Protecting Electrical Workers in Conducting Locations with Restricted Movements

Massimo Mitolo

Irvine Valley College, Irvine, CA, USA
E-mail: mitolo@ieee.org

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Abstract

Conducting Locations with Restricted Movements (CLRs) pose unique electrical hazards due to the extensive presence of grounded conductive materials with which a person is likely to come into contact and the restricted freedom of movement of workers within these spaces. Extended physical contact is not solely a result of spatial constraints. It could also be associated with the specific tasks that workers need to execute. An example of this is work conducted on a transmission tower.

This paper investigates the electrical safety measures necessary to protect operators in such environments. By examining the role of body resistance and the impact of different current pathways, this author highlights the inadequacy of the conventional disconnection of supply fault protection measure in CLRs. The paper discusses protective strategies, including supplementary equipotential bonding, use of double or reinforced insulation, electrical separation, and extra-low voltage systems. These measures are critical in mitigating the risk of electric shock and ensuring safety of workers in CLRs.

Keywords: Automatic disconnection, body resistance, conductive locations, electrical safety, equipotential bonding, fault protection, hand-held equipment, low voltage systems, restricted movements, supplementary bonding.

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1 Introduction

Conducting locations with restricted movements (CLRs), as defined in [1], are specific areas predominantly enclosed by extraneous-conductive-parts (EXCPs). The EXCPs are conductive parts that are not part of the electrical installation but are likely to introduce the electric potential of a local ground into the premises. In these areas, it is probable that a person may come into contact with these EXCPs at one or more points on their body. Furthermore, these are locations where the potential to disrupt such contact is minimal. Common examples of CLR include environments with a significant presence of metallic or conductive materials that are well-grounded. These can be transmission towers, metal tanks, damp tunnels, and similar settings in good contact with the earth. Reference [2] provides a similar definition, characterizing a CLR as a location composed mainly of metallic or conductive surrounding parts, within which a worker is likely to come into contact through a substantial portion of their body, and where preventing such contact may not be entirely possible.

The extended bodily contact in CLRs can arise not only from the reduced dimensions of the location restricting freedom of movement, but also potentially due to the nature of the task workers must perform. For instance, a transmission tower qualifies as a CLR. This is because linepersons, during their ascent, descent, and maintenance work, maintain substantial contact with the grounded structure. This contact is not just incidental, but an unavoidable aspect of their work.

A significant hazard within the CRL is the presence of electrical equipment, either fixed or hand-held, that may experience electrical breakdowns or faults. In CLR, the body's resistance to ground can be significantly reduced due to extensive contact with large, grounded conductive surfaces. This situation can lower the threshold for dangerous heart conditions like ventricular fibrillation, which is a life-threatening heart rhythm that results in a rapid, inadequate heartbeat. Furthermore, in CLRs, the current pathway from hands-to-feet, which is typical in ordinary locations, may not be the only possible path. A more dangerous path, such as hands-to-chest, can be established.

In this paper, the author analyzes the unique hazards present in these environments and discusses the proper electrical safety measures to be implemented in CRLs to safeguard the worker's well-being and prevent potentially fatal electrical incidents.

2 Automatic Disconnection of Supply in Case of a Fault

The automatic disconnection of supply requires that in the event of a fault between the line conductor and an exposed-conductive-part of equipment, due to the failure of the basic insulation, a protective device automatically cut off the power supply. The disconnection should happen within a maximum timeframe as outlined in [3]. The disconnection time depends on the type of system (i.e., TT, TN) [4] and the nominal a.c. or d.c. line-to-ground voltage U_0 (Table 1).

According to [3], the maximum disconnection times provided of Table I are deemed safe only if two resistances are present to limit the body current: the resistance of the person's body R_B and the resistance R_{BG} between the person's body and the ground, as discussed in the following sections.

2.1 Person's Body Resistance

The human body is modeled as a four-terminal network, with the terminals representing the upper and lower extremities. In calculations, the body's trunk resistance is typically ignored because of its larger cross-sectional area and the presence of conductive fluids. Consequently, the resistances R_l of the limbs are the primary factors to determine the total body resistance R_B. In common settings such as homes, the body resistance correlates with the current pathway that extends from both hands to both feet. In this configuration the arms (in parallel) are in series with the legs (also in parallel). This model aligns with a scenario where an individual is standing and comes into contact with an electrified object. Calculations of body resistance can be performed by using the body resistance values that do not exceed the 50th percentile of the population at 200 V, found in [5]. The 50th percentile is considered the most statistically significant. In ordinary locations, the resistance of the limbs can be calculated considering a person in dry conditions, with medium contact surface areas for the hands (i.e., 10 cm^2), and large contact surface areas for the feet (i.e., 100 cm^2). Under these conditions, $R_B = R_l$ and the body resistance is determined to be 741 Ω [6].

Table 1 Maximum Disconnection Times (adapted from [3])

System	120 V $< U_0 \leq$ 230 V
TN	0.4 s
TT	0.2 s

2.2 Person's Body Resistance-to-ground

The safe disconnection times of Table I also call for the additional series resistance R_{BG} of the person's body resistance-to-ground, which is determined by the floor covering. For ordinary locations R_{BG} can be typically quantified as 1 kΩ [6]. This estimation arises from the fact that even in the absence of a floor covering, the resistance-to-ground of the feet (considered as parallel ground-electrodes) remains present. The resistance of footwear is not considered in ordinary locations, and it is conservatively assumed that the person is shoeless.

As anticipated, in CLRs the above conditions are likely not met since both the body resistance and the body resistance-to-ground may have lower values. Consequently, shorter disconnection times may be necessary for the fault protection disconnection of supply to be safe.

3 Conducting Locations

As per [3], a floor is classified as *non-conducting* if its measured resistance-to-ground is at least 50 kΩ for systems operating at voltages up to 500 V. For systems operating at voltages above 500 V, the resistance-to-ground must be at least 100 kΩ. The methods to measure this resistance are detailed in [7]. These involve the application of a test current and the subsequent measurement of the voltage that arises between an electrode (which is applied to the floor with a force of 750 N) and the main ground terminal (i.e., point at zero potential). A non-conducting location limits the body current to levels considered safe, eliminating the need for any fault protection.

If the measured resistance-to-ground of a floor in a location falls below the specified thresholds, it necessitates the implementation of fault protection to protect persons against the risk of electric shock. The location can be classified as *ordinary* and be safeguarded against indirect contact by automatic disconnection of power supply.

However, if the measured resistance-to-ground of the floor is less than 1 kΩ, the location is classified as *conducting*. In this context, the type of conductive material present at the location is irrelevant; the only factor that matters in terms of electric shock hazard is its low resistance-to-ground.

4 Locations with Restricted Movements

A person's movements become constrained within a space when the dimensions of that space are comparable to the person's body size. In this situation,

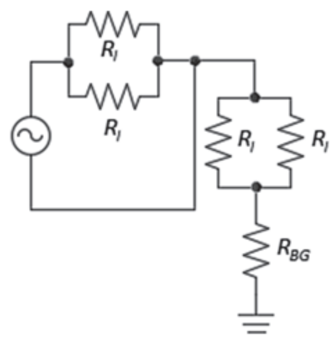

Figure 1 Current pathway from hands to chest.

the current pathway from hands to chest is very likely, as exemplified in the circuit of Figure 1.

In these conditions, the total body resistance R_B is half the limb's resistance R_l. It is important to note that in restrictive locations, the areas of the body that come into contact with conductive materials are larger compared to those in ordinary locations. Furthermore, these locations may also be in environments that are wet due to water, which can significantly affect the body resistance values. These factors can lead to a reduction in the resistance of the limbs, and therefore to a hazardous increase of the body current, for a given touch voltage.

The probability of ventricular fibrillation, a life-threatening heart rhythm disturbance, is influenced by the amount of current passing through the heart, which varies based on the path the current takes. The heart-current factor (F) has been introduced by [5] to quantify this probability based on statistical investigations of electrical injuries and from experiments on animals. The heart-current factor provides a rough estimate of the relative risk associated with different current paths in terms of inducing ventricular fibrillation. A higher F value indicates a more hazardous current pathway. It has been found that the hands-to-chest pathway, for which $F = 1.5$, is more hazardous than the both-hands-to-both-feet pathway, for which F = 1. For instance, a 66.7 mA hands-to-chest current poses the same ventricular fibrillation risk as a 100-mA left-hand-to-both-feet body current. According to simulations presented in [6, 8], it would take just a 17.5 mA current through the chest to cause a ventricular fibrillation with the same probability as a 100-mA body current for the both-hands-to-both-feet path. In addition, the hands-to-chest pathway does not include the person's body resistance-to-ground R_{BG}, and this further increases the body current, for a given touch voltage.

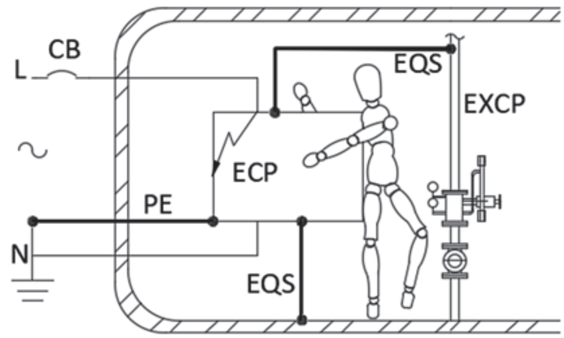

Figure 2 Automatic disconnection of supply in conjunction with supplementary protective equipotential bonding (EQS) and protective device (CB).

5 Fixed Electric Equipment

According to [9], Class I equipment is characterized by having at least one provision for basic protection (i.e., basic insulation), along with the protective-equipotential-bonding connection, which safeguards against faults in partnership with a protective device. Fixed electric equipment, as defined by [10], refers to equipment that is securely fastened in a specific location.

5.1 Automatic Disconnection of Supply

Class I fixed equipment can be installed in CLRs and the protection measure of automatically disconnecting the power supply, earlier discussed, can still be implemented, provided that a supplementary protective equipotential bonding (EQS) is in place. The supplementary bonding must establish a connection between the exposed-conductive-parts (ECPs) of the fixed equipment and the extraneous-conductive-parts (EXCPs) (e.g., metalwork of a boiler, vessel, duct, or similar structures which may be at zero potential) within the CLR. If the floor is conductive, it must also be incorporated in the equipotential system (Figure 2).

The supplementary equipotential bonding plays a pivotal role in reducing the potential difference between a faulty piece of equipment and all the extraneous-conductive-parts present within the conducting location.

5.2 Double or Reinforced Insulation

Reference [1] allows the use of electrical equipment with double or reinforced insulation [3] (also referred to as Class II equipment) in RLCs. This protective measure is designed to prevent the emergence of hazardous voltage on accessible parts of equipment, due to failure of the basic insulation, thanks to an additional insulating layer. In RLCs, this measure is contingent upon the additional protection carried out by Residual Current Devices (RCDs) (referred to as GFCI in the U.S.) of the circuits that power those locations. The RCDs should have a rated residual current that does not exceed 30 mA.

5.3 Electrical Separation

Electrical separation, in line with [3], can also serve as a protective measure in CLRs, also for hand-held and mobile electrical equipment. The system must be equipped with an isolating transformer with double (or reinforced) insulation between primary and secondary sides, as per [11]. These types of transformers, characterized by identical primary and secondary voltages (e.g., 120 V/120 V), galvanically separate the equipment in the CLR from the power source and prevent the flow of currents in the event of ground-faults. The grounding of circuits and ECPs is, therefore, not allowed in the CLR. Under this measure, only one piece of equipment can be connected to the isolating transformer's secondary winding. Should multiple devices be powered by a single transformer, a hazardous situation can occur if a double ground-fault happens, involving both secondary poles of the transformer (Figure 3).

In such a scenario, workers can be exposed to a hazardous potential difference if they come into contact at the same time with two faulty ECPs. The two ground-faults could indefinitely persist, creating great hazard for the workers.

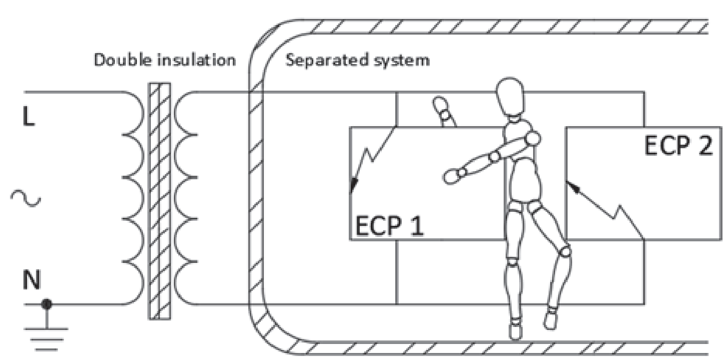

Figure 3 Double ground-fault when a single isolating transformer supplies two pieces of equipment.

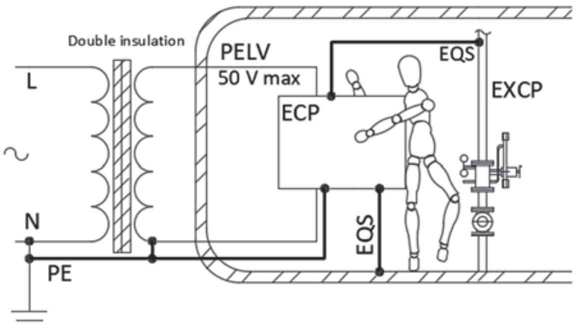

Figure 4 PELV system with equipotential bonding.

5.4 Safety Extra-Low Voltage (SELV) and Protective Extra-Low Voltage (PELV)

Another protection strategy consists of the Safety Extra-Low Voltage (SELV) systems, where the supply voltage, provided with safety isolating transformers, is not allowed to exceed the extra-low voltage limit. This means it is restricted to a maximum of 50 V for alternating current and 120 V for direct current, measured both between line and ground and between lines, under normal and single fault conditions. Additionally, within the CLR the connection to the ground of circuits and/or ECPs of equipment is not permitted. SELV may also be used for hand-held and mobile electrical equipment.

The Protective Extra-Low Voltage (PELV) may also be used, provided that equipotential bonding is in place. This bonding connects all ECPs and EXCPs of the location, along with the grounding terminal of the PELV supply (Figure 4). PELV system, other than being grounded, meets all the criteria set for SELV systems.

Sources for SELV and PELV may be situated inside the CLR as long as they are part of the fixed installation.

6 Hand-held Equipment

According to [1], hand-held tools used in CLRs should be powered either by electrical separation or by a SELV supply. In both scenarios, the isolating transformer must be located outside the CLR to avoid hazards associated with the primary voltage.

For handlamps, the only permitted safety measure is the use of SELV. This is to prevent the risk of direct contact when replacing the lamp without first

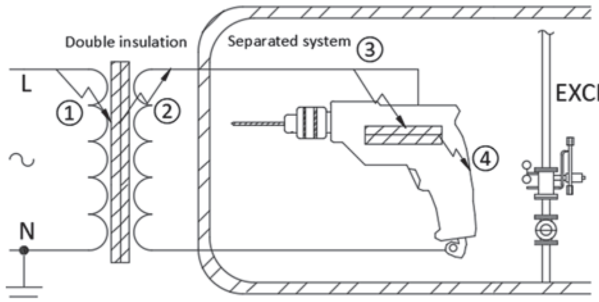

Figure 5 Separated system and Class II hand-held equipment.

disconnecting the supply. The SELV supply can also power a fluorescent light fixture that does not operate at extra-low voltage. In fact, this fixture includes an integrated step-up transformer with electrically separated windings.

While it is not a requirement according to [1], it is always recommended to use Class II hand-held equipment in CLRs. As shown in Figure 5, Class II hand-held equipment that is powered via an isolating transformer (e.g., 230 V/230 V) provides the same safety level as equipment powered by SELV circuits.

There is a potential risk of electric shock if the double insulations of both the transformer and the equipment fail. This scenario would entail a total of four faults occurring. Under these circumstances, the supply source to the CLR would effectively be grounded. If a worker were to come into contact with the faulty handheld device under these conditions, an electric shock could occur. However, it is important to note that the probability of this happening is considered to be extremely low. This holds true even if the faults do not occur simultaneously.

With SELV supply, even if the double insulations fail, there is no risk of electric shock. This is because the voltage does not exceed 50 V.

7 Conclusion

Conducting locations with restricted movements (CLRs) present unique electrical hazards due to the extensive bodily contact with grounded conductive surfaces and the potential for more hazardous current pathways like hands-to-chest. The automatic disconnection of supply, although effective in ordinary locations, requires shorter disconnection times in CLRs due to the lower body resistance values. Thus, supplementary equipotential bonding becomes essential, connecting all exposed-conductive-parts and extraneous-conductive-parts to minimize potential differences during faults. However, alternative protective measures are available for this special location.

The use of Class II equipment, which features double or reinforced insulation combined with Residual Current Devices (RCDs), enhances protection by preventing hazardous voltages on accessible parts. Electrical separation, achieved through isolating transformers with double insulation, can effectively separate CLR equipment from the power source, preventing current flow in the event of a ground-fault.

Safety Extra-Low Voltage (SELV) and Protective Extra-Low Voltage (PELV) systems provide safe power supplies, significantly reducing the risk of electric shock by maintaining voltages below hazardous levels. For hand-held equipment, SELV or electrical separation with the transformer located outside the CLR reduces the risk associated with primary voltage exposure.

The proper implementation of these protective measures tailored to the unique risks in CLRs is crucial to mitigate electrical hazards, prevent ventricular fibrillation and electric shock incidents, and safeguard worker well-being in these high-risk environments with restricted movement and conductive surroundings.

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Biography

Massimo Mitolo, a distinguished scholar and scientist, has been bestowed the Knighthood in the *Order of Merit of the Italian Republic* in acknowledgment of his exceptional contributions to scientific endeavors that have brought great honor to the nation. He is renowned for his remarkable achievements in the field of electrical engineering.

Sir Massimo earned his Ph.D. in Electrical Engineering from the University of Napoli "Federico II" in Italy. His unwavering dedication and significant impact on the field have led to his recognition as a Fellow of IEEE "*for contributions to the electrical safety of low-voltage systems*". Furthermore, he holds the distinguished title of Fellow from the Institution of Engineering and Technology (IET) in London, United Kingdom, and is a member of the *IEEE-HKN* Honor Society. Additionally, he is a registered Professional Engineer in both the state of California and Italy.

Presently, Dr. Mitolo serves as a Full Professor of Electrical Engineering at Irvine Valley College in California. In addition to his academic responsibilities, he is a senior consultant specializing in the domains of failure analysis and electrical safety. His extensive research and industrial experience revolve around the comprehensive analysis and grounding of power systems, as well as electrical safety engineering.

Dr. Mitolo's expertise is reflected in his publication record, encompassing more than 180 journal papers, as well as the authorship of several influential books. Noteworthy titles authored by him include "*Electrical Safety of Low-Voltage Systems*" (McGraw-Hill, 2009), "*Laboratory Manual for Introduction to Electronics: A Basic Approach*" (Pearson, 2013), "*Analysis of Grounding and Bonding Systems*" (CRC Press, 2020), "*Electrical Safety Engineering of Renewable Energy Systems*" (IEEE Wiley, 2021), "*Smart and Power Grid Systems: Design Challenges and Paradigms*" (River Publishers 2022), and "*Simulation-based Labs for Circuit analysis*." (River Publishers, 2024).

His scholarly endeavors have garnered significant recognition, culminating in his inclusion in the 2020, 2021 and 2022 *World's Top 2% Most-cited Scientists List*, as compiled by Stanford University.

Within the Industrial and Commercial Power Systems Department of the IEEE Industry Applications Society (IAS), Dr. Mitolo actively engages in various committees and working groups, demonstrating his commitment to advancing the field and fostering collaborative efforts.

Acknowledging his achievements, Dr. Mitolo has been the recipient of numerous prestigious accolades throughout his career. Notably, he has been honored with the IEEE Region 6 *Outstanding Engineer Award* and has garnered nine *Best Paper Awards* for his exceptional scholarly contributions. Furthermore, he has received recognitions such as the *IEEE Ralph H. Lee I&CPS Department Prize Award*, the *IEEE I&CPS Department Achievement Award*, and the *James E. Ballinger Engineer of the Year Award* from the Orange County Engineering Council in California.