:

- Arc flash containment/arc-resistant equipment: switch elements, switch gear, or switch gear assemblies are constructed to be able to withstand the energy release and limit the effects to the space inside the casing or containment. Sufficient attention must be given to redirecting the blast energy to a safe location.
- Current limiting fuses: the current limiting characteristic of the fuse significantly reduces the maximum fault value. However, detecting the minimum fault value can prove very challenging.
- Arc flash detection and high-speed switching: the occurrence of an arc flash is detected, either by specifically configured relays recognizing an arc fault current profile, by optical (UV) sensors, or by a combination of both. Upon detection, an upstream (high-speed) breaker is tripped. The incident energy is limited through limitation of the arc flash duration.
- Arc flash quenching: a (power electronic) device is tripped upon detection of an arc flash that creates a controlled short circuit of the busbar. This effectively deflects the energy from the arc and gives rise to a normal short circuit capable of tripping the classic overcurrent protective devices. The use of a quenching device combined with current limiting fuses often provides interesting options.
- Remote operation: remotely operating switches (and even remote racking in LV motor control centers) moves persons away from the danger zone
- Strict application of safe work procedures: limiting live work to the absolute minimum clearly reduces exposure of persons to the potential hazards.
- Personal protective equipment is self-evident for those situations where exposure of persons cannot be avoided, including the use of arc flash protective clothing, face shield, gloves, et cetera.
- Labeling and marking: clear indications of possible arc flash risks, in particular for scenarios involving maintenance of electrical cabinets and switch gear while the doors are open.

None of these techniques will succeed in making an installation arc flash safe by themselves. Containment of enclosed switch gear will provide sufficient safety in normal operation with closed covers, but what will happen with an open door during maintenance or inspection?

Only careful and prudent developed strategy implementing a well-engineered combination of techniques can create a sufficiently safe situation with respect to arc flash hazards.

ELECTRIC SHOCK AND ELECTROCUTION PROTECTION

Among the various engineering solutions available for electric shock and electrocution protection, this guide discusses:

- Extra-low voltage systems
- Automatic disconnection of supply
- Insulation, reinforced insulation, and double insulation

EXTRA-LOW VOLTAGE SYSTEMS: SELV, PELV, FELV

The effect of an electric shock depends on the current going through the human body. When the electrical power source has a limited voltage, then by application of Ohm's law it is immediately clear that the current will be limited as well.

Extra-low voltage (ELV) is defined as a voltage not exceeding the relevant voltage limit of 50 V AC RMS and 120 V DC (ripple free) Also known as *band I* defined in IEC 60449.

In a dry skin condition, this extra-low voltage can be assumed safe to touch, for an indefinite period of time. Thus, the SELV and PELV systems aim to reduce the risk resulting from direct contact with current carrying parts by reduction of the consequences. Note that safe to touch does not automatically imply comfortable to touch. These limit values are also referred to as absolute conventional touch voltage limits.

However, in wet skin conditions, lower voltage levels need to be observed since the contact resistance is significantly lowered. In general 25 V AC and 60 V DC is considered safe for wet skin conditions. When submerged in water this is further reduced to 12 V AC and 30 V DC. The reader should note that these wet condition values can be different in various national implementations of electrical safety regulations.

Obviously, if persons can come into contact with a reduced voltage electrical system, the technical equipment generating the extra-low voltage must be reliable. An unreliable voltage source experiencing occasional voltage surges would still be quite dangerous. One only needs to imagine the consequences of contact coinciding with a voltage surge to grasp the necessity for reliability and fault tolerance of the voltage source.

50 V AC is not itself an intrinsically safe level unless the power source and the whole electrical installation also comply with additional requirements. For example:

- The ELV power source shall comply with the requirements of IEC 61558-2-6 to ensure that a hazardous voltage will not appear on the power source
- The ELV electrical installation shall comply with the requirements of IEC 60364

The ELV electrical installations are primarily classified as follows:

- **Safety** extra-low voltage (SELV)
  Electric installation in which the voltage cannot exceed the value of extra-low voltage:
  - under normal conditions, and
  - under single fault conditions, including earth faults in other electric circuits;
- **Protective** extra-low voltage (PELV)
  Electric installation in which the voltage cannot exceed the value of extra-low voltage:
  - under normal conditions, and
  - under single fault conditions, except earth faults in other electric circuits;
- **Functional** extra-low voltage (FELV)
  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.

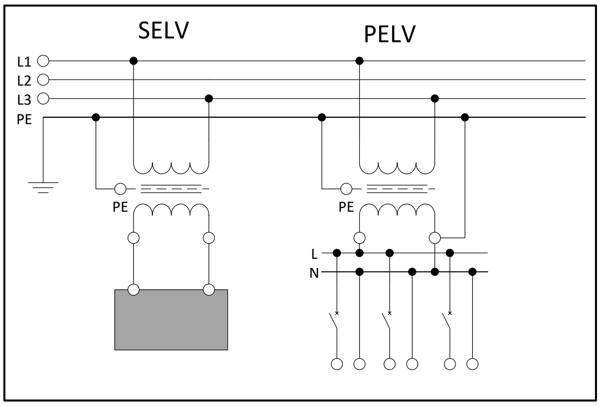

Figure 3 – Typical SELV/PELV circuit configuration

A SELV system needs protective separation from all non-SELV or non-PELV systems, and simple separation from all PELV systems, protective earth, and all other SELV systems. A typical arrangement for implementing a SELV system is the use of a safety separation transformer providing galvanic separation from the mains supply, with voltage output characteristics within the ELV voltage limits, and offering adequate isolation between primary and secondary windings (double insulation, protective screen, et cetera). The output circuit is floating (not referenced to earth) to avoid influence from earth faults in other systems. A separate transformer is used for each SELV system.

A PELV system needs protective separation from all non-SELV or non-PELV systems, but can have connections to other PELV systems and protective earthing. A typical arrangement for implementing a PELV system is the use of a safety separation transformer providing galvanic separation from the mains supply, with voltage output characteristics within the ELV voltage limits, and offering adequate isolation between primary and secondary windings (double insulation, protective screen, et cetera). The output circuit can be earthed and multiple PELV systems can be supplied from the same transformer.

In addition to safety separation transformers, typical arrangements to achieve a SELV or PELV system include supply from batteries, dedicated combustion engine driven generators, solar panels, and galvanically separated switched mode power supplies. Adequate reliability of the output voltage levels must be incorporated in the design.

A typical arrangement to implement a FELV system could be a simple transformer creating galvanic separation.

The nature of all ELV systems makes them less suitable for high-power applications. The low voltage levels require elevated currents to transmit power, which can prove notoriously difficult to harness.

Typical applications of SELV are welding (exposure of the welding operator to the metal), specific medical applications in hospital operating rooms (protecting the patient from electric shock requires very stringent electrical separation), and power supply to devices for use in high electric shock risk environments (such as metal enclosed confined spaces and those near water basins). Typical applications of PELV are various control systems, in particular machinery control circuits constructed to EN-IEC60204-1.

AUTOMATIC DISCONNECTION OF SUPPLY

The concept of automatic disconnection of supply involves opening the supply circuit in the event of a fault, indicated usually by an increase in current. For a given voltage value, the fault current amplitude is strongly dependent on the earthing system.

The theoretical contact voltage that occurs during earth fault conditions in an electric apparatus supplied by the circuit under consideration is dependent on the earth fault current and the resistance of the protective earth return path for the fault current.

Automatic disconnection of supply requires a protective earth and a disconnection device able to recognize the fault condition. It is not technically possible to set up this kind of protection without a proper protective earth.

The concept of a protective earth aims to reduce risk resulting from indirect contact. The basic intention is to avoid elevating the electrical potential – for example of the casing of an electrical apparatus – to a dangerous voltage level with reference to the earth surface. If the voltage between the apparatus casing and the floor on which a person is standing cannot reach dangerous levels, then electric shock risk due to indirect touch is eliminated.

In an ideal world, a (close to) zero impedance connection between the conductive housing of a device and the earth would solve all indirect touch issues. Unfortunately, the earth does not come readily equipped with a low impedance connection terminal. Creating a real world earth connection is cumbersome: earth rods driven into the soil, buried earth plates or (meshed) cabling underneath building foundations are some of the technical solutions. The impedance of real world earth connections is highly dependent on local conditions. In good circumstances, relatively low values in the range 5 to 30 ohms are easily reached. Bringing the impedance down to acceptable levels can be challenging in more difficult environments such as dry sandy ground or mountain bedrock.

The question of what constitutes an acceptable impedance value of a protective earth connection has no readily available answer. The main factors in determining acceptable impedance levels are:

- The earth connection system used (IT, TT, TN see Briefing Paper Earthing Configurations, Paul De Potter, Cu0101 for more information on these systems)
- Type of protective system used (fuses, circuit breaker, residual current device in TT or TN earthed networks, insulation monitor in IT earthed networks)
- Power supply type (single phase, tri-phase, et cetera) and voltage level (low voltage, high voltage)
- Cable design calculation results such as operational current, expected prospective short circuit current, cable cross section, et cetera
- Environmental conditions with respect to exposed persons (wet or dry, persons in close contact to, or isolated from, conductive structures, et cetera)

The basis for achieving an appropriate level of safety in an **IT network** is the interruption of the current loop by the isolation of the power supply, thus preventing dangerous currents from flowing through a person touching a device housing containing compromised insulation. Such a fault condition needs to be detected and resolved as soon as possible, since the occurrence of a second fault elsewhere in the network can have serious, even deadly consequences. This explains the need for a continuous insulation monitoring system in such a network. In general, the electrical system can be allowed to continue operation during faultfinding and repairs, which is the main advantage of the IT system.

If an earth fault current is present in a **TT network**, it may be of sufficient magnitude to constitute a hazard to persons yet unable to guarantee the triggering of short circuit protective systems in due time. The basis of safety for indirect touch needs to be created by the introduction of a residual current device (RCD) of appropriate sensitivity together with the earth system. Timely detection of the potentially dangerous earth fault current, followed by power supply disconnection, eliminates the risk for indirect touch electric shock. Although it is possible that the RCD will react sufficiently fast to limit the consequences of a direct touch electric shock incident, it must not be considered a primary safeguard for these scenarios.

The basis for achieving an appropriate level of safety in a **TN network** is a well-defined earth fault current (fully-engineered return path) of sufficient magnitude to operate the short circuit protective system almost instantly, thus selectively switching off the device or network branch containing an earth fault. Once the faulty circuit is switched off, the hazard is eliminated. For completeness, it should be mentioned that the same principle applies in part to TT networks, but in such networks it is not sufficiently reliable to ensure safety.

Since the PE return path is well defined in TN networks, the theoretical contact voltage which occurs during earth fault conditions in an electric apparatus supplied by the circuit under consideration can be calculated fairly accurately.

If the theoretical contact voltage is calculated to be below the extra-low voltage limits (see the section Arc flash protection

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Experience of arc flash standardization is rather limited (no more than two decades) compared to electric shock prevention. It is clear that methods and techniques for arc flash protection have not yet reached the same level of maturity and general acceptance as electrocution and fire prevention.

The current state of the art in arc flash protection consists in a combined approach.

The first step is a risk analysis, in particular conducting an arc flash study of the electric network. The aim of such a study is to determine the amount of incident energy that could be released for each busbar in the network, taking into account all relevant switching scenarios. This comes down to calculation of the arc fault current for each busbar in every selected switching scenario. The calculations at first sight resemble classic short circuit calculations (often designated as bolted fault). There is, however, an important difference: the arc itself has impedance. The arc impedance is difficult to predict. At best, estimates of minimal and maximal value can be obtained in real life situations. The impact of the arc impedance can be significant, especially in low voltage distribution systems. Low voltage system arc fault currents are often only about half the bolted short circuit current. In many cases, this renders the ordinary short circuit protection devices totally inadequate, since reaction times increase with lower fault currents. The minimum fault value is required to develop a protection system able to detect arc faults reliably. The maximum fault value is required for construction of equipment able to withstand the consequences.

A protection strategy is developed based on the information from the arc flash study. Generally, the strategy will encompass a number of techniques such as:

- Arc flash containment/arc-resistant equipment: switch elements, switch gear, or switch gear assemblies are constructed to be able to withstand the energy release and limit the effects to the space inside the casing or containment. Sufficient attention must be given to redirecting the blast energy to a safe location.
- Current limiting fuses: the current limiting characteristic of the fuse significantly reduces the maximum fault value. However, detecting the minimum fault value can prove very challenging.
- Arc flash detection and high-speed switching: the occurrence of an arc flash is detected, either by specifically configured relays recognizing an arc fault current profile, by optical (UV) sensors, or by a combination of both. Upon detection, an upstream (high-speed) breaker is tripped. The incident energy is limited through limitation of the arc flash duration.
- Arc flash quenching: a (power electronic) device is tripped upon detection of an arc flash that creates a controlled short circuit of the busbar. This effectively deflects the energy from the arc and gives rise

to a normal short circuit capable of tripping the classic overcurrent protective devices. The use of a quenching device combined with current limiting fuses often provides interesting options.

- Remote operation: remotely operating switches (and even remote racking in LV motor control centers) moves persons away from the danger zone
- Strict application of safe work procedures: limiting live work to the absolute minimum clearly reduces exposure of persons to the potential hazards.
- Personal protective equipment is self-evident for those situations where exposure of persons cannot be avoided, including the use of arc flash protective clothing, face shield, gloves, et cetera.
- Labeling and marking: clear indications of possible arc flash risks, in particular for scenarios involving maintenance of electrical cabinets and switch gear while the doors are open.

None of these techniques will succeed in making an installation arc flash safe by themselves. Containment of enclosed switch gear will provide sufficient safety in normal operation with closed covers, but what will happen with an open door during maintenance or inspection?

Only careful and prudent developed strategy implementing a well-engineered combination of techniques can create a sufficiently safe situation with respect to arc flash hazards.

Electric shock and electrocution protection

Among the various engineering solutions available for electric shock and electrocution protection, this guide discusses:

- Extra-low voltage systems
- Automatic disconnection of supply
- Insulation, reinforced insulation, and double insulation

Extra-low voltage systems: SELV, PELV, FELV), there is no real danger for persons touching the device’s housing during an earth fault. From the point of view of human protection, such a situation can be tolerated for an indefinite period of time.

If the calculated contact voltage is above the ELV limits, there is a genuine hazard for persons touching the device. The risk must therefore be reduced to an acceptable level. This is achieved by switching the faulty circuit off sufficiently rapidly. A potentially dangerous situation existing for a very short time results in only a slight probability of an incident actually happening. Limited exposure time to a significant hazard can be considered a limited residual risk.

From scientific research and historical accident analysis, it is known that voltage exceeding the ELV limits for very short periods can be survived without serious consequences. As the voltage rises, the time a person can be exposed without serious consequences decreases. This knowledge forms the basis of the definition of conventional relative touch voltage limit curves as a function of time, as shown in Figure 4. It must be noted that national electrical safety regulations use these curves differently in their respective implementations.

If it can be shown—from the cable design calculation and the technical characteristics of the short circuit protection—that the circuit will be disconnected from the mains in a time shorter than the highest operating time allowed for the calculated touch voltage, then the risk is assumed to be sufficiently reduced.

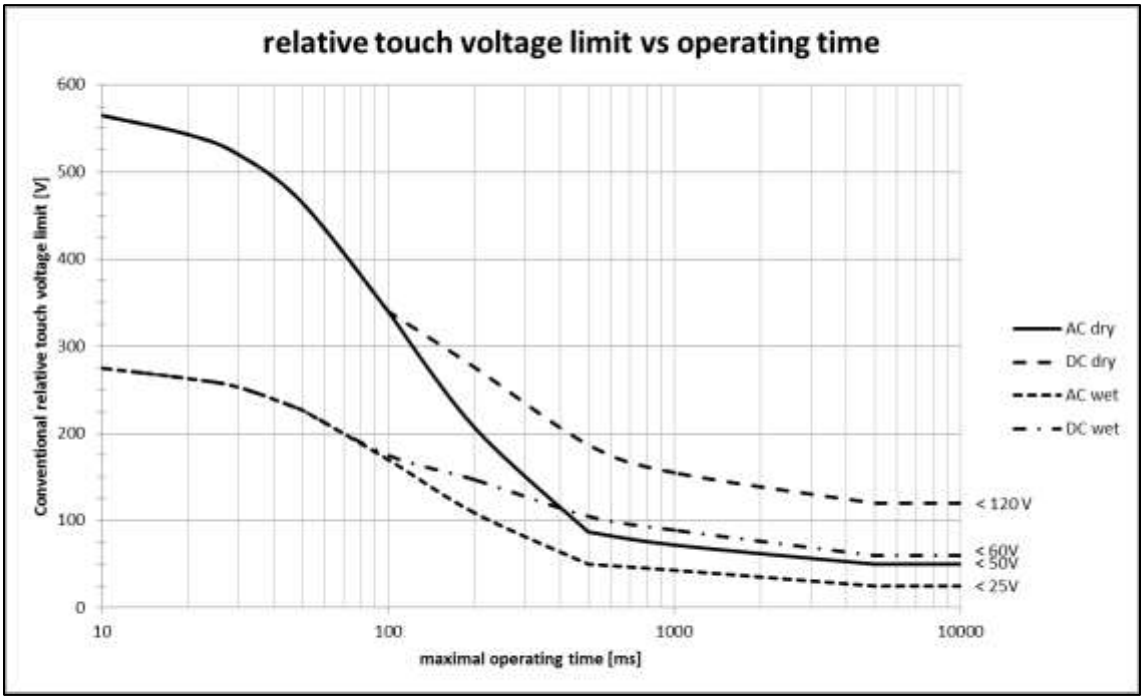

Figure 4 – Relative touch voltage limit as a function of protective system operating time

The following example illustrates the above Figure:

For a given AC circuit, the calculated contact voltage is 100V at an earth fault current about 15 times the nominal circuit current. In an indoor situation with no special presence of water where a person's skin will be dry, the AC dry curve (continuous line in Figure 4) intersects the 100V mark at approximately 430ms. In this example, any short circuit device that will disconnect in less than 430ms will create a compliant and safe situation with respect to indirect touch electric shock. This disconnection device could, for example, be a C-curve miniature circuit breaker giving virtually instantaneous operation for fault currents over 10 times the nominal current.

In particular cases, for example extended cable runs, design calculations can indicate a diminished earth fault current, thus compromising the basis for safety. In this event, the design engineer has to provide a resolution using either modified cable sizing or introducing a residual current device.

Insulation, reinforced insulation, and double insulation

The primary function of electrical insulation is to separate current carrying conductive elements from other parts, components, and elements.

Since the insulation of current carrying elements prevents contact with the current carrying parts, it is immediately clear that insulation has an impact on safety. By convention, various levels of insulation are defined, as shown below.

Term	Definition
Insulation	All the materials and parts used to insulate conductive elements of a device
Functional insulation	Insulation between conductive parts, necessary for the proper functioning of the equipment
Basic insulation	Insulation of hazardous live-parts which provides basic protection (this concept does not apply to insulation used exclusively for functional purposes)

Supplementary insulation	Independent insulation applied in addition to basic insulation, for fault protection
Double insulation	Insulation comprising both basic insulation and supplementary insulation
Reinforced insulation	Insulation of hazardous live-parts which provides a degree of protection against electric shock equivalent to double insulation (reinforced insulation may comprise several layers which cannot be tested singly as basic insulation or supplementary insulation)

Table 3 – Terms and definitions relative to electric insulation

Whether or not any of the various types of insulation (as defined in the electro-technical standards in *Table 3*) can be considered for safety purposes depends upon circumstances and environment.

Functional insulation must not be considered a safety feature.

Basic insulation can be adequate in situations where contact (either direct or indirect) is not expected, or where it can be shown that the effects of contact with current carrying parts do not present a hazard (e.g. PELV/SELV systems).

In situations where failure of the basic insulation results in an immediate hazardous situation, basic insulation alone definitely does not bring about adequate risk reduction. In such cases, double or reinforced insulation can be an adequate solution. Typical examples are handheld devices and tools, where insulation breakdown would immediately expose the operator of the tool to the mains voltage.

OVERVOLTAGE PROTECTION

Overvoltages can originate from various sources and scenarios. The appearance and effects of overvoltages can be equally diverse. A few typical examples are:

- Malfunctioning of generating equipment (limited amplitude, possible prolonged presence)
- Overvoltages induced by switching actions (significant amplitudes, relatively short durations)
- High voltage ground faults
- Atmospheric overvoltages (significant to extreme amplitudes, very short durations, indirect and direct lightning strikes)

In case of overvoltage from atmospheric origin or due to switching, IEC 60364-4-44 requires the use of surge protective device (SPD), according to IEC 61643-11 for AC circuits and according to IEC 61643-31 for PV applications.

In general, most overvoltage scenarios do not present a direct safety hazard, but rather pose a threat to equipment integrity. Equipment compromised by overvoltage will often result in significant consequential hazards, such as: increased indirect touch hazard through unintentional electric shock of objects, mechanical hazards due to unexpected behavior of faulty equipment and machinery, other non-electrical hazards through failure of critical systems.

A few noteworthy exceptions to this general statement are:

- Overvoltage in SELV or PELV systems can be a direct hazard for persons working with the system
- The effects of a direct lightning strike are of such an extreme nature that the consequence are likely to pose a direct hazard in itself
- Voltage gradients due to dispersion surrounding earth connection systems during high voltage ground faults or lightning deflection can pose direct hazard known as step voltage and touch voltage

The design of overvoltage protective systems is based on both the coordination of the maximal voltage surge that equipment can withstand, and methods to limit the voltage surges passed on to the equipment. This concept is known as Insulation Coordination.

The maximum allowable voltage surge is a function of the insulation levels of active components and the construction of the electrical equipment. Various types of equipment can have very different characteristics, e.g. electronics and power electronics are generally quite vulnerable with regard to overvoltage. The design of active parts and insulation determines the capability of the equipment to withstand overvoltage.

Limiting the voltage surges passed on to equipment can be achieved through a number of strategies. Some only apply in specific conditions, while others apply generally. The essential strategies are:

- Preventing atmospheric overvoltages from entering the electrical system. The use of lightning protective systems (LPS) to deflect a lightning strike via the air terminal of the LPS to the ground terminal of the LPS is the most representative example.
- Prevention of overvoltage originating from switching actions through the implementation of power electronic soft switching strategies (e.g. zero-crossing switching).
- Automatic supply disconnection can be an effective strategy to protect against moderate over-voltages of relatively long duration, typically originating from power supply malfunctioning. Obviously, this is not an option in critical installations where power supply needs to be maintained.
- Surge suppression, or the deflection of the excess energy associated with the surge by temporary shorting to earth. Typical components are arcing horns, spark gaps, voltage dependent resistors, and metal oxide varistors. They create a short-term low impedance connection from the protected lines to ground.

Engineering and construction of lightning protective systems is often considered an engineering domain in its own right.

The complexity of overvoltage protection can be equal to the complexity of the electrical network it aims to protect. Considering the public electricity transport and distribution grid, it is immediately clear that all involved parties need to contribute to insulation coordination. This includes generator facilities, step up and step down transformation stations, the high voltage transmission network, and the low and medium voltage distribution network.

Static Electricity

Countermeasures are required in applications where static electricity can introduce a hazard. The most common control measures are those that prevent generation of electrostatic charges by avoiding large non-conductive surfaces and allow electrostatic charges to dissipate by effective equipotential bonding and grounding of all conductive and dissipative (semi-conductive) objects.

A conductive path is created to allow electrostatically generated charges to flow to earth. Note that in most applications, even relatively high impedance earth connections (magnitude 0.5 to 2 GOhm) will provide sufficient charge relaxation to prevent dangerous charge accumulation leading to spark discharge. This is in sharp contrast to the range of a few (to tens of) Ohms required for protection from indirect contact, as indicated above.

Some special applications do not allow effective equipotential bonding or elimination of large non-conductive surfaces. One of the most illustrative examples is unwinding of plastic foils. Especially in industrial size handling of plastic foil materials, extremely high charge generation is to be expected, since most plastic foils have extremely high surface resistances. Since the highly insulating, fast moving foil cannot be connected to ground. In these applications, special countermeasures such as ionized air blow off guns and air ionization bars are employed. These devices bring ionized air in contact with the charged surface, and allow the surface charges to dissipate into the ionized air layer.

POWER OUTAGE, UNDER VOLTAGE, EMI, AND VARIOUS POWER QUALITY ISSUES AND DISTURBANCES

At first sight, these phenomena are not generally associated with specific hazards or safety issues. On the contrary, the absence of electrical energy during a power outage might even be considered a safe situation. However, when considered in a broader perspective, the possible hazards become clear. All deviations from normal operation can cause critical services to fail or trigger malfunctions and unexpected erroneous behavior of systems and machinery.

Power outage scenarios present a significant and pertinent risk, which is nevertheless often overlooked. When the power is restored, all the connected systems, equipment, and machinery might suddenly restart, resulting in severe hazards.

The design for such systems and machinery should incorporate proper provisions for the detection of a deviant situation and elimination of the associated risk that could give rise to these types of hazards. Well-known examples are automatic restart prevention for machinery and line RFI filtering for sensitive electronic equipment.

CONCLUSION

Electricity is a form of energy of major importance in modern society.

As with any form of energy, specific hazards are associated to the use of electricity. Compared to certain other forms of energy, electricity has the benefit that the occurrence of hazardous events is influenced relatively easily by proper design of the electrical systems and devices. This effectively reduces the risk to an acceptable level.

Various design and engineering solutions to improve the safety of electrical systems have been developed over time. These solutions have been captured in technical legislation, national and international standards, and sound engineering practices. These are in fact a materialization of acquired knowledge and engineering expertise gathered since the initial discovery of electricity. Appropriate application of this expertise enables engineers to create safe electrical applications, without going through the hazards of trial and error.

The complexity of the electrical design and engineering domain has significantly increased due to the vast amount of documented knowledge accumulated. This enables electrical (power system) engineers to achieve profound insight into the scientific properties of electrical energy and to master the vital level of competence embedded in the present state of the art. It also brings the tremendous advantage of virtually eliminating the need for trial and error experimentation for every single design, thus dramatically reducing the exposure of all involved persons to risk.

The examples covered in this Application Note clearly illustrate how electrical design requires continuous attention. This holds true not only for functional aspects such as delivering the right amount of power in a reliable way, but also in ensuring all of the related safety aspects.