Of International Terminology and Wiring Methods Used in the Matter of Bonding and Earthing of Low-Voltage Power Systems

Massimo Mitolo, Senior Member, IEEE, Michele Tartaglia, Senior Member, IEEE, and Sergio Panetta, Senior Member, IEEE

Abstract—The worldwide global market requires electrical engineers to have a deep understanding of the bonding and earthing practices adopted in different countries around the world. This knowledge is essential to obtain effective designs and high safety standards and can promote the elimination of technical obstacles that can still create market barriers. The full comprehension of the “grounding” theory requires the command of key technical concepts regarding the earthing methods, which may cause confusion when used in the North American technical realm rather than in the International Electrotechnical Commission (IEC) world. This issue is further worsened by the lack of literature in this matter, as well as of harmonization documents between national codes and international standards. This paper, by analyzing the protection against indirect contact in ac (50/60-Hz) low-voltage power systems by automatic disconnection of supply, seeks to clarify both the terminologies and each type of grounding system adopted in IEC standards, with the intent to create a common reference for practicing engineers in the matter of bonding and earthing of power systems. Major differences encountered between sizing procedures adopted in IEC standards and the North American National Electrical Code are also examined.

Index Terms—Direct contact, earth, exposed conductive part (ECP), extraneous conductive part (EXCP), ground, indirect contact, Isolation Terre (IT) systems, protective conductors (PEs), single-phase line-to-ground (SLG) fault, Terre–Neutral (TN) systems, Terre–Terre (TT) systems.

IEC NOMENCLATURE

ECP Exposed conductive part. Conductive enclosure of electrical equipment.

EXCP Extraneous conductive part.

PE Protective conductor.

PEN Protective earthed neutral. Neutral wire acting also as PE.

TT Terre–Terre. Solidly grounded power system. ECPs directly connected to ground, independently grounded of the power system.

I. FUNDAMENTAL DEFINITIONS

TN Terre–Neutral. Solidly grounded power system. ECPs directly connected to the grounded point of the power system (e.g., neutral point).

TN-S Same definition as TN. PE is separate from the neutral conductor.

TN-C-S Same definition as TN. PE and neutral are combined in a single conductor in a part of the system.

IT Isolation Terre. Ungrounded, or high resistance grounded, power system. ECPs are independently grounded of the power source.

R_N Ground grid/ground electrode resistance at the supply transformer (it is not an intentional resistance).

R_U Ground electrode resistance at the user panel (it is not an intentional resistance).

Direct contact Contact with parts normally live.

Indirect contact Contact with conductive parts normally not energized, but likely to become live upon faults (e.g., enclosures of equipment).


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A typical indirect contact is the contact with ECPs. Reference [3] defines ECP as a conductive part, forming part of electrical equipment, which can be touched (even if out of reach) and is not live but likely to become live when basic insulation fails (e.g., a dishwasher). Reference [4] prescribes that ECPs be connected to the same earthing system individually, in groups, or collectively, via a PE, also referred to as equipment-grounding conductor in [5]. PEs allow single-phase line-to-ground (SLG) fault currents to flow back to the source, thereby permitting protective devices to automatically disconnect the supply within a safe time. Alternative to the automatic disconnection of the supply, passive methods can be utilized as a fault protection when skilled or instructed persons supervise the installation [4].

EXCPs are conductive parts, not forming part of the electrical system, liable to introduce a “zero” potential (local earth potential) or an arbitrary potential, which has a resistance to ground that is less than 1000 Ω [6]. A simultaneous contact with such metal parts (e.g., metallic pipes supplying services into the building from outside) and energized objects (e.g., faulted enclosures) puts persons at a higher risk of electrocution, as they are exposed to the whole earth potential [7]. For this reason, [4] requires that EXCPs be bonded to the main earthing terminal of the building, as close as possible to their point of entry within it, regardless of the grounding system adopted, as substantiated in the next sections. This protective equipotential bonding eliminates, or reduces, potential differences between simultaneous accessible metal parts under fault conditions.

Reference [5], applicable to North America, does not have the definition of EXCP, but considers such conductive parts as grounding electrodes. Reference [5] mandates that all the grounding electrodes present in a building must be bonded together to form a grounding electrode system. This directive achieves the purpose to reduce voltage gradients, but is also aimed at improving the reliability of the earthing systems required by [5] at the service entrance of the structure.

However, in order to ensure the electrical continuity of grounding electrodes, such as metal underground water pipes, [5] requires the installation of bonding jumpers around any insulating joints or pipes. This obligation is not present in the International Electrotechnical Commission (IEC) realm, as its fulfillment by facilitating the introduction of both earth and dangerous potentials into the building lowers the safety of the installation.

Both [4] and [5] do not permit the use of natural gas pipes as electrodes. However, [4] does require the inclusion of this pipe into the main equipotential system, as it is an EXCP, by bonding it downstream of the meter; [5] does permit such connection, but only if the pipe in question is likely to become energized (which is, indeed, the definition of an EXCP) and therefore may introduce safety hazards to persons.

II. TT SYSTEM

Reference [3] defines TT systems as the electrical systems whose ECPs are connected to earth independently of the ground electrodes of the source (e.g., the local utility) (Fig. 1).

This is the earthing method adopted for low-voltage systems (i.e., not exceeding 1 kV) supplying dwelling units in several countries, among which are Algeria, Belgium, Denmark, Egypt, France, Greece, Italy, Japan, Kenya, Luxemburg, Morocco, Tunisia, Spain, Portugal, Turkey, United Arab Emirates, etc.

It should be noted that [5] neither contemplates nor allows this earthing solution. The reason for this prohibition lies in the limitation of the fault current traveling through the earth, due to the earth resistance $R_N$ at the utility substation and $R_G$ at the user (Fig. 1). A reduced fault current renders unlikely the operation of overcurrent protective devices within a safe time, as it is substantiated later on.

TT users must install and maintain a grounding system at their premises. A major difference between the IEC and the National Electrical Code (NEC) worlds concerns the electrodes permitted for the grounding of the systems. While [5] allows metal underground water pipes, [4] prohibits its use in several countries, such as Austria, Belgium, Finland, France, Germany, Sweden, Switzerland, and the U.K.; in Italy, a water pipe system can be used as an electrode only with the consent of the water utility. In Germany, there is the obligation to erect in new constructions a foundation earth electrode.

As anticipated, in the case of SLG faults, the current $I_G$ returns to the source by traveling through the actual earth. Its magnitude, therefore, is limited by the series of the earth resistances $R_N$ and $R_G$. Overcurrent devices can protect against indirect contact if the following condition is fulfilled, as per [4]

$$I_G = \frac{V_{ph}}{Z_{Loop}} \geq I_a.$$  \hspace{1cm} (1)

$Z_{Loop}$ is the magnitude of the fault-loop impedance as composed of the source, the line conductor up to the point of the fault, the user’s ground $R_G$, and the utility ground $R_N$; $R_G$ is generally the largest element in the loop. $V_{ph}$ is the nominal voltage between the line and the neutral conductors, and $I_a$ is the current that causes the tripping of the overcurrent protective device within the safe time specified in Table I.

Table I is applicable to final circuits not exceeding 32 A. For final circuits exceeding 32 A and for distribution circuits, a disconnection time not exceeding 5 s is permitted. Reference [4], in fact, assumes that such circuits are less likely to fail than
final ones, which are, by nature, more prone to electrical and mechanical stresses.

If (1) is fulfilled, persons touching faulted equipment will be exposed to touch voltages for a time so brief that no harmful physiological effects will be caused.

In practice, (1) is very difficult to fulfill, as, generally, $Z_{\text{Loop}}$ is not a suitable, or permanent, low value. Consequently, $I_a$ may be on the order of hundreds of amperes, while the magnitude of $I_G$ may be on the order of a few tens of amperes. Ergo, in TT systems, protection against indirect contact by overcurrent devices may not be effective, and residual current devices (RCDs) [9], [10], also referred to as ground-fault circuit interrupters in [5], must be employed. In this case, safety against indirect contact is achieved if the following condition is fulfilled:

$$R_G \cdot I_{\text{dn}} \leq 50 \text{ V.}$$  \hspace{1cm} (2)

$R_G$ is the sum of the resistance in ohms of the earth electrode and the PE at the faulty ECPs; $I_{\text{dn}}$ is the rated residual operating current of the RCD in amperes, providing disconnection in the time specified in the previous Table I; 50 V is the safe value of the touch voltage during the clearing time of the RCD in correspondence with $I_{\text{dn}}$. Typically, actual ground-fault currents in TT systems are significantly higher than $I_{\text{dn}}$ (e.g., at least five times $I_{\text{dn}}$). However, if (2) is fulfilled, safety is assured also in correspondence with higher ground-fault currents, which, on the one hand, do cause touch voltages greater than 50 V, but, on the other hand, also cause shorter clearing times of the RCD.

III. TN System

Reference [3] defines TN systems as the electrical systems whose ECPs are directly connected by a PE to the solidly grounded point of the source (e.g., the neutral point) (Fig. 2).

The different arrangements of neutral conductors and PEs determine three types of TN systems.

In TN-S systems (Fig. 2), two separate wires are used as PEs and neutral conductors throughout the system.

In TN-C-S systems, the functions of the neutral conductor and PE are combined in a single conductor in a part of the system. Such conductor is referred to as PEN (Fig. 3).

When the grounding point is provided to low-voltage users by a utility network, the TN-C-S system is also referred to as protective multiple earthing (PME) [11].

The PME is in use in several countries, although with differences in Australia, Canada, China, Germany, South Africa, Sweden, Switzerland, the U.K., U.S., etc. In PME systems, the user’s ECPs are permanently connected to the neutral conductor of the supply network of the operator, which therefore provide for their grounding. Thus, the operator is responsible for meeting all the requirements necessary for the safety of persons in the case of faults energizing the PEN conductor [12], [13]. In the U.S., [5] mandates the connection of the utility neutral wire to a local intentional earth electrode at the users’ first means of disconnection located at the service entrance. This arrangement, therefore, is a hybrid combination between TN-C-S and TT.

In TN-C systems, the functions of the neutral conductor and PE are combined in the PEN conductor throughout the system (Fig. 4).

This is the case of industrial facilities supplied by the electrical utility in medium or high tension. Users, therefore, must step down the incoming voltage at the service entrance by means of the front-end substations, usually, of their property.

In TN systems, the SLG fault current $I_G$ returns to the source via the PE and, unlike in TT systems, will not circulate through
TABLE II
MAXIMUM DISCONNECTION TIMES IN TN SYSTEMS

<table>
<thead>
<tr>
<th>Voltage (V)</th>
<th>Maximum disconnection times $I_a$ (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$50 &lt; V_{ph} \leq 120$</td>
<td>0.8</td>
</tr>
<tr>
<td>$120 &lt; V_{ph} \leq 230$</td>
<td>0.4</td>
</tr>
<tr>
<td>$230 &lt; V_{ph} \leq 400$</td>
<td>0.2</td>
</tr>
<tr>
<td>$V_{ph} &gt; 400$</td>
<td>0.1</td>
</tr>
</tbody>
</table>

the ground. The term equipment-grounding conductor used in [5] may therefore be misleading when used in TN systems. Protective devices can protect against indirect contact if the following condition is fulfilled, as per [4]:

$$Z_{\text{Loop}} \cdot I_a \leq V_{\text{ph}}.$$  \hspace{1cm} (3)

$Z_{\text{Loop}}$ is the magnitude of the impedance of the fault loop comprising the source, the line conductor up to the point of the fault, and the PE between the point of the fault and the source. $I_a$ is the current causing the automatic operation of the overcurrent device within the safe times specified in Table II.

If a residual current protective device is instead used, $I_a$ represents its residual operating current that allows a disconnection of the supply within the same times of Table II.

It is important to note that RCDs cannot be used in TN-C systems, as fault currents, by circulating through their toroids over the PEN, will not cause any tripping unbalance, thereby preventing their operation. In TN-C-S systems, RCDs can still be employed, as long as the connection between PE and neutral conductor is made on their source side.

IV. IT SYSTEM

Reference [3] defines IT systems as the electrical systems whose source is insulated from ground or connected to it through a sufficiently high impedance (e.g., 5-A rated neutral grounding resistor). In this arrangement, it is advisable, although not forbidden, not to ship the neutral wire to loads, in order to safeguard its isolation from ground.

In the event of a first fault between a line conductor and an ECP, or earth, fault currents can still flow, due the distributed capacitance to ground of the electrical system. Such currents are relatively low in intensity, but may be sufficient to cause harmful touch voltages over faulted enclosures. Thus, in order to limit such hazard, ECPs are required to be earthed individually (Fig. 5), in groups, or collectively (Fig. 6).

As a result, if touch voltages are kept below 50 V, the disconnection of supply as a protection against indirect contact is neither required nor necessary for safety.

After a first SLG fault, which practically earths the system, a second SLG fault, involving a different phase conductor, may occur. The IT system becomes a TT or TN, depending on how the ECPs are grounded (i.e., individually, in groups, or collectively).

If the ECPs are earthed individually (Fig. 5), or in groups, the IT system becomes TT and the following condition must be fulfilled for each ECP:

$$R_{Gi} \cdot I_a \leq 50 \text{ V}.$$  \hspace{1cm} (4)

$R_{Gi}$ is the sum of the resistance (in ohms) of the ground electrode and the PE to the generic $i$th ECP; $I_a$ is the current that causes the tripping of the protective device within the safe times specified in the previous Section II.

When ECPs are linked together via a PE, and collectively earthed to the same grounding electrode, the IT system becomes TN (Fig. 6). In this situation, the following condition to assure protection against indirect contact must be fulfilled, where the neutral wire is not distributed:

$$\sqrt{3} V_{\text{ph}} Z_s \geq I_a.$$  \hspace{1cm} (5)

$Z_s$ is the fault-loop impedance comprising the line conductor and the PE of the faulted circuit; $I_a$ is the current causing the automatic operation of protective devices within the safe times specified in Table II.

When the neutral wire is distributed, the second fault may involve this conductor and the safety condition becomes:

$$V_{\text{ph}} Z_s' \geq I_a.$$  \hspace{1cm} (6)

$Z_s'$ is the impedance of the fault-loop composed of the neutral conductor and the PE. The factor two in both (5) and (6) doubles
the fault-loop impedance to take into account the possibility that the second fault may involve an ECP supplied by a different circuit (Fig. 6).

Equations (5) and (6) should be applied in the most conservative conditions for the fault-loop impedance. This may be the case of a first fault on a live wire at the beginning of a circuit and a subsequent second fault on the neutral conductor of the farthest ECP supplied by the same circuit. This case corresponds to the minimum value for the fault current as it is driven by the phase-to-neutral voltage and limited by the maximum impedance of the circuit. In these circumstances, the amount of fault current circulating may not be sufficient to operate the protective device within the safe times described in Table II.

V. PEs

A major difference between the IEC and the North American NEC [5] is in the sizing procedure for the protective/equipment-grounding conductors.

Reference [5, Table 250.122] lists their minimum sizes $S_{EGC}$ as a function of the continuous ratings $I_N$ of the overcurrent devices protecting the circuit. Table III reports the sizes of equipment-grounding conductors, with $I_N$ ranging between 15 and 200 A.

Reference [8] instead provides the minimum cross-sectional area of PEs as a function of the cross-sectional area $S$ of the line conductor. In Table IV, such sizes are reported, by assuming the same conductive materials for both the PE and the line wire.

Reference [8] also prescribes that if a PE is in common with more than one circuit, its cross-sectional area must be sized in correspondence with the cross-sectional area of the largest line conductor of the circuits.

In Table V, a comparison between the two sizing methodologies in correspondence with the same ratings of the overcurrent devices is presented, assuming the case of a polyvinyl-chloride-insulated conductor, or a single-core cable, in a conduit on a wooden or masonry wall and in the presence of only two loaded conductors in the conduit [14].

$I_Z$ in column 4 is the current-carrying capacity of the aforementioned conductor, chosen to match, or exceed, the continuous rating $I_N$ of the overcurrent device. Columns 5 and 6 list trade wire sizes.

By comparing column 3 with column 6, it appears clear that [8] is more conservative than [5], beginning from the continuous rating of 40 A of the overcurrent device. More accurate results, as well as possibly smaller sizes for the PEs in the IEC realm, can be obtained by applying an analytical method of computation, which is based on the calculated value of the SLG fault current and the actual clearing time of protective devices [7], [14].

Both [5] and [8] permit several types of intentional PEs, not limited to the wire type. In China, Italy, the U.K., and the U.S., cable trays and cable ladders can be employed as PEs, as long as within the limits called for by local regulations or standards. In the U.K., water pipes are permitted to be used as PEs, provided that water meters are properly bonded across, if this is necessary to the electrical continuity of the pipe.

VI. Earthing Conductors

Earthing conductors, also referred to as grounding electrode conductors (GECs) in [5], are important components of the earthing arrangements, as they provide a conductive path between the main earth terminal and the grounding electrode.

Reference [5, Table 250.66] lists the minimum size $S_{GEC}$ of the GECs in ac systems as a function of the size $S$ of the largest service-entrance line conductor. Reference [4] determines the size $S_{EC}$ of earthing conductors by utilizing the same table as the PEs (Table III). Reference [4] also prescribes minimum cross-sectional areas for earthing conductors that are buried in the soil.

Even though the two sizing strategies are both based on the cross-sectional area of the line conductors, the minimum sizes of the PEs greatly differ. In Table VI, a comparison between

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|}
\hline
$I_N$ (A) & $S_{EGC}$ (AWG) & $S_{EGC}$ (mm$^2$) \\
\hline
15 & #14 & 2.08 \\
20 & #12 & 3.31 \\
30 & #10 & 5.26 \\
40 & #10 & 5.26 \\
60 & #8 & 8.36 \\
100 & #6 & 13.30 \\
200 & #6 & 13.30 \\
\hline
\end{tabular}
\caption{Minimum Sizes of Equipment-Grounding Conductors (NEC)}
\end{table}

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|}
\hline
$I_N$ (A) & $S_{GEC}$ (AWG) & $S_{GEC}$ (mm$^2$) & $I_Z$ (A) & $S$ (mm$^2$) & $S_{pg}$ (mm$^2$) \\
\hline
15 & #14 & 2.08 & 17.5 & 1.5 & 1.5 \\
20 & #12 & 3.31 & 24 & 2.5 & 2.5 \\
30 & #10 & 5.26 & 32 & 4 & 4 \\
40 & #10 & 5.26 & 41 & 6 & 6 \\
60 & #10 & 5.26 & 76 & 16 & 16 \\
100 & #8 & 8.36 & 101 & 25 & 16 \\
200 & #6 & 13.30 & 232 & 95 & 50 \\
\hline
\end{tabular}
\caption{Comparison Between Minimum Sizes of Protective Conductors (NEC Versus IEC)}
\end{table}
the minimum copper earthing conductor sizes per the two aforementioned approaches is shown.

Columns 1 and 3 represent the sizing procedure as per [5]; columns 2 and 4 report the equivalent cross-sectional areas as the result of the metrication of columns 1 and 3. Column 5 reports the equivalent areas of the earthing conductor per the application of the IEC Table IV. Column 6 lists the IEC trade sizes of earthing conductors.

VII. Conclusion

The description of the different states of the neutral, as contemplated in IEC standards and used in installations around the world, has been presented. The conditions that must be fulfilled to assure protection against indirect contact indeed provide the designer with effective, and safe, criteria to size the electrical installation. However, their application calls for the careful determination of the specific earthing system adopted in the system being designed, which may vary with, or even within, the country and/or the application.

It has been also substantiated that fault loops do not necessarily include the actual earth; therefore, the terms earth/ground as applied to conductors should be used accordingly to prevent confusion.

Major differences between NEC and IEC have also been discussed, and it has been shown that IEC yields larger minimum cross-sectional areas of protective/earthing conductors than NEC.

<table>
<thead>
<tr>
<th>S (AWG or kmil)</th>
<th>S (mm²)</th>
<th>$S_{EC}$ (AWG or kmil)</th>
<th>$S_{EC}$ (mm²)</th>
<th>$S_{EC}$ (mm²) (per IEC Table IV)</th>
<th>$S_{EC}$ (mm²) IEC trade sizes</th>
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<td>316.5</td>
<td>-</td>
</tr>
</tbody>
</table>

REFERENCES


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