CHAPTER 2

Fundamentals of Electrical Safety

Mysterious affair, electricity.

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2.1 Introduction

Electrical safety is not exclusively defined by the prudent conduct of individuals in the presence of energized objects. A sensible attitude toward electrical equipment may only prevent direct contact, that is, an accidental contact with parts normally live (e.g., energized conductors, terminals, bus bars inside of equipment, etc.).

Persons are also exposed to the risk of indirect contact, that is, contact with faulty *exposed-conductive-parts* (ECPs). ECPs are items supplied by the electrical systems that are not normally live, but that are accidentally energized due to failure of the basic insulation (Fig. 2.1).

Indirect contact is more insidious than direct contact, as it may occur even during the reasonable use of electrical equipment. Safety is carried out by systematically applying measures of protection against both types of contacts, which might occur during the common interaction between a person and an electrical equipment. Protection against direct contact, also referred to as *basic protection*, is achieved with effective separation of persons from live parts, whereas protection against indirect contact, also referred to as *fault protection*, is accomplished by automatically disconnecting the supply. In some specific situations, discussed later in this chapter, fault protection can also be carried out without disconnection of supply.[1]

It is important to note that all electrical systems must be properly maintained, so as to reasonably prevent danger of electric contacts.

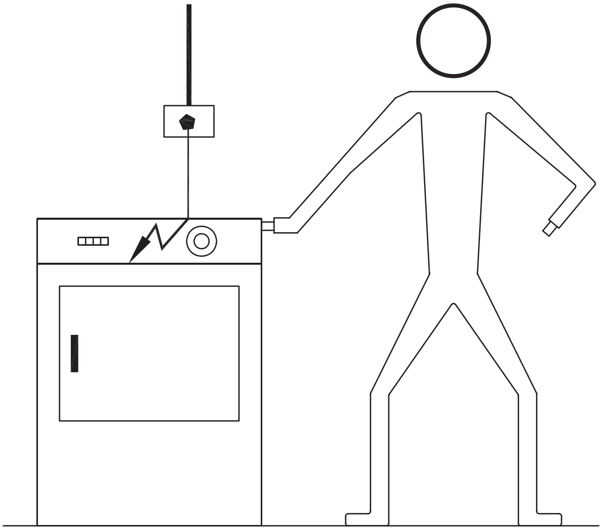


Figure 2.1 Indirect contact.

2.2 Protection Against Direct Contact

It is understood that all electrical equipment must have provisions to guarantee protection against direct contact. In the following sections, the fundamental strategies of basic protection are examined.

2.2.1 Insulation of Live Parts

In order to operate, electric equipment contains parts at different potentials, which must be properly insulated from each other and from their enclosure through the functional insulation.

The basic insulation prevents persons from coming in contact with live parts and is the fundamental protection against direct contact. To be effective as a protection, the insulation material must completely cover the live parts and should be removable only by destruction (Fig. 2.2).

The basic insulation must be capable of withstanding the possible stresses during the functioning of the equipment without losing its integrity. Electric fields, mechanical collisions, high temperatures, and the aging of the insulating material are the possible causes of failure of the basic insulation. It is essential, then, that the basic insulation has sufficient mechanical strength to withstand the stress caused by the normal operation of equipment. As a consequence, insulating paints, and similar products, cannot be considered suitable for the basic insulation; however, they can be used as the functional insulation (e.g., insulation between windings of transformers or motors).

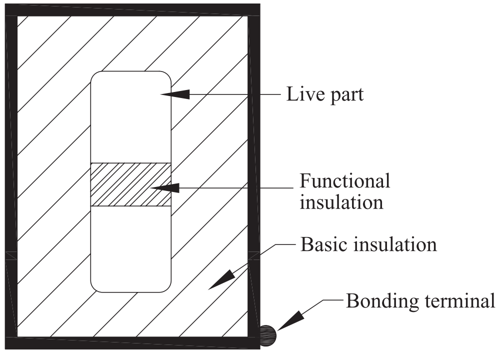


Figure 2.2 Diagrammatic representation of functional and basic insulations in Class I equipment.

Figure 2.2 shows a piece of Class I equipment, that is, an ECP outfitted with a bonding terminal to allow the grounding of the enclosure.

2.2.2 Enclosures and Barriers

Both enclosures and barriers are constructions, firmly held in their positions, intended to prevent persons from intentionally, or accidentally, touching live parts without the aid of tools.

As the term suggests, enclosures provide protection in any approaching direction to the equipment by "enclosing" it. Live parts are inside the protective construction. Barriers, instead, may offer the same defined degree of protection against direct contact, but only in a limited number of approaching "routes" to the equipment. Safety is equally achieved if live parts are kept "behind" barriers, instead of inside of an enclosure.

For instance, barriers may be used around an open-type piece of equipment when, due to its height, the access from above is naturally precluded to persons. The "top" is, therefore, deemed unnecessary for safety and the enclosure is not strictly required.

Removal of barriers, or opening of enclosures, must be possible only by using keys or tools so as to prevent the accidental elimination of the fundamental protection against direct contact. The necessity of keys or tools as a "rule of engagement" to the equipment can be waived if removal/opening of protection can occur only after the supply is disconnected.

The minimum insulation requirement for enclosures and barriers is that live parts be inaccessible to a person's finger. This requirement limits the size of openings in equipment, for example, vents.

The IEC *International Protection Code*[2] has standardized designations composed of the letters IP followed by two characteristic numerals, which describe the degree of protection offered by different types of enclosures and barriers. The first characteristic numeral (0 to

6) indicates the degree of protection against access of person's finger/back of hand to hazardous parts as well as against ingress of solid foreign objects. The second numeral (0 to 8) designates the degree of protection against ingress of water through enclosures and barriers. An optional letter (A to D) designates, just like the first numeral, the degree of protection against direct contact. A brief description of the characteristic numerals and optional letters can be found in Fig. 2.3.

1st Numeral	Protection of Equipment Against Solid Particles	Against Person's Access With
0	Nonprotected	Nonprotected
1	> 50 mm diam.	Back of hand
2	> 12.5 mm diam.	Finger
3	> 2.5 mm diam.	Tool
4	> 1 mm diam.	Wire
5	Dust	Wire
6	Dust proof	Wire

2nd Numeral	Protection of Equipment Against Ingress of Water
0	Nonprotected
1	Vertical dripping
2	Dripping (15° tilted)
3	Rain (spraying water at an angle up to 60° on either side of the vertical)
4	Splashes from any direction
5	Jets from any direction
6	Powerful jets from any direction (flow rate > 12.5 dm^3/min)
7	Temporary immersion
8	Continuous immersion

Optional Letter	Protection Against Person's Access With
A	Back of hand
B	Finger
C	Tool
D	Wire

FIGURE 2.3 Brief description of the IP designations.

Each numeral requires different tests be applied to equipment to obtain the IP rating. The jointed test finger, the rigid sphere, and the test wire are the standard rating tools.

To guarantee safety, enclosures and barriers are required by international standards to have at least a degree of protection of IPXXB, which does not allow access to a person's finger. The symbol X means there are no requirements for that specific characteristic numeral. The IP2X degree of insulation is not equivalent to IPXXB, but better. An IP2X enclosure, or barrier, in fact, must pass the following two tests:

1. The standard jointed finger (length 80 mm and diameter 12 mm), applied with a test force[3] of 10 N to all sides and openings of the enclosure, must not touch any live parts in every possible position of its two joints.
2. A 12.5-mm-diameter rigid sphere must not entirely pass through any opening (test force of 30 N).

An IPXXB enclosure, instead, must pass only the above first test to provide the same degree of safety against electrocution. However, IPXXB enclosures, although safe for persons, may allow the ingress of foreign objects of 12.5 mm diameter, or smaller, into the equipment, and, therefore, might not be suitable in certain locations.

Let us examine the case in Fig. 2.4. The enclosure is "permeable" to the test sphere, which can penetrate inside, and thus cannot be classified as IP2X; at the same time, though the enclosure does not allow contact with live parts, as the jointed finger cannot touch any live part, ergo its rating is IPXXB.

If enclosures or barriers have readily accessible horizontal top surfaces (e.g., height less than 2.5 m), a more stringent insulation is required. To prevent the additional risk of direct contact due to small

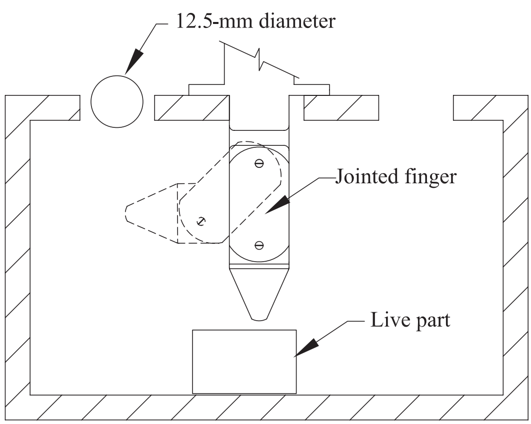


FIGURE 2.4 Enclosure IP1XB.

metal objects, which falling through openings may bridge the gap between persons and live parts, the degree of protection IPXXD or IP4X is necessary. These two designations maintain the same previously exemplified logic, with the only difference being the use of the test wire (length 100 mm and diameter 1 mm) instead of the jointed finger.

It must be clear that the judgment of the electrical engineer is necessary to establish the optimum degree of insulation of equipment, in light of both the actual environmental conditions of the location and its normal operations. It is also important to note that a too severe degree of insulation, if unnecessary, can damage the equipment by limiting its ventilation and, thereby, raising its internal temperature beyond safe limits.

2.2.2.1 Enclosures and Mechanical Impacts

A serious hazard for persons is the accidental rupture of enclosures due to external mechanical impacts, which can expose live parts and trigger explosive atmospheres. Enclosures, therefore, must have the capability to protect their own contents. Such ability is specified by the international IK code,[4] which indicates the degree of protection against harmful impacts. The IK code rates enclosures through the code letters IK followed by the characteristic group numeral (00 to 10), indicating an impact energy value in joules (see Table 2.1).

The IK code contemplates the maximum value of impact energy of 20 J; when higher impact energy is required, the IK code recommends a value of 50 J.

2.2.3 Protection by Obstacles

Obstacles are elements placed between exposed live parts and persons (e.g., fence, handrail, mesh, screen, etc.). They prevent direct contacts by increasing the distance from energized parts, which, otherwise, would be accessible. Safety is, therefore, assured by keeping exposed live parts out of reach. Unlike enclosures and barriers, obstacles could be intentionally circumvented, as, by definition, they may not be firmly held in their positions; therefore, obstacles offer only a limited degree of protection and that too only for accidental touch. This protective measure, consequently, should be exclusively adopted in areas accessible to skilled personnel in the field of electricity.

	IK01	IK02	IK03	IK04	IK05	IK06	IK07	IK08	IK09	IK10
Impact energy (J)	0.15	0.2	0.35	0.5	0.7	1	2	5	10	20

Table 2.1 Relation Between IK Code and Impact Energy

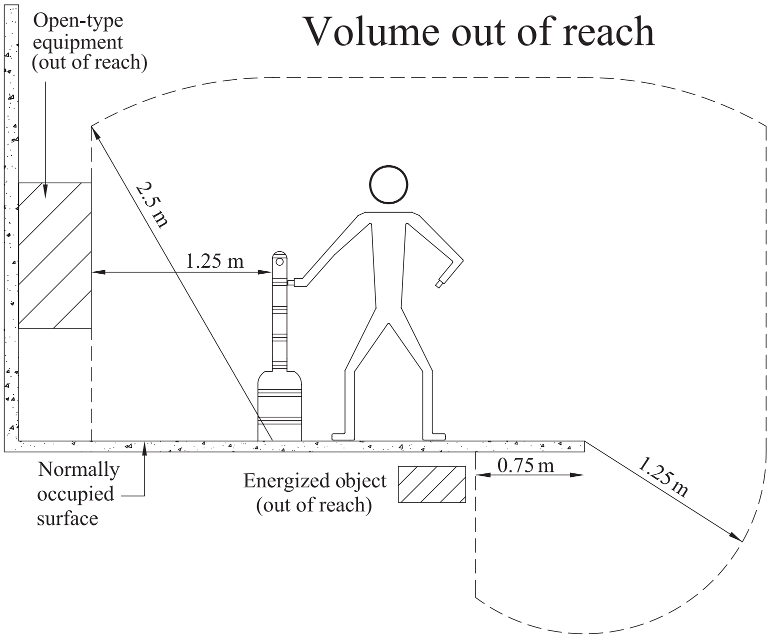


Figure 2.5 Volume out of reach.

We conventionally deem out-of-reach energized objects placed outside of the volume defined by the reach of the person's arm. The horizontal arm's extent is conventionally assumed to be 1.25 m, but as the contact can also occur in the overhead direction, the average height of persons must be included. Therefore, the conventional length of 2.5 m from the floor is also considered arm's reach. The extent of arm's reach is to be measured from the obstacle (Fig. 2.5).

Skilled persons are deemed safe as long as exposed energized parts are in the volume out of reach (i.e., outside of the dotted line).

If persons normally handle long conductive items (e.g., tools, ladders, etc.), larger clearance distances must be considered to take into account the additional risk due to their length so as to provide the same level of safety.

2.2.4 Additional Protection by Residual Current Devices

Residual current devices (RCDs) are also referred to as *residual current operated circuit-breakers* (RCCBs) or *ground-fault circuit interrupters* (GFCIs). RCDs with operating current I_{dn} not exceeding 30 mA are additional means of protection against direct contact. When they are used in households and similar environments, nontrained people should be able to easily operate them.

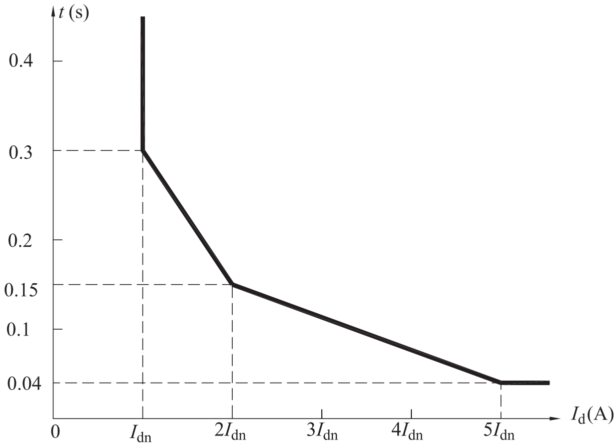


FIGURE 2.6 Permissible operating time as a function of the ground-fault current.

The term residual current[5] I_d indicates the vector sum of all alternating currents flowing through a circuit's wires, single-phase or three-phase,[6] including the neutral conductor, and is expressed in terms of the root mean square (r.m.s.) value. The RCD executes this sum, which is zero in normal conditions. Should a fault occur, I_d becomes greater than zero and is equal to the r.m.s. of the ground-fault current I_G. The RCD compares this nonzero value to its rated operating current I_{dn} and if $I_d > I_{dn}$ disconnects the supply to the faulty circuit. The clearing time will occur within a conventional safe time as established by applicable standards. RCDs, in fact, do not limit the magnitude of the ground-fault current, but only the time this current circulates to ground. Figure 2.6 shows the permissible operating times[7] not to be exceeded by general purpose RCDs as a function of the residual current I_d, usually expressed as a multiple of the rated operating current I_{dn}.

Besides the residual operating current, the RCD is characterized by another important parameter: the residual nonoperating current I_{dNO}, which represents the maximum r.m.s value of the residual current that does not cause its operation. Standard value for I_{dNO} is $0.5I_{dn}$ and therefore the RCD does not operate for $I_d < 0.5I_{dn}$; it might operate in the range $0.5I_{dn} < I_d \leq I_{dn}$ and must surely operate for $I_d < I_{dn}$.

For a better understanding of the functioning of the residual current devices, let us examine Fig. 2.7, which shows a single-phase RCD.

In the absence of ground faults, we have

$$\underline{I}_{Ph} = \underline{I}_N \Rightarrow \underline{I}_{Ph} - \underline{I}_N = 0 \tag{2.1}$$

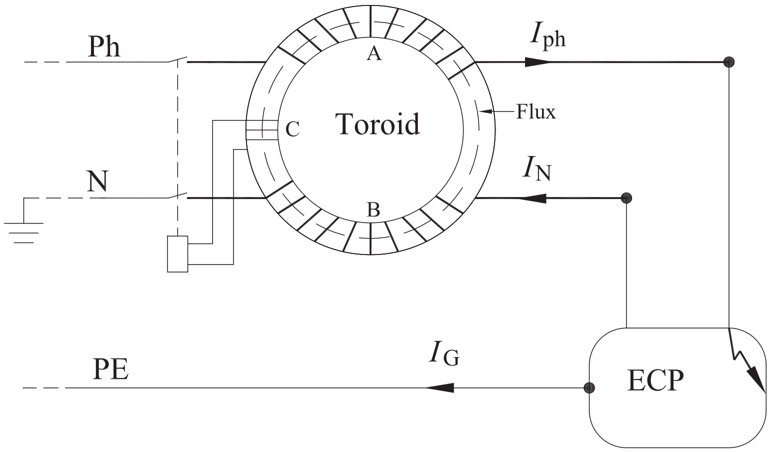


Figure 2.7 Single-phase RCD.

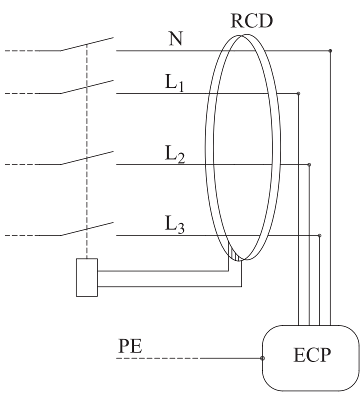
If a fault puts in contact the phase conductor with the enclosure, a current $\underline{I}_G$ will flow through the protective conductor,[8] causing phase and the neutral currents to differ. If we consider the point of contact with the enclosure as a "generalized" node, we can apply the first Kirchoff's principle:

$$\underline{I}_{Ph} = \underline{I}_N + \underline{I}_G \Rightarrow \underline{I}_{Ph} - \underline{I}_N = \underline{I}_G \neq 0 \quad (2.2)$$

As a consequence, the resulting magnetic flux $\underline{\Phi}$ along the RCD's toroid, which is proportional to the net current $\underline{I}_G$ flowing through the windings A and B, is no longer zero. Thus, an electromotive force is generated within the dedicated coil C, which will quickly activate the circuit breaker if $|\underline{I}_G| > I_{dn}$ and disconnect the supply.

The same protective residual logic can be applied to three-phase systems (Fig. 2.8).

Figure 2.8 A residual current device in a three-phase circuit.



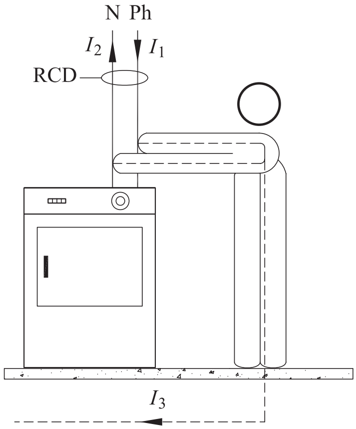


Figure 2.9 Direct contact phase-to-neutral.

The three-phase RCD is a transformer whose primary winding is constituted by the line conductors themselves. The vector sum of the line currents and the neutral current in healthy three-phase circuits is always zero, and therefore, in the secondary winding, which has the task of switching off the supply, no current will circulate. If a fault occurs, the vector sum becomes nonzero due to the current leaving the system through the PE not passing through the toroid. The RCD, then, activated by its secondary winding, will trip the circuit breaker.

RCDs must be considered as an additional means of protection and do not substitute for the other fundamental protective measures against direct contact previously examined. RCDs, in fact, can protect persons by disconnecting the supply only in the case of contact between energized objects and the ground. They can sense only fault currents not returning to the source through the legitimate path. Consequently, direct contact between the phase and the neutral conductors may not activate the RCD, as there may not be enough ground current circulation for it to sense (Fig. 2.9).

The RCD will only sense the component $\underline{I}_3$, while the larger current $\underline{I}_1$ will circulate through the person's body. $\underline{I}_3$ may not be large enough to exceed the RCD's operating threshold, which cannot disconnect the supply.

2.3 Protection Against Indirect Contact

The failure of the basic insulation may cause electrocution owing to the accidental presence of voltage-to-ground over metal parts not normally live (Fig. 2.1). This condition is particularly dangerous as it is not under a person's control despite any prudent conduct. Protective