Earthing of Low Voltage Electrical Systems: Personnel Protection Equipment Protection

1. Introduction

Earthing of electrical equipment and power systems in buildings provides a number of advantageous functions, including the following:

- Limitation of touch and step potentials to prevent electric shock
- Equipotential bonding of exposed metal conductors to prevent electric shock
- Limitation of overvoltages on equipment for prevention of damage
- Fast operation of electrical protection and limitation of earth fault damage

In general, all of these required functions may be reduced to just two general purposes of an earthing (grounding) system:

(i) To provide protection of personnel against electric shock and possible burns when in contact with bare conductive metal at the time that an electrical fault involving the metal occurs.
(ii) To maintain the good working order of the power system and associated equipment. (In particular, to prevent overheating and possible fire in the event of electrical faults).

To achieve the above objectives, the system must satisfy a number of requirements:

- It must have a **low impedance path** (including both resistance and reactance) to the main local earth and to the earth conductor of the local supply system and thence to the main earth of the supply at the main substation source. Low impedance in the local earthing system in the building is achieved by using metallic conductors of low impedance. Low impedance to the main (remote) substation can be achieved either by a direct conductive connection or by passage of current through the general mass of earth via an earth stake, or by both. The **MEN (multiple earthed neutral) earth system** uses the utility neutral as part of the earth connection.

- All equipment items which have or need earthing facilities (eg metal casings) must be connected to the main earth by conductors of low enough impedance to provide equipotential bonding between all equipment items. Earth loops should be avoided.

- The **earth potential rise (EPR)** associated with any fault current involving the earth system must be limited to safe levels. This is particularly true with lightning earths.
The earth conductors must be capable of handling the maximum level of fault current that may occur in the system without suffering any thermal or mechanical damage.

It should be noted that earthing systems for the prevention of static charge buildup on equipment and for lightning protection systems do not necessarily utilize the power system earthing circuits. In the case of static charge the earthing resistance required can be quite high and still be satisfactory for dissipation of charge, while for lightning earthing the primary requirement is minimal inductance in the earth down conductors, because of the high frequency and thus the high $L(di/dt)$ voltages that occur and which may cause side-flashes within the building.

2. Methods of Power System Earthing

2.1 Methods of earthing

There are a variety of different methods of earthing power systems and building electrical systems, including the option of having an unearthed system. The various options are (see Figures 1 and 2):

- The unearthed system
- The solidly earthed system
- Resistance earthed system
- Reactance earthed system
- Use of an earthing transformer
2.1.1 The Unearthed System

The unearthed system is not used widely although it does have some advantages, but these are normally outweighed by the disadvantages. The name is a misnomer because, although there is no low value resistive earth connection in an unearthed system, there is a capacitive coupling to earth, even though this is of high impedance.

The main advantage of the unearthed system is that it allows system operation to be maintained even in the event of an earth fault. Such a fault would cause system tripping in an earthed system. However with no electrical system earth there is very low fault current (only via the capacitance) and thus no damage to equipment and no personnel hazard. The main application of unearthed systems is in industry where it may be necessary to maintain operation even if a fault occurs.

Power supply operation will only cease when a second fault occurs: this will then cause a phase to phase fault that will then operate overcurrent protection. One disadvantage of such a system is that the initial fault in unearthed operation can impose line-line voltage across insulation designed normally for phase voltage and this may be a problem if the faulty system is left in operation for a long period (see Figure 1).

It should be noted that the Wring Rules do not allow connection of unearthed systems to the utility supply.
2.1.2 Solidly Earthed System

The solidly earthed (grounded) method is the most commonly used system whereby the neutral of the main power supply substation is directly connected to a low resistance stake or buried distributed mesh in the ground or connected via the MEN system. The MEN system uses the supply utility’s neutral conductor for earth use with connections to earth stakes at regular locations (every few poles) along the route of the power lines. This additional earth path provides a lower overall earth resistance and a more reliable one than when only the earth stake is used and earth current is confined to the general mass of earth.

This low earth resistance MEN connection gives high fault current and thus fast operation of protection. A low resistance ground also limits earth potential rise and thus the hazards of touch potential and step potential. Solid earthing is almost universal practice for low and medium voltage systems (up to 1000 V).

A very low resistance earth was a requirement for adequate earth leakage protection where the fault currents may be quite low and are quite difficult with early earth leakage detection. However modern developments of very sensitive earth leakage detection using core balance residual current devices have alleviated the need to have extremely low earth impedance.
Comparison between solidly earthed and unearthed electrical systems

**Advantages**

*Solidly earthed*
- High fault current and fast protection operation
- Better personnel and equipment safety
- Earth fault current easy to detect

*Unearthed*
- Line to earth fault will not interrupt supply
- Improves reliability
- Low fault current (limited by capacitance) will not cause damage

**Disadvantages**

*Solidly earthed*
- Line to earth fault causes loss of supply
- Line to ground fault current may be high enough to cause damage

*Unearthed*
- Line to line fault current may be low and may not trip protection
- May have prolonged arc faults and associated damage
- Line to line voltage is imposed on phase insulation if an earth fault occurs
- Overvoltages may cause increased insulation stress if there is an earth fault
- Finding faults may be difficult
- Regular maintenance is required
2.1.3 Resistance earthing

Resistance earthing is achieved by connecting a resistance between the main supply neutral point and the earth stake of the grid at the substation. The resistance earthing can be **high resistance** or **low resistance**: low voltage systems will use high resistance earthing and high voltage systems will use low resistance. The **primary aim of resistance earthing** is to limit the magnitude of the fault currents that occur. This is done to protect equipment from damage. Low resistance earthing normally limits current to a few hundred amps. Resistance earthing generally requires good earth leakage protection sensitivity.

2.1.4 Reactance earthing

Reactance earthing involves the use of a reactor in place of the resistor in the above method. It is not often used and then normally only with generators.

2.1.5 Earthing transformers

Earthing transformers are often used to provide earthing means for systems such as the delta-connected windings of transformers where a neutral point is not accessible for earthing connection. The earthing transformer may be, for example, a delta-star transformer with earthed neutral and shorted delta and is used to provide an earth path for fault current (zero sequence current) on the main unearthed delta winding. Alternatively, a so-called **zig-zag**
transformer using centre-tapped windings can be used for the same purpose.

Figure 1: Earthed and unearthed 3-φ electrical systems

Figure 2: Different methods of earthing 3-φ systems.
2.2 Protection of Personnel

The essential aim of protective earthing for personnel protection is to limit the magnitude of the Touch and Step potentials (these will be defined later), to which a person may be exposed when an electrical fault occurs. If the person is touching an earth conductor or is in the general vicinity of the earth conductor and in contact with exposed metal, he or she may suffer touch or step voltages across the body to another earth point. The earth circuit impedance must be designed to keep the magnitude of these potentials below levels which would cause potential electrocution to a person in contact with exposed live parts when a fault occurs.

This is achieved by providing an earth circuit with both low impedance and with good equipotential bonding so that voltage differences in the overall earth circuit system are not sufficient to cause significant electric shock to personnel.

2.3 System Equipment Protection

A major aim of the earth system is to provide a low impedance fault circuit which will allow a sufficiently high fault current to operate protection quickly so that the fault can be isolated before significant damage is done by the thermal or mechanical effects of the fault current or of any arcing that may occur in such faults.
In general, the requirements for achieving personnel protection and equipment protection are quite compatible, but in some (unusual) instances, there may be conflicting requirements between the two aims. In such cases personnel protection needs must be given preference in the design of the earthing system.

3. **Personnel Protection**

The aim of protective earthing for personnel is to ensure that, in any situation, the electric potential that occurs across the body is not high enough to cause injurious current levels to flow through the body. Obviously, the design of good personnel protective earthing systems requires detailed knowledge of the effects of electric current on the human body, including the actual electrical resistance represented by the human body. It also requires some attention to be paid to the potential contact resistance between earthed objects and the body as these will affect the current through the body by imposing additional resistance in the circuit. For example the skin resistance, area of contact, contact pressure etc. will all affect the current flow and the voltage generated in the body.

3.1 **Effect of Electric Current on the Human Body**

The effects of current and the characteristics of the body as a resistance element are dealt with in the International Electrotechnical Commission documents IEC 479-1 &
479-2 (Ref.1) which are also copied in an identical Australian Standard (AS/NZS 60479.1:2002 : Effects of current on human beings and livestock - General aspects ; and AS/NZS 60479.2:2002 : Special aspects).

The IEC approach to determination of electric shock effects, as detailed in IEC 479 has been adopted in Europe and many other countries, including Australia. This method defines “zones” of hazard which are based on the current flow magnitude and its duration of flow in the body. Figure 3 shows the standardized zones of electric shock hazard according to IEC 479 and AS 60479.

In USA and Canada, a more quantitative and formulaic approach has been adopted for the determination of the possibility of electric shock and electrocution. The well-known “electrocution” equation of Dalziel (2) is used [see, for example, IEEE Std.80 - 1986 (3)] to determine permissible touch and step voltages and to assist in earthing design for installations. This equation defines the hazard of current flow in terms of current and time.

The Dalziel equation defines a specific energy \( (I^2t) \) as the determining factor for potential electrocution (fibrillation). The values of hazardous \( (I^2t) \) levels are based on tests carried out on humans and animals (4). The generally used form of the equation is:

\[
I_B = \frac{k}{\sqrt{t_s}}
\]
where \( I_B \) is the current through the body, \( t_s \) is the duration of current flow and \( k \) is a constant \([k \sim 0.16]\). It should be noted that both the IEC and IEEE approaches give essentially the same levels of hazard in terms of their potential for electrocution. [try compare with Fig 3]

### 3.2 Limitation of Touch Voltage

In conjunction with the two approaches to prescription of the hazardous effects of current on the body, there are also two approaches to the principle of earthing design for achieving successful limitation of touch and step voltages. These are detailed respectively in, for example, Rudolph (5) (which is based on the details of IEC 479-1), and the IEEE Earthing Standard, IEEE Std. #80 (3).

#### 3.2.1 IEC Approach

The permissible touch voltages in a selection of the countries adopting the IEC approach are shown in Fig.4. In general, these levels are based on the typical curves such as shown in IEC 479-1 (Fig.3). Fig.5 shows the guidelines which are adopted in Australia, based on ESAA (Energy Supply Association of Australia) specifications (6). The curve A1 in Fig.5 is used for earthing design for personnel protection. It is defined mathematically by the following:

\[
\begin{align*}
\text{t < 0.2 sec.} & \quad V = 600 \text{ volts} \\
0.2 < t < 2 \text{ sec.} & \quad V = \frac{120}{t} \text{ volts} \\
t > 2 \text{ sec} & \quad V = 60 \text{ volts}
\end{align*}
\]
where $t$ is the fault current flow duration and $V$ is the maximum permissible level of touch voltage for the current duration specified. Thus 60 volts is the maximum permissible steady-state touch voltage. It should be noted that the permissible touch voltages for DC systems are considerably higher (typically about 120 V) than for AC.

Fig.3a: Body impedance (Ref. AS/NZS 60479.1:2002)
### Table 1: Electric shock hazard zones due to AC currents according to IEC479 and AS/NZS 60479.1:2002.

<table>
<thead>
<tr>
<th>Zone designation</th>
<th>Zone limits</th>
<th>Physiological effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC-1</td>
<td>Up to 0.5 mA line a</td>
<td>Usually no reaction.</td>
</tr>
<tr>
<td>AC-2</td>
<td>0.5 mA up to line b *</td>
<td>Usually no harmful physiological effects.</td>
</tr>
<tr>
<td>AC-3</td>
<td>Line b up to curve c₁</td>
<td>Usually no organic damage to be expected. Likelihood of cramp-like muscular contractions and difficulty in breathing for durations of current-flow longer than 2 s. Reversible disturbances of formation and conduction of impulses in the heart, including atrial fibrillation and transient cardiac arrest without ventricular fibrillation increasing with current magnitude and time.</td>
</tr>
<tr>
<td>AC-4</td>
<td>Above curve c₁</td>
<td>Increasing with magnitude and time, dangerous pathophysiological effects such as cardiac arrest, breathing arrest and severe burns may occur in addition to the effects of zone AC-3.</td>
</tr>
<tr>
<td>AC-4.1</td>
<td>c₁-c₂</td>
<td>Probability of ventricular fibrillation increasing up to about 50%.</td>
</tr>
<tr>
<td>AC-4.2</td>
<td>c₂-c₃</td>
<td>Probability of ventricular fibrillation up to about 50%.</td>
</tr>
<tr>
<td>AC-4.3</td>
<td>Beyond curve c₃</td>
<td>Probability of ventricular fibrillation above 50%.</td>
</tr>
</tbody>
</table>

* For durations of current-flow below 10 ms, the limit for the body current for line b remains constant at a value of 200 mA.

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**Fig.3b:** Electric shock hazard zones due to AC currents according to IEC479 and AS/NZS 60479.1:2002.
<table>
<thead>
<tr>
<th>Zone designation</th>
<th>Zone limits</th>
<th>Physiological effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC-1</td>
<td>Up to 2 mA line a up to line b *</td>
<td>Usually no reaction. Slight pricking pain when switching on or off. Usually no harmful physiological effects.</td>
</tr>
<tr>
<td>DC-2</td>
<td>2 mA up to curve c₁</td>
<td>Usually no organic damage to be expected. Increasing with current magnitude and time, reversible disturbances of formation and conduction of impulses in the heart may occur.</td>
</tr>
<tr>
<td>DC-3</td>
<td>Line b up to curve c₁</td>
<td>Increasing with current magnitude and time, dangerous pathophysiological effects, for example severe burns, are to be expected in addition to the effects of zone DC-2.</td>
</tr>
<tr>
<td>DC-4</td>
<td>Above curve c₁</td>
<td>Probability of ventricular fibrillation increasing up to about 5%.</td>
</tr>
<tr>
<td>DC-4.1</td>
<td>c₁-c₂</td>
<td>Probability of ventricular fibrillation up to about 50%.</td>
</tr>
<tr>
<td>DC-4.2</td>
<td>c₂-c₃</td>
<td>Probability of ventricular fibrillation above 50%.</td>
</tr>
<tr>
<td>DC-4.3</td>
<td>Beyond curve c₃</td>
<td></td>
</tr>
</tbody>
</table>

* For durations of current flow below 10 ms, the limit for the body current for line b remains constant at a value of 200 mA.

Fig.3c: Electric shock hazard zones due to DC currents according to IEC479 and AS/NZS 60479.1:2002.
### TOUCH VOLTAGE LIMITS

<table>
<thead>
<tr>
<th>NATIONAL RECOMMENDATION</th>
<th>MAX. TOUCH VOLTAGE $U_t$ (V)</th>
<th>BODY RESISTANCE $R_b$ (ohm)</th>
<th>PROBE AREA $A$ (cm²)</th>
<th>TOUCH DISTANCE $d$ (m)</th>
<th>FORCE ON PROBE $F$ (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Finland</td>
<td>$U_t = 1000t^{-0.5}$</td>
<td>3000</td>
<td>400</td>
<td>1.25</td>
<td>500</td>
</tr>
<tr>
<td>Finland</td>
<td>$U_t = 500t^{-0.5}$</td>
<td>3000</td>
<td>400</td>
<td>1.25</td>
<td>500</td>
</tr>
<tr>
<td>VDE (Germany)</td>
<td>$U_t = 90t^{-1}$</td>
<td>1000</td>
<td>400</td>
<td>1</td>
<td>500</td>
</tr>
<tr>
<td>VDE (Germany)</td>
<td>$U_t = 70t^{-1}$</td>
<td>1000</td>
<td>400</td>
<td>1</td>
<td>500</td>
</tr>
<tr>
<td>IEEE (USA)</td>
<td>$U_t = 120t^{-0.5}$</td>
<td>1000</td>
<td>400</td>
<td>1</td>
<td>Not Defined</td>
</tr>
<tr>
<td>Sweden</td>
<td>$U_t = 600t^0 \begin{cases} 1 \text{ if } t \leq 0.5s \ 1.25 \text{ if } t &lt; 0.25s \end{cases}$</td>
<td>3000</td>
<td>300</td>
<td>1</td>
<td>Not Defined</td>
</tr>
<tr>
<td>CCITT (high security lines)</td>
<td>$U_t = 650t^0 \begin{cases} 1 \text{ if } t \leq 0.5s \ 1.25 \text{ if } t &lt; 0.25s \end{cases}$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CCITT (other lines)</td>
<td>$U_t = 430t^0$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Dalziel (1946)</td>
<td>$U_t = 165t^{-0.5}$</td>
<td>1000</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Biegelmeier &amp; Lee</td>
<td>$U_t = 100t^{-1}$</td>
<td>1000</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>$500 &lt; U_t &lt; 50$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Australia** - Between Finland $U \geq 110kV$ and Germany $U \geq 110kV$ for (EA of NSW) $R = 1000$ Ohm

**USSR** - Between Germany $U \geq 110kV$ and USA for $T < 0.7$ sec.

**Switzerland** - Equivalent to Germany $< 110kV$ with $R_b = 2000$ Ohm

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**Figure 4:** Recommended touch voltage limits in various countries
3.2.2 IEEE Approach

The IEEE approach is based primarily on experimental work by Dalziel and provides a more deterministic approach which is outlined in IEEE Std.80. It also
provides a means of incorporating hand and foot contact resistance, which is not included in the IEC data.

The governing equation used to specify potential electrocution is:

\[ I_B = \frac{0.157}{\sqrt{t_s}} \]

which corresponds to a person with a body weight of 70kg. \( I_B \) is the potential fibrillating (electrocution) current and \( t_s \) is duration of flow of the current through the body. [Previously the equation \( I_B = 0.116/\sqrt{t_s} \) was used, for a body weight of 50 kg, but the 70 kg equation was taken as being more representative].

The touch voltage determined by the above equation (for 70 kg) for a typical 1000Ω body resistance is plotted on the curves of Fig.5 to provide a comparison of the two approaches. It can be seen that there is not a very significant difference between the two representations of potentially lethal touch voltage.

Both approaches show the importance of high speed fault clearing and a low impedance earthing system provides this function, as well as providing limitation of touch and step potentials.

IEEE Std.80 also provides, in addition to body resistance, quantitative determinations of contact resistances for the feet. It models foot contact as a metal disc of radius, \( b \), for
which the contact resistance for soil of electrical resistivity, $\rho$, is:

$$R_f = \frac{\rho}{4b}$$

This is used with the $I^2t$ equation to determine permissible step and touch voltages in the vicinity of earth electrodes.

4. **Typical Situations in Substations**

Figs. 6 and 7 illustrates the possible hazardous situations which can occur when there is an earth surface potential rise (EPR) in the vicinity of an earth electrode due to fault current flowing to earth through that earth electrode.

The four possible situations which can arise are also shown in Figs. 7 and 8, and can be described as follows:

(i) **Step Potential (or Voltage)**: [B in Figure 6]

This is the voltage difference between a person's feet when spaced 1 metre apart.

(ii) **Touch Potential**: [A in Figure 6]

This is the voltage difference between an exposed metal object, connected directly to the earth electrode, and the ground surface potential where the feet are placed. (Usually, a distance of 1 metre is used).
(iii) **Grid Potential:** [See Figure 7]

This is the maximum possible touch voltage in an earth grid area.

(iv) **Transferred Potential:** [C in Figure 6]

This is the voltage difference between the earth surface potential and an exposed metal object connected to a remote earth (which is effectively at true earth potential of zero volts).

![Figure 6: Potential hazards existing due to Earth Potential Rise from a fault.](image)
Figures 7 and 8: Potential Shock Situations in Substations [Ref.3].
5. Earthing for Equipment Protection – Thermal effects

5.1 Earth Faults

Earth faults are the most common type of electrical fault and unless the fault can be isolated from the supply in a short time, the heating effect of the fault current can cause very significant damage to equipment, as well as presenting a potential hazard to personnel in the vicinity.

Earth faults can be caused by a variety of causes and thus have a wide range of magnitudes and can cause a correspondingly wide and variable degree of damage. The **arcing earth fault, or high impedance arcing fault** is potentially the most damaging of earth fault types.

Earth faults can be initiated by (among others) the following causes:

(i) Contaminated insulation (moisture, insulation ageing, foreign objects)
(ii) Physical damage to insulation.
(iii) Transient or continuous overvoltages on insulation.

5.2 Arc Fault Damage

Arc faults produce substantial heat in localised areas at extremely high temperatures (thousands of degrees). There is thus the high probability of fire and fusion of metal. The arc impedance produces an arc-circuit
interaction which acts to reduce fault current level and the effect is to increase protection operating time or even to reduce fault current to levels below the protection trip setting thus rendering the protection ineffective.

Typical arc voltages in low voltage systems are about the order of 100 volts and this is thus a substantial part of the common 120 or 240 volts supply, leading to significant current decrease. Reference 7, for example, gives the following typical levels of current reduction by arcing fault current. These can be used for protection design purposes to determine the minimum levels of fault current when arcing occurs. Studies indicate that the arcing fault currents, in per unit of the bolted-fault current levels, may be as low as:

1) 0.89 at 480V and 0.12 at 208V for 3-φ arcing
2) 0.74 at 480V and 0.02 at 208V for line-to-line arcing.
3) 0.38 at 277V and 0.01 at 120V for line-to-neutral arcing.

6. Systems of Earthing in LV Installations

There are four systems allowed in Australia:

- Direct earthing system
- Multiple earthed neutral (MEN) system
- Earth leakage circuit breaker (ELCB or RCD) system
- Common multiple earthed neutral (CMEN) system
The supply utility will specify in its Service Rules which system should be used in any particular area. The supply utility may specify use of the ELCB method in addition to another earthing method in areas which are of particular hazard. The consumer may also use the RCD system in addition to another specified system to provide extra safety.

The basic configurations of the above systems are shown in Figures 9-13. The direct earthing system relies on current flow through the ground and this in turn requires low earth resistivity and a good earth electrode. This is not always able to be achieved and thus the multiple earthed neutral or MEN system is preferred as it utilizes the supply utilities neutral to provide an additional earth return path.

### 6.1 The MEN System

The essential feature is that the neutral conductor of the distribution system furnishes a low impedance path for return current and the potential above earth of this neutral is kept low by many connections of the neutral line to earth (Fig 10). It requires earth connections to the neutral at the consumer’s installation and along the route to the supply substation.

From the basic protection viewpoint there is no difference between the direct earth system shown in Figure 9 and the MEN system. Both require the operation of a fuse or circuit breaker to isolate the fault. In both systems, the
consumer’s apparatus is connected to earth at the consumer’s installation and the distribution system neutral is connected to earth at the distribution substation. Both systems require a low impedance path between the fault and the neutral earth at the substation. In the MEN system the neutral provides the return path while in the direct earth system the metallic path is provided by water pipes, cable sheaths or by special earthing connections if provided.

As the neutral is connected to metal conduits, water services and exposed metal frames of appliances in the MEN system it is essential that the neutral remain intact. A discontinuous (floating) neutral can cause high voltages to appear on the load side if it is disconnected from the supply source.

There are situations where the MEN system does cause voltage drop problems along its length. This can assume levels of 12 volts or more with respect to true earth in some cases and although this is normally of no significance in terms of system operation it can present problems of nuisance electric shock in damp areas such as the dairying industry or in swimming pool locations.

Balancing of the load over the three phases is also important in the MEN system to utilize the phase current cancellation in the return neutral to minimize the voltage drop.
6.2 **Connection of the neutral to earth**

The neutral conductor must be earthed at the substation and at other locations as necessary to ensure that the total impedance between neutral and earth does not exceed 10 ohms. In determining the impedance between the neutral and earth all connections of the neutral to earth should be taken into account, including:

- The earth connection at the substation
- The earth connections on the distribution system
- The earth connection at the consumer’s installation

6.3 **Earthing conductors within the distribution system**

Any conductors used to earth the neutral conductor of the distribution system must have a cross-section area of at least 20% that of the smallest size of neutral used in the system. Appropriate precautions to prevent damage and to maintain the integrity of the connections must be taken in all cases.

6.4 **Common multiple earthed neutral (CMEN)**

This is a logical extension of the MEN system and is one where high voltage and low voltage equipment is bonded (via a neutral conductor) to a single common earth. In this system the LV neutral is usually bonded to earth at the following locations:
- Each of the distribution substations forming part of the system
- All consumers’ premises as for the MEN system

The CMEN system is usually introduced to a defined area which has been reticulated using conductive structures (poles) and as such forms the basis of an effective conductive earthing structure. The system utilizes the LV neutral to interconnect all distribution substation earths, high voltage earths, consumers’ earths and LV earths within the defined CMEN area. The impedance to ground of the interconnected system of earthing is thus very low and is typically an ohm or less in impedance.
Figures 9-12: Methods of earthing allowed in Australia
7. Types of Earthing Systems in Consumer’s Installations

In typical consumers’ internal distribution systems there are five main types of earthing systems in (relatively) common use. Recent international agreement has specified these variants by identifying letters. The five designated systems used are:

(i) TT
(ii) TN-C
(iii) TN-S
(iv) TN-C-S
(v) IT

The first letter (either T or I) gives the relationship of the supply to the earth:

- **T** (for terra) - there is direct connection of one point of the supply system to earth.
- **I** (for insulation) - all live parts of the supply are isolated from earth or one point is connected to earth through an impedance.

The second letter (either T or N) gives the relationship of the exposed conductive parts of the general installation to earth:

- **T** (for terra) - there is direct electrical connection of exposed conductive parts to earth, independent of the earthing of any point of the supply system.
- **N** (for neutral) - there is direct electrical connection of the exposed conductive parts to the earthed point.
of the supply (in AC systems the earthed point is normally the neutral point).

There are then three different variations of the TN system, according to the arrangement of the neutral and protective (earth) conductors:

**TN-S** There are separate (S) neutral and protective conductors throughout the system.

**TN-C** The neutral and protective conductors are combined (C) in a single conductor throughout the system.

**TN-C-S** The neutral and protective conductors are combined in a single conductor in only a part of system.

Figs. 14 -18 show typical representations of the five different earthing systems. In practice, only the TT and TN systems are commonly used. The IT system is less common in LV systems and is prohibited in some countries (e.g. UK).

Figure 19 shows the typical equipotential bonding arrangements for earth systems and exposed metal parts, metal pipes, telecommunications, exposed conductive parts, etc.
Figures 14 - 18: Protective Earth Configurations.
Figure 19: Examples of equipotential bonding principles and layout.
41.2.2 Protection by automatic disconnection of supply

- measures with application of protective conductors (PE)

DIN VDE 0100: Part 410, Clause 6.1
IEC 364-4-41: Clause 413.1

The automatic disconnection of the supply on the occurrence of a fault is intended to prevent dangerous touch voltages existing for such a time as to be considered dangerous. This protective measure necessitates co-ordination of type of system earthing and the characteristics of protective devices:
- the type of earthing of the power supply system, i.e. the relation between the source (transformer, generator) of the supply system and earth;
- the type of earthing of the equipment in the installation, i.e. the connection to earth via a protective conductor in the wiring system of the installation, or direct with an independent earth electrode;
- the characteristics of protective devices, e.g. overcurrent protective devices, residual-current protective devices, insulation monitoring devices.

For classification of types of system earthing see Section 31 of this Commentary. Figures of the three systems TN, TT and IT:

41.2.2.1 Fundamental principles

a) Earthing

Exposed conductive parts shall be connected to a protective conductor under specific conditions for each type of system earthing. Simultaneously accessible exposed conductive parts shall be connected to the same earthing system individually, in groups or collectively.

For earthing arrangements and protective conductors see Section 54 of this Commentary.

b) Conventional voltage limit

The conventional voltage limit \( U_{c} \) is the maximum prospective touch voltage which can be maintained indefinitely and is equal to 50 V a.c., r.m.s. or 120 V ripple-free d.c.

Lower values may be required in special environmental conditions.

Higher values may be admitted in systems for electrical power generation and distribution; see IEC, draft 64 (Central Office) 193, January 1989.

c) Disconnection of supply

A protective device shall automatically disconnect the supply to the part of the installation protected by that device, so that, following a fault in that part, a dangerous touch voltage cannot be maintained at any point of the installation.

For IT systems, on the occurrence of the first fault automatic disconnection of supply is not usually required (further details regarding insulation monitoring and automatic disconnection in an IT system: see Sub-clause 41.2.2.6 of this Commentary).

According to IEC and German Standards the disconnecting time shall not exceed 5 s for parts of particular installations which only supply equipment at fixed points, provided that a clear and permanent distinction exists between those parts of the installation and the parts intended to supply portable, mobile and other equipment having exposed conductive parts which are hand-held (for example, equipment supplied from socket-outlets).

Higher values for the disconnecting time may be admitted in systems for electrical power generation and distribution, see draft 64 (Central Office) 193.

In the German Standards DIN VDE 0100 Part 410/11.83 the requirement regarding touch voltage duration and disconnecting time is simplified in a practical way, prescribing for TN systems with circuits of max. 35 A nominal current and with socket-outlets a disconnecting time of 0.2 s.

The max. disconnecting time for residual-current protective devices is 0.2 s.

Note: Disconnection of supply is also necessary for other reasons, e.g. protection against overcurrent, protection against fire.

41.2.2.2 Main equipotential bonding

In each building a main equipotential bonding conductor shall interconnect at the entrance point of the supplies the following conductive parts:
- main protective conductor,
- main earthing conductor or main earthing terminal,
- PEN conductor (in TN-C system),
- water pipes,
- gas pipes,
- risers of central heating, and
- air conditioning systems,

as well metallic parts of building structure and other metal pipework (Figures 41-5 and 41-6).

Note: The entrance point of the supplies often is also called "origin of an electrical installation" or "service entrance" (USA) or "point of intake".

An equipotential bonding is an electrical connection intended to prevent the occurrence of dangerous touch voltages between simultaneously accessible conductive parts.

Such parts may be exposed conductive parts, in other words metal casings for electrical equipment, or extraneous conductive parts, such as conductive structures or pipes in buildings.

For safety and protective purposes the equipotential bonding should have a potential approaching that of earth potential.

The measure "main equipotential bonding" is the important basis for safety of electrical installations in buildings. Exteraneous conductive parts are required to be connected to the main earthing terminal of the installation thereby creating an equipotential zone. The small installations such as the typical one-family house installation will usually comprise one such zone. In the larger installations (e.g.
for factories, big office buildings, hospitals, high-rise buildings) there may well be a number of these equipotential zones. When the supply system supplies a number of buildings, the main equipotential bonding has to be carried out for each building at the point of intake (origin of an installation), thereby creating a separate equipotential zone in each building.

When a factory or a high-rise building, for instance, have a number of points of intake, at each of these points a main equipotential bonding has to be carried out.

The purpose of this creation of an equipotential zone is to minimise the touch voltages between extraneous conductive parts or between extraneous conductive parts and exposed conductive parts. All these parts will have same potential or at least similar potential.

In high-rise buildings the main earthing terminals for the main equipotential bonding conductors of several points of intake are inter-connected by the main protective conductor of the distribution circuits (feeding systems) of such buildings. In buildings with horizontal extent with several points of intake a horizontal interconnection of the main earthing terminals is recommended (see DIN VDE 0800 Part 2, 07.85, Clauses 3.1.7 and 6.2.2: „Erdungsammelleiter“).

In the case of an earth fault and under certain circumstances the main earthing terminal of the zone may acquire some volts above earth potential but all the extraneous and exposed conductive parts connected to that terminal will also acquire the same potential. There is no risk of electric shock for persons staying in the equipotential zone.
The main equipotential bonding in buildings has no direct influence on the areas around the building, e.g. on gardens, fields, yards. The main equipotential bonding has besides safety aspects an other important advantage: it is of great importance for electromagnetic compatibility (EMC) of the electrical installations of buildings. For reasons of EMC in large buildings the equipotential bonding should be carried out not only at the points of intake but also at other technical points, e.g. at some subdistribution boards or at several floors of high-rise buildings.

The connection to earth, i.e. the total earthing resistance of a building or of the main equipotential bonding, is of minor importance for the electrical safety in buildings. The earthing resistance depending from the foundation of buildings (see Section 54) and the surrounding soil is quite sufficient so that e.g. for large buildings the installation of additional earth electrodes besides the building is not necessary. The important point for safety is the creation of an equipotential zone, comparable with the situation in an aircraft (Figure 41-7) [1, 2].

Within the three types of system earthing TN, TT and IT, the main equipotential bonding has a different significance for the protective measures:

a) TN system and IT system

The main equipotential bonding is important within the TN system and when applying an IT system where all exposed conductive parts are interconnected by protective conductors.

In these cases the effect of main equipotential bonding is as follows:
- reduction of the touch voltage in circuits with an admissible disconnecting time of \( \leq 5\) s;
- reduction of the touch voltage in the event of an insulation fault within the distribution system;
- reduction of the touch voltage on hand-held equipment in the event of an insulation fault within a circuit where a disconnection time of \( \leq 5\) s is required.

b) TT system and IT system

The main equipotential bonding is less important in the TT system and when applying an IT system where the exposed conductive parts are earthed individually or in groups.

In this cases:
- the condition for automatic disconnection of supply ensures safety even without the main equipotential bonding;
- an insulation fault within the distribution circuit cannot affect the final circuits.

Nevertheless the main equipotential bonding reduces the risks of electric shocks in consumers installations, independent from the types of system earthing.

The different significance of the main equipotential bonding in the three types of system earthing should be considered in the case of installations where it is difficult or not possible to realize a main equipotential bonding, e.g. outside of buildings; see for example IEC 364, Section 708, Electrical installations in caravan parks and caravans; Section 709, Electrical installations in marinas and pleasure craft; Section 711, Electrical installations for fairs, exhibitions (particularly temporary installations, at the time being under consideration).

41.2.2.3 Supplementary equipotential bonding

If in an installation or in a part of an installation the conditions for disconnection of supply (see Sub-clause 41.2.2.1) cannot be fulfilled a so called supplementary equipotential bonding shall be applied. This measure is also known as "local bonding". The use of supplementary equipotential bonding does not exclude the need to disconnect the supply (Figure 41-5, conductors marked with No. 4).

Supplementary equipotential bonding may involve the entire installation, a part of the installation, an item of apparatus, or a location.

Supplementary requirements may be necessary for special locations, for instance for bath rooms or swimming pools. This supplementary equipotential bonding system shall include all simultaneously accessible conductive parts which are exposed in the location, for instance:
- exposed conductive parts of fixed equipment,
- extraneous conductive parts (e.g. pipes, ducts),
- main metallic reinforcements of concrete, where practicable, furthermore:
- protective conductors of all equipment and socket-outlets.

Supplementary equipotential bonding may be necessary, for example, in TN or IT systems in circuits of great length and such that the fault loop impedance is too high to ensure operation of the protective device in prescribed time.

In regard to disconnecting times, the time of five seconds is valid if the protective device is a fuse. If the protective device is a circuit-breaker, the current to take into consideration is the smallest current ensuring the magnetic operation of the circuit-breaker.
8. Computer System and Equipment Earthing

Earthing of computer systems and general information technology equipment requires coordination of power equipment, communication circuits, special earthing for microelectronics and surge protective devices for all of the above components to protect such systems against transient voltage surges. While much IT equipment does have inbuilt overvoltage protection, it is not always the case and thus the protection requirements of equipment must be ascertained beforehand. The distributed network of the communication cables, in particular, causes problems by propagating induced overvoltage transients between interconnected systems and thus spreading the effects of the interference. Both induced overvoltages and the general local earth potential rise due to nearby lightning strikes, resulting in a voltage rise relative to true earth at the other end of the cable, is a particular problem in distributed systems.

All computer frames must be connected to a common earthing point by low impedance cables to give adequate equipotential bonding and earthing. The common point is then connected directly to the supply earth only: earth loops must be avoided, as circulating currents may be generated in such situations.

It should also be remembered that static voltages on polymer surfaces can cause considerable damage to microelectronic circuits and as the very low humidity of air conditioned rooms can result in significant static
charge, some attention should be given to the possible need for static control earthing systems. This may simply be just a charge bleed resistor system. In other cases involving large surfaces, use of an antistatic spray and wipe coating on the surface may be required.

4.1 Data Link Connections

Data link transmission connections provide a difficulty - should they be earthed to the main power earth and, if so how, or should they be isolated? Overvoltage transient propagation over signal lines is a common problem.

There are 3 possible earthing systems that can be used for such data links.

(i) Floating Earth

In this case, the data or signal cables are totally isolated from the building earthing system and other conductive components (see Fig. 20a). However, it is very difficult to achieve true isolation and this method is thus only useable in small localized systems and in situations where the electrical supply is isolated.

(ii) Single-Point Earth

In this situation all signal circuit earths are referenced to a single earth point and this is connected to the main supply earth (see Fig. 20b). For large systems, this method may become uneconomical because of the number and size of earth connection conductors required.
(iii) **Multiple-Point Earth**

This method provides many alternative paths for microelectronic systems in a large facility (see Figs. 20c and 20d). It simplifies circuit construction compared to the single point method described above. However, 50Hz power current can couple inductively into data and signal lines and produce interference and ground loops will increase the possible inductive pickup. This problem is becoming worse with the increasing use of power electronic systems such as switch-mode power supplies which generate high harmonic content and this make the inductive coupling more efficient, in terms of induced voltage generation levels. The solution is to reduce voltage differentials as much as possible (equipotential...
bonding) and to shield items properly against inductive pickup.

This method reduces earth impedance and thus makes touch voltages lower and thus improves personnel safety. It is also a good method for protection against lightning effects as it keeps the impedance low.

9 Earth Resistance of Buried Electrodes

The ideal earth electrode should provide a zero resistance interface with the general mass of earth. However, the finite dimensions of the buried metal electrode system make this an impossible aim to achieve. The best that can be done is to design a buried electrode system with the minimum possible Earth Resistance.

The ultimate earth resistance is determined by a number of factors, which include the following:

- The shape of the electrode(s)
- The extent of the electrode(s)
- The earth electrical resistivity

We can analyse some simple electrode configurations to gain an understanding of the typical levels of earth resistance and their dependence. The simplest configuration to analyse is the hemispherical electrode, buried flush with the earth surface, as below.
If the electrical resistivity of the earth is $\rho$ then the incremental resistance between the two hemispherical surfaces in the ground at radii $r$ and $r + dr$ is:

$$dR = \frac{\rho dr}{2\pi r^2}$$

Thus, the resistance between the electrode surface hemisphere $r_0$ and the arbitrary ground hemisphere at radius $r_1$ is:

$$R(r_1) = \int_{r_0}^{r_1} \frac{\rho dr}{2\pi r^2} = \frac{\rho}{2\pi} \left( \frac{1}{r_0} - \frac{1}{r_1} \right) \text{ ohms}$$

Note that when $r_1 \to \infty$, $R(\infty) = \frac{\rho}{2\pi r_0} \text{ ohms}$

This is the effective earth resistance of the buried hemispherical electrode.
**Example:** for $r_o = 0.25$ metre, and $\rho = 50$ ohm.m units, the resistances between the electrode and ground at various distances from the electrode are:

$$R(1) = 23.9 \ \Omega$$
$$R(5) = 30.2 \ \Omega$$
$$R_\infty = 31.8 \ \Omega \quad \text{(true earth resistance)}$$

It can be seen that most of the earth resistance occurs within 2-3 m of the electrode.

**10. Equivalent Hemisphere Model of an Earth Electrode**

The most common form of earth electrode is a driven rod or pipe or a more complex distributed structure in the ground. Such geometries are not as amenable to simple analytic calculation as the hemisphere model, although some approximations are possible but the resulting analysis is complex.

In order to simplify calculations it is common to model buried rods, plates, etc for earth electrodes by determining an **equivalent hemisphere** which gives the same earth resistance. We use known formulae for the appropriate shape and then find the radius of a hemisphere giving the equivalent earth resistance. The equivalent hemisphere is then used for potential distribution calculations.
Example:

For a buried horizontal wire of radius $r_0$, length $L$, depth $s$, where $r_0 \ll s \ll L$, the formula gives:

$$R = \frac{\rho}{2\pi L} \left[ \ln\left(\frac{4L}{r_0}\right) - 2 \right] \text{ ohms}$$

For the equivalent hemisphere, of unknown radius $a_0$, we have:

$$R_\infty = \frac{\rho}{2\pi a_0} \text{ ohms}$$

Equating the two expressions gives the equivalent hemisphere radius $a_0$ of a hemisphere with the same earth resistance as the buried horizontal wire of length $L$ and radius $r_0$:

$$a_0 = \frac{L}{\ln\left(\frac{4L}{r_0}\right) - 2} \text{ metres}$$

This then allows easier determination of quantities such as the step, touch and transferred potentials.
11. **Use of equivalent hemisphere model to calculate touch, step & transferred potentials**

At an arbitrary distance, \( r \), from the earth:

\[
R(r) = \frac{\rho I}{2\pi} \left( \frac{1}{r_0} - \frac{1}{r} \right) \quad \text{and} \quad V(r) = \frac{\rho I}{2\pi} \left( \frac{1}{r_0} - \frac{1}{r} \right)
\]

where \( V(r) \) is the ground potential with respect to the earth electrode.

1. If the person is touching conductor A, that person is then subject to the voltage

\[
V(r_1) = \frac{\rho I}{2\pi} \left( \frac{1}{r_0} - \frac{1}{r_1} \right) = V_{\text{touch}}
\]

This is the **Touch Potential**.
[N.B. \( r_1 \) is normally taken to be 1m, i.e. arm’s reach]

2. If the person is touching a conductor at B, that person is subject to the voltage:

\[
V = V_0 - V(r_1) = \frac{\rho I}{2\pi r_0} - \frac{\rho I}{2\pi} \left( \frac{1}{r_0} - \frac{1}{r_1} \right).
\]

that is:

\[
V_{\text{trans}} = \frac{\rho I}{2\pi r_1}
\]

This is the **Transferred Potential**.

3. Between radii \( r_1 \) and \( r_2 \) relative to the hemisphere, the potential is:

\[
V_{r_1-r_2} = \frac{\rho I}{2\pi} \left( \frac{1}{r_1} - \frac{1}{r_2} \right) = V_{\text{STEP}}
\]

This is the **Step Potential**.

[Usually, \( r_2 - r_1 \) is taken to be being 1m]

12. **Earth Resistance of Closely-Spaced Identical Electrodes**

When two or more separate earth electrodes, connected to the one earth conductor configuration above ground, are buried close to one another, the earth potential fields around the separate electrodes when current flows to earth will interact with each other and the overall earth
resistance of the combined electrode system will be higher than that of the parallel combination the isolated electrode system.

The following are simple formulae for the equivalent resistance of such groups of earthing electrodes where the spacing is close enough that the earth systems will interact when current flows into the earth electrodes. ($r$ is the equivalent hemisphere radius, $s$ is the electrode spacing, and $R$ is the earth resistance of a single isolated electrode).

1. Two electrodes:

$$R_{eq} = \frac{R}{2} \left(1 + \frac{r}{s}\right) \text{ ohms}$$

2. Three electrodes (equilateral spacing):

$$R_{eq} = \frac{R}{3} \left(1 + 2 \frac{r}{s}\right) \text{ ohms}$$

3. Three electrodes (linear configuration):

$$R_{eq} = \frac{R}{3} \left[1 + \frac{r}{2s} - \frac{2r^2}{s^2} \frac{r}{1 - \frac{7r}{6s}}\right] \text{ ohms}$$
13. Measurement of Earth Resistance

13.1 Three-electrode Method

\[ R_A = R_A + R_B \]
\[ R_2 = R_B + R_C \]
\[ R_3 = R_A + R_C \]

The electrode spacing must be much greater than the electrode radius and depth of burial so that the potential fields of each electrode do not interact. \( R_B \) and \( R_C \) should each be not much greater than \( R_A \): if not, the measurement error can be high.

13.2 Fall of Potential Method

The earth resistance of electrode \( A \) is given by \( R_A = V/I \) :
The electrodes $A$ and $C$ must be at least 50m apart and $A$ and $B$ at least 25m apart. The current used is a high current AC. In this method the electrode $B$ is used as part of a high impedance voltage detector and so its earth resistance will not cause error.

**14. Earth Resistivites**

The earth is not a particularly good conductor of electricity compared with the metals used for electrical reticulation. Soil electrical resistivity is variable depending upon its physical nature and chemical composition and is heavily influenced by moisture content and any dissolved salts. The typical resistivities at 20°C below give the position of earth resistivities in the spectrum between good conductors and insulators.
### Typical Soil and Other Material Resistivities

<table>
<thead>
<tr>
<th>Material</th>
<th>$\rho_{20}$ (Ω.m)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>$17.24 \times 10^{-9}$</td>
<td>International Annealed Cu. Standard.</td>
</tr>
<tr>
<td>Aluminium</td>
<td>$28.26 \times 10^{-9}$</td>
<td></td>
</tr>
<tr>
<td>Lead</td>
<td>$214 \times 10^{-9}$</td>
<td></td>
</tr>
<tr>
<td>Mild Steel</td>
<td>$127 \times 10^{-9}$</td>
<td></td>
</tr>
<tr>
<td>Swampy earth</td>
<td>10</td>
<td>* If no factual data then use $100\Omega.m$ for average soils with moisture content of order of 25%. Lowering moisture content to 5% could raise resistivity to $500\Omega.m$. Totally dry soil can have resistivities 1 or 2 orders of magnitude higher.</td>
</tr>
<tr>
<td>Clays</td>
<td>8 - 50</td>
<td></td>
</tr>
<tr>
<td>Clay, sand &amp; gravel mix</td>
<td>40 - 250 *</td>
<td></td>
</tr>
<tr>
<td>Sand &amp; gravel</td>
<td>60 - 100</td>
<td></td>
</tr>
<tr>
<td>Slate, shale, sandstone</td>
<td>10 - 500</td>
<td></td>
</tr>
<tr>
<td>Rock</td>
<td>200 - 10000</td>
<td></td>
</tr>
<tr>
<td>Glass</td>
<td>$10^6 - 10^{15}$</td>
<td></td>
</tr>
<tr>
<td>Rubber, bitumen, PVC</td>
<td>$10^{13} - 10^{14}$</td>
<td></td>
</tr>
<tr>
<td>Polyethylene</td>
<td>$10^{13} - 10^{15}$</td>
<td></td>
</tr>
<tr>
<td>Mica</td>
<td>$10^{12} - 10^{16}$</td>
<td></td>
</tr>
</tbody>
</table>

A rough rule of thumb for soil resistivities:

- **Mud (compressed coal):** $1$ Ωm,
- **Wet soil:** $10$ Ωm,
- **Moist soil:** $100$ Ωm,
- **Dry soil:** $1000$ Ωm,
- **Rock:** $10\,000$ Ωm.
Table 13-2. Resistivity of Different Soils

<table>
<thead>
<tr>
<th>Soil Description</th>
<th>Resistance, *</th>
<th>Resistivity, ohms/cm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>Hills (ash, condensate, brine</td>
<td>14</td>
<td>3.5</td>
</tr>
<tr>
<td>waters)</td>
<td>24</td>
<td>2</td>
</tr>
<tr>
<td>Clay, shale, cove, loam</td>
<td>93</td>
<td>6</td>
</tr>
<tr>
<td>Sand plus varying proportions of</td>
<td>554</td>
<td>12</td>
</tr>
<tr>
<td>gravel, sand, silt, with</td>
<td></td>
<td></td>
</tr>
<tr>
<td>gravel on or loam</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


FIG. 13-2. The variation of soil resistivity with moisture content. Red clay soil.

FIG. 13-3. The variation of soil resistivity with temperature. Red clay soil. 18.6%, moisture.

TEST SITE - CAMDEN N.S.W.
SANDY SOIL - SLOPING GROUND
N.1 ELECTRODE - 8" x 5/8" DIA. COPPER COVERED STEEL ROD.
N.2 ELECTRODE - 16" x 5/8" DIA. COPPER COVERED STEEL ROD.
A - RESISTIVITY AT 8" DEPTH
B - RESISTIVITY AT 16" DEPTH
15 Electric Shock Effects on Personnel

The potential danger of the touch, step and transferred potentials depends on the electrical resistance of the human body and on the electrical resistance between the feet and the ground.

It is usual to represent the body by an equivalent resistance of about $1000\Omega$, although this value is very voltage dependent.

Foot contact resistance with the ground is taken to be equivalent to that of a metal disc of radius $a = 0.08\text{m}$, for which:

$$R_f = \frac{\rho}{4a} \approx 3\rho \text{ ohms}$$

where $\rho = \text{soil resistivity}$.

Thus, equivalent circuits for touch and step potentials, including the body paths, are shown below:
(a) Touch
\[ R_{\text{touch}} = (1000 + 1.5 \rho) \ \Omega \]
\[ V_{\text{touch}} = (1000 + 1.5 \rho) I_t \ \text{V} \]

(b) Step
\[ R_{\text{step}} = (1000 + 6 \rho) \ \Omega \]
\[ V_{\text{step}} = (1000 + 6 \rho) I_s \quad \Rightarrow \quad I_s = \frac{V_{\text{step}}}{(1000+6\rho)} \]

This assumes bare feet or conducting footwear.

**Tolerable Touch and Step Potentials**

Tolerable values (levels unlikely to cause electrocution) can be obtained by use of Dalziel’s ‘Electrocution’ equation: this says electrocution occurs when the \( I^2t \) product exceed a specific value:

\[ \text{i.e. } I_E^2 t \geq k^2 \quad \text{where} \quad k = \text{constant} \]
\[ I_E = \text{current through body} \]
\[ t = \text{duration of flow} \]

Thus: \[ I_E = \frac{k}{\sqrt{t}} \] defines onset of potential electrocution.

For the average body, \( k \approx 0.16 \).

[It should be noted that while this approach is adapted by USA and IEEE standards, the European dominated IEC prefer a less definitive approach on the basis that]
variations in body response do not allow such an analytic approach.]

Using \( I_E = \frac{k}{\sqrt{t}} \) and the touch and step resistances derived, we can find tolerable values as follows.

**TOUCH:**
\[
V_{\text{touch}} = I_E \left( 1000 + 1.5 \rho \right) \\
= (1000 + 1.5 \rho) \frac{k}{\sqrt{t}} \text{ volts}
\]

**STEP:**
\[
V_{\text{step}} = I_E \left( 1000 + 6 \rho \right) \\
= (1000 + 6 \rho) \frac{k}{\sqrt{t}} \text{ volts}
\]

The time \( t \) will be determined by the protection operating time, typically 1 – 3s.

**Example:** for \( \rho = 100 \ \Omega.m \)

\[
V_{\text{touch}} = 1150 \times \frac{0.16}{\sqrt{t}} \\
= 184V \ (t = 1s) \\
= 106V \ (t = 3s)
\]

\[
V_{\text{step}} = 1600 \times \frac{0.16}{\sqrt{t}} \\
= 256V \ (t = 1s) \\
= 148V \ (t = 3s)
\]
References


### Table 13-1. Formulas for Calculation of Resistances to Ground*

(Approximate formulas including effects of images. Dimensions must be in centimeters when resistivity is in ohm-centimeters.)

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hemisphere radius (a)</td>
<td>(R = \frac{\rho}{2\pi a})</td>
</tr>
<tr>
<td>One ground rod Length (L), radius (a)</td>
<td>(R = \frac{\rho}{2\pi L} \left( \log \frac{4L}{a} - 1 \right))</td>
</tr>
<tr>
<td>Two ground rods (s &gt; L), spacing (s)</td>
<td>(R = \frac{\rho}{4\pi L} \left( \log \frac{4L}{a} - 1 \right) + \frac{\rho}{4\pi s} \left(1 - \frac{L^2}{2s} + \frac{1}{5} \frac{L^4}{s^4} \ldots \right))</td>
</tr>
<tr>
<td>Two ground rods (s &lt; L), spacing (s)</td>
<td>(R = \frac{\rho}{4\pi L} \left( \log \frac{4L}{a} + \log \frac{4L}{s} - 2 + \frac{3}{2} \frac{s^2}{L^2} - \frac{\gamma^2}{16L^2} \right) + \frac{\rho}{512L^4} \left(\ldots\right))</td>
</tr>
<tr>
<td>Buried horizontal wire Length (2L), depth (s/2)</td>
<td>(R = \frac{\rho}{4\pi L} \left( \log \frac{4L}{a} + \log \frac{4L}{s} - 2 + \frac{3}{2} \frac{s^2}{L^2} - \frac{s^2}{16L^2} \right) + \frac{\rho}{512L^4} \left(\ldots\right))</td>
</tr>
<tr>
<td>Right-angle turn of wire Length of arm (L), depth (s/2)</td>
<td>(R = \frac{\rho}{4\pi L} \left( \log \frac{2L}{a} + \log \frac{2L}{s} - 0.2373 + 0.2146 \frac{L}{s} + 0.1035 \frac{L^2}{s^2} - 0.0626 \frac{L^4}{s^4} \ldots \right))</td>
</tr>
<tr>
<td>Three-point star Length of arm (L), depth (s/2)</td>
<td>(R = \frac{\rho}{6\pi L} \left( \log \frac{2L}{a} + \log \frac{2L}{s} + 1.071 - 0.209 \frac{L}{s} + 0.338 \frac{L^2}{s^2} - 0.054 \frac{L^4}{s^4} \ldots \right))</td>
</tr>
<tr>
<td>Four-point star Length of arm (L), depth (s/2)</td>
<td>(R = \frac{\rho}{8\pi L} \left( \log \frac{2L}{a} + \log \frac{2L}{s} + 2.912 - 1.071 \frac{L}{s} + 0.645 \frac{L^2}{s^2} - 0.145 \frac{L^4}{s^4} \ldots \right))</td>
</tr>
<tr>
<td>Six-point star Length of arm (L), depth (s/2)</td>
<td>(R = \frac{\rho}{12\pi L} \left( \log \frac{2L}{a} + \log \frac{2L}{s} + 6.851 - 3.128 \frac{L}{s} + 1.758 \frac{L^2}{s^2} - 0.490 \frac{L^4}{s^4} \ldots \right))</td>
</tr>
<tr>
<td>Eight-point star Length of arm (L), depth (s/2)</td>
<td>(R = \frac{\rho}{16\pi L} \left( \log \frac{2L}{a} + \log \frac{2L}{s} + 10.98 - 5.51 \frac{L}{s} + 3.26 \frac{L^2}{s^2} - 1.17 \frac{L^4}{s^4} \ldots \right))</td>
</tr>
<tr>
<td>Ring of wire Diameter of ring (D), diameter of wire (a), depth (s/2)</td>
<td>(R = \frac{\rho}{2\pi^2 D} \left( \log \frac{8D}{a} + \log \frac{4D}{s} \right))</td>
</tr>
<tr>
<td>Buried horizontal strip Length (2L), section (a) by (b), depth (s/2), (b &lt; a/8)</td>
<td>(R = \frac{\rho}{4\pi L} \left( \log \frac{2L}{a} + \frac{a^2 - b^2}{2a + b} \right) + \frac{\rho}{4\pi s} \left(1 - \frac{L^2}{2s} + \frac{1}{5} \frac{L^4}{s^4} \ldots \right))</td>
</tr>
<tr>
<td>Buried horizontal round plate Radius (a), depth (s/2)</td>
<td>(R = \frac{\rho}{8a} + \frac{\rho}{4\pi s} \left(1 - \frac{7}{12} \frac{a^2}{s^2} + \frac{1}{30} \frac{a^4}{s^4} \ldots \right))</td>
</tr>
<tr>
<td>Buried vertical round plate Radius (a), depth (s/2)</td>
<td>(R = \frac{\rho}{8a} + \frac{\rho}{4\pi s} \left(1 + \frac{7}{12} \frac{a^2}{s^2} - \frac{7}{30} \frac{a^4}{s^4} \ldots \right))</td>
</tr>
</tbody>
</table>