Grounding theory
and ground fault
protection schemes

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21.1 Protection of a domestic or an industrial single-phase system

21.1.1 Effects of current passing through a human body and the body’s tolerable limits

An electric current, rather than voltage, through a human body may cause shock and can damage vital organs of the body as follows:

1. It may cause muscular contraction, unconsciousness, fibrillation of the heart, respiratory nerve blockage and burning. These are all functions of body weight. The muscular contraction makes it difficult to release an energized object if held by the hand and can also make the breathing difficult. The heart, being the most vulnerable organ of a human body, is damaged most, mainly by ventricular fibrillation, which may result in an immediate arrest of the blood circulation (electrocution). In Table 21.1 we provide likely intensities of body currents when lasting for more than a heartbeat (nearly 60–300 ms or 3–15 cycles for a 50 Hz system).

2. It is generally seen that a human body can sustain a much higher current at a lightning or switching frequency (5 kHz or above) due to the extremely short duration of such surges (30 μs or less).

The current can pass through the heart, when the current passes through hand to hand, or through one hand and a foot. Current flowing between one foot to the other may not be considered dangerous, but may cause muscular contraction and pain. The subsequent body fall, if it occurs, may, however, be fatal as now the current can also flow through the hand involving the heart. Ground fault protection emphasizes keeping the fault current below the fibrillation threshold and for a period of less than a heartbeat, in the range of 60–300 ms. It has been established that the electric shock energy which a human body can endure, without damage has a relationship with the leakage current through the body and its duration, i.e.

\[ S_b = I_b \cdot t_b \]

or

\[ I_b = \frac{S_b}{\sqrt{t_b}} \] (21.1)

where

\( S_b = \) shock energy in watt-seconds (Ws)
\( I_b = \) r.m.s value of the leakage current through the body in Amperes (A)
\( t_b = \) duration of leakage current in seconds (s)

The energy, \( S_b \), for a 50 kg body is regarded safe at 0.0135 Ws and for a 70 kg body at 0.0246 Ws

\[ \therefore I_b (50 \text{ kg}) = \sqrt{\frac{0.0135}{t_b}} = 0.116 \] (21.2)

and

\[ I_b (70 \text{ kg}) = \sqrt{\frac{0.0246}{t_b}} = 0.157 \] (21.3)

Figure 21.1 as in IEC 60479-1 illustrates the various zones of ground leakage current versus duration of fault and its effect on a human body. For safe leakage current in terms of touch voltages as a function of time see Figure 22.12.

To enable the body sustain a high fault current it is essential that the fault interrupting device (relay or release) is quick responding. For domestic applications, it is recommended to be less than a heartbeat.

Note
Prevention from ground leakage as such is important, as it causes corrosion through electrolysis and may damage the insulation of wires due to ageing.

21.1.2 Use of ground leakage circuit breakers (GLCBs)*

It is likely that smaller installations, such as a domestic light or power distribution network, and single-phase industrial or light loads may not always meet the requirements, as discussed in Section 21.2, Table 21.2, due to the circuit’s own high impedance (other than the impedance of the ground conductors). It is therefore possible that the fuses, if provided for the short-circuit protection of the system, may be too large to detect a ground leakage. The ground leakage circuit breakers (GLCBs) usually called as residual current devices (RCDs) provide an effective solution to this problem and are easily available and extensively used. They are extremely sensitive to very feeble ground leakages, of the order of 10 mA or more, and trip the faulty circuit within a safe period on the smallest leakage current and provide effective protection to the human body. Figure 21.2(a) illustrates the tripping scheme for such a breaker and the principle of operation is

Table 21.1 Likely intensities of body currents when lasting for more than a heartbeat (≈ 60–300 ms)

<table>
<thead>
<tr>
<th>Sr. no.</th>
<th>Body current (mA)</th>
<th>At frequency (Hz)</th>
<th>Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>50–60</td>
<td>Lethal</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
<td>3–10 kHz</td>
<td>Tolerable (because of extremely short duration)</td>
</tr>
<tr>
<td>3</td>
<td>60–100</td>
<td>50–60</td>
<td>Fatal</td>
</tr>
<tr>
<td>4</td>
<td>16–60</td>
<td>50–60</td>
<td>Breathing may become difficult due to muscular contraction</td>
</tr>
<tr>
<td>5</td>
<td>10–16</td>
<td>50–60</td>
<td>It is the let-go current and makes it hard to release an energized object if held by hand</td>
</tr>
<tr>
<td>6</td>
<td>5–9</td>
<td>50–60</td>
<td>No dangerous effects</td>
</tr>
<tr>
<td>7</td>
<td>1–4</td>
<td>50–60</td>
<td>Threshold of sensation</td>
</tr>
</tbody>
</table>

*More commonly known as earth leakage circuit breakers (ELCBs), residual current circuit breakers (RCCBs) or residual current devices (RCDs). They operate on the principle of residual current.
discussed below. Normally four types of RCDs are in use, 10 mA, 30 mA, 100 mA and 300 mA (IEC 61008, 9). Figure 21.2(b) shows some views of RCDs.

The selection of RCDs depends on the type of application i.e. to protect a circuit, equipment or device. The 10 mA and 30 mA RCDs are to protect the human body from shocks and electrocution, while the others are to protect the circuit from fire risk. Normally the 300 mA RCD is used as the incomer and 30 mA as the outgoing for the individual feeding circuits.

The RCDs can be with or without over-current (o/c) protection. Most household appliances and office equipment are fixed type loads and may not call for o/c protection. But loads using electric motors like, mixers, grinders and washers may sometimes be overloaded due to excessive load or under-voltage and may call for o/c protection too. To meet this requirement RCDs with built-in o/c protection are also available and called RCBOs (residual current breakers with o/c protection).

**Discrimination**

To ensure that residual ground fault current in a sub-circuit causes the RCD of this circuit only to trip and not the upstream RCD, the tripping time of the upstream RCD should be higher than the downstream RCD. As a rule of thumb tripping time of the upstream RCD should be minimum 3 times the tripping time of the downstream RCD.

**Electromagnetic Compatibility (EMC)**

Since these devices are highly sensitive, they are also susceptible to EM interferences in the vicinity. It is imperative that they are made immune to such effects and are EM compatible to avoid nuisance tripping (IEC 61543). Many manufacturers provide a high frequency L-C filter circuit as an EM suppressor to make it immune from tripping due to spurious voltages and currents caused by lightning, transferred and switching surges and presence

![Figure 21.1 Effects of current leakage through a human body](image)

<table>
<thead>
<tr>
<th>Zone</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Usually no reaction</td>
</tr>
<tr>
<td>2</td>
<td>Usually no dangerous physiological effect</td>
</tr>
<tr>
<td>3</td>
<td>Usually no danger of heart failure (ventricular fibrillation)</td>
</tr>
<tr>
<td>4</td>
<td>Probability of heart failure up to 50%</td>
</tr>
<tr>
<td>5</td>
<td>Probability of heart failure more than 50%</td>
</tr>
</tbody>
</table>

![Figure 21.2(a) Schematic drawing of an RCD](image)

- $i_t$ – Leakage current through the appliance. But for simplicity the whole current is considered through the body only
- $i_i$ – Leakage current through the human body
- $Z_g$ – Ground fault loop impedance
- Test button to check periodically the operation of the ELCB

Effects of a.c. currents (50 Hz) on a person at least 50 kg in weight.
Grounding theory and ground fault protection schemes

Surges can cause electrostatic discharges giving rise to high frequency leakage currents. Also due to switching of inductive and capacitive loads causing heavy in-rush currents and phase-to-phase faults etc. See Sections 6.13 and 17.7 for sources and causes of overvoltages and surges.

Usually a RCD may feed a number of load points in the same circuit such as clubbing of a few light and power points. It is possible that the RCD may trip even under healthy condition due to spurious currents. For instance devices like computers, printers and office workstations having built-in EM suppressors through L-C filter circuits may have constant ground leakage currents via the filter circuits. It may cause nuisance tripping even on small line disturbances in the same circuit (switching of devices causing surges and harmonics). Similarly fluorescent tubes having electronic ballasts (reactors) generate high frequency currents during a switching operation and that may find their path to the ground through their built-in capacitors to cause nuisance tripping. In such cases loads may be divided into more circuits. Experience of the project engineer is the best guide. As a rule of thumb when leakage ground current of a device (computer or fluorescent tube) is known from its manufacturer, the total leakage current of all such devices connected on one circuit may be kept around one third of RCD threshold value. Like for a 30 mA RCD it may be kept at about 10 mA and the appropriate number of devices in a circuit be determined accordingly.

To account for line disturbances and high frequency currents some manufacturers adjust their EM L-C filters to suit a particular application such as x-ray devices, circuits associated with frequency converters or variable speed drives (PWM inverters) etc. User may contact the manufacturer for the right choice of RCDs. For more details see reference 7 and 8 in the Further Reading.

\[
Z_g = \frac{240}{3a} \quad \text{or} \quad 1.5b \Omega
\]

Table 21.2 Maximum impedances of ground loop, when protected by overcurrent releases of circuit breakers or fuses

<table>
<thead>
<tr>
<th>Current rating of circuit fuse</th>
<th>Overcurrent of the circuit breaker MCCB or ACB</th>
<th>Maximum desirable impedance of ground fault loop on a 240 V circuit (415/\sqrt{3})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amp</td>
<td>Amp</td>
<td>[ Z_g = \frac{240}{3a} \text{ or } 1.5b \Omega ]</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>16</td>
</tr>
<tr>
<td>10</td>
<td>20</td>
<td>8</td>
</tr>
<tr>
<td>15</td>
<td>30</td>
<td>5.3</td>
</tr>
<tr>
<td>20</td>
<td>40</td>
<td>4</td>
</tr>
<tr>
<td>30</td>
<td>60</td>
<td>2.7</td>
</tr>
<tr>
<td>40</td>
<td>80</td>
<td>2</td>
</tr>
<tr>
<td>60</td>
<td>120</td>
<td>1.33</td>
</tr>
<tr>
<td>80</td>
<td>160</td>
<td>1</td>
</tr>
<tr>
<td>100</td>
<td>200</td>
<td>0.8</td>
</tr>
<tr>
<td>125</td>
<td>250</td>
<td>0.64</td>
</tr>
<tr>
<td>150</td>
<td>300</td>
<td>0.53</td>
</tr>
<tr>
<td>175</td>
<td>350</td>
<td>0.46</td>
</tr>
<tr>
<td>200</td>
<td>400</td>
<td>0.4</td>
</tr>
<tr>
<td>300</td>
<td>600</td>
<td>0.27</td>
</tr>
<tr>
<td>400 etc.</td>
<td>800 etc.</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Figure 21.2(b) Two-pole and four-pole ground leakage circuit breakers (RCDs) and layout of a DB
Influence of SPDs

The ground fault severity may mitigate when an SPD (Section 17.13) is provided upstream of an installation for surge protection. But, when the SPD is provided downstream to an RCD it is possible that while SPD is discharging the arriving surge to the ground, the RCD may detect the ground discharge current and trip when it is not wanted. In such cases special types of RCDs may be employed that play immune to certain level of ground discharge currents. To meet this, RCDs are designed with the following immunity levels,

- General type RCDs with a minimum surge immunity of 200 A with 0.5 μs/100 kHz wave.
- S type RCDs with minimum surge immunity of 3kA with an 8/20 μs wave.

It is advisable to use SPDs upstream of RCDs or select RCDs as noted.

Other applications

Ground leakage device can also be built into or associated with a circuit breaker (MCCB or ACB) to detect feeble ground leakages due to bearing currents, electrostatic discharges or insulation faults of a motor or generator, or insulation fault in cables.

Using the principle of RCD some manufacturers have developed the device into a ground leakage relay that can be incorporated in a protective scheme through a breaker in all current ranges. Using a filter circuit they are made immune to spurious voltages and currents to avoid nuisance trippings, as noted already.

21.1.3 Principle of operation of a ground leakage circuit breaker (application of a core-balanced CT)

Refer to Figure 21.2(a) showing a single-phase circuit breaker having a thermal over-current and a magnetic short-circuit element, OCR. A core-balanced transformer is arranged in the circuit as shown. When the system is healthy, the current through the phase, \( I_R \), and the neutral, \( I_n \), will be equal and the magnetic effect of the load current on the primary windings, \( P_1 \) and \( P_2 \), will be almost zero. In the event of a ground leakage, \( I_f \), this balance is disturbed and some of the leakage current will also flow through one of the primary windings of this core-balanced CT, as shown in the circuit. This will cause a magnetic flux in the core, inducing a voltage in the secondary winding \( S \). In the circuit shown, it feeds a rectifier circuit provided on the secondary side of the circuit. This unit facilitates a direct current flow through the leakage trip coil, which trips the breaker. These breakers are extremely fast operating on fault (operating time may be less than 5 ms), and have a low let-through energy. Refer to \( F^2 - t \) characteristics (Figure 21.1). The ground fault current will also be comprised of a current through the appliance, \( I_A \) (Figure 21.2(a)). But since the basic purpose of this device is to protect the human body from an electric shock or electrocution, we have considered the leakage current, \( I_f \), through the body alone to be safer. To ensure total safety, the device should be able to detect this leakage, assuming there was no ground current through the appliance. When the device will be able to do so, the circuit in any case will be protected.

21.2 Ground fault on an LV system

21.2.1 System protected through over-current releases and HRC fuses

The value of ground loop impedance is always predetermined, depending upon the system requirement and the type of protection available to the system, its accuracy to detect the fault and time to operate. For systems protected through over-current releases or HRC fuses only, the ground loop must have a comparatively low impedance. It will allow a high ground fault current through the faulty circuit, sufficient to trip the over-current-cum-short-circuit releases of the breaker if the circuit is protected through such releases of the breaker or blow out the HRC fuses, if the circuit is protected through HRC fuses. Such a requirement is more desirable for higher rating systems, where discrimination between a healthy and a faulty condition by such devices may be difficult. Medium-rating systems may cause a relatively much higher fault current and be automatically protected, as the normal ground fault current would be sufficient to trip the short-circuit releases or blow out the HRC fuses.

The rule of thumb to determine the ground loop impedance is to consider the ground fault current as one and a half times that of the over-current setting of the circuit breaker for breaker-controlled systems (a fault condition for a breaker) or three times the rating of the fuses, for fuse-protected systems (an over-current condition for the fuses). Based on this rule, Table 21.2 suggests the optimum values of ground loop impedances for circuits of different current ratings for an LV system. At these values of currents, the over-current releases will trip in about 130–370 seconds. Refer to \( \sqrt{F} - t \) characteristic curves of such releases as shown in Figure 21.3. The HRC fuses will blow out in about 40/60 seconds. Refer to \( F^2 - t \) characteristic curves of fuses, as shown in Figure 21.4.

Notes

1. Ground fault protection through over-current releases or HRC fuses is not a reliable practice. It requires a very low ground circuit resistance to maintain a high ground fault current, which may not be possible in the long run. As a consequence, in certain cases the system may remain intact on a ground fault and damage the healthy circuits. It is therefore good practice to provide a ground leakage MCB, ground leakage MCCB or a conventional MCCB with a CBCT and a ground fault leakage relay for low-rating incoming feeders.

For domestic light and power distribution this practice is common. Modern industrial installations can now adopt a fuse-free system and use MCCBs and provide a more sensitive ground leakage protection scheme for more safety and reliability.

2. For clarity one may note that single-phase loads or unevenly distributed loads on a balanced three-phase system do not lead to a faulty condition as a result of unbalanced currents. The single-phase load currents will always have the return path through the neutral and not the ground. The current through the ground circuit will flow only when there is a ground fault and the circuit completes through the ground loop. See Figures 21.4(a) and (b).
21.2.2 System protected through relays

A system protected through a separate ground fault relay will require a different concept from that discussed above. A relay can be

- Electro-magnetic (being quickly outdated)
- Static, based on discrete ICs or
- Solid-state microprocessor based.

The relay is very sensitive and quick responding and can reliably actuate at low leakage currents (0.1 A or less). It is therefore operated through the secondary of a CT (1 or 5 A), provided in the ground circuit. Figures 21.5(a) and (b) show different methods of CT connections for a ground fault protection. The fault current in this case need not be very high. It should rather be limited to a low value, to limit damage to the equipment. As a rule of thumb it may be up to the rated current of the feeding transformer, or the rating of the incoming feeder, or twice the rating of the largest outgoing feeder, depending upon the circuit to be protected.

The most common practice, however, is to limit the ground fault current to only half the rated current of the system, or the circuit that is being protected. This is also in line with the universal practice of having the neutral of half the size that of the phases. The neutral is normally grounded to form a complete circuit through the ground conductor in the event of a ground fault. Refer to

Figure 21.3 $I^2-t$ characteristics of an OCR (Figure 12.13(a), reproduced for illustration) (Courtesy: L & T)

Figure 21.4 Figure 12.19 reproduced for illustration (Courtesy: Siemens)
more single-phase light or power loads, a higher setting would be necessary, depending upon the likely single-phase loads. This is to avoid false tripping on a healthy system, as all the out-of-balance current will flow through the neutral only.

The theory of operation of such a protection scheme is based on the principle that in a balanced circuit the phasor sum of currents in the three healthy phases is zero, as illustrated in Figure 21.7, and the current through the grounded neutral is zero. In the event of a ground fault, i.e. when one of the phases becomes grounded, this balance is upset and the out-of-balance current flows through the grounded neutral. A healthy three-phase circuit, however, does not necessarily mean that each current phasor $R$, $Y$ or $B$ individually is equal in magnitude and phase. Even if it has unbalanced currents in the three phases (which is a likely situation in a three-phase system, see also Section 12.2(v)), it will not cause a current to flow through the ground circuit, as illustrated in Figure 21.4(a). The current through the ground circuit will flow only when any one or more of the phases has a ground fault and forms a complete circuit through the ground loop conductor, as illustrated in Figure 21.4(b), and disturbs the balance of the system. Similarly, on a single phasing, although the balance is upset, there is no current through the ground circuit and this scheme would not detect a single phasing.

21.3 Ground fault protection in hazardous areas

These are highly sensitive areas and a little higher level of a ground fault current can be catastrophic. It is therefore mandatory at such locations to keep their ground leakage current (rather than the ground fault currents) low by maintaining a certain level of ground loop impedance and then be able to detect and isolate these currents promptly.
The leakage current at hazardous locations such as refineries, petrochemical plants and mines should not exceed 15% of the rated current of the circuit or 5 A, whichever is greater. Table 21.3 indicates the maximum permissible ground leakage currents for such areas at 15% of the rated current and the recommended maximum ground loop impedances.

The use of core-balanced CTs is quite common for such applications. They are specially designed to detect the ground leakage current of a circuit. This ground leakage is then used to trip the faulty circuit through a ground fault relay, wired at the secondary of such CTs, as shown in Figure 21.8.

The theory of operation of a ground leakage circuit breaker (GLCB) is also the same as the combination of a core-balanced CT and a ground leakage relay. For industrial application, use of a core-balanced CT with a ground leakage relay and for domestic application use of a GLCB is more common.

### 21.4 Ground fault protection of MV and HV systems

Now the situation is different from that in LV due to high phase to ground voltage $V_g$. It is now capable of causing high ground fault currents. Too large a ground fault current is not desirable for reasons of safety to personnel from high ground touch voltages. To contain
these currents in such a system the normal practice is to increase the ground impedance by inserting some impedance into the ground circuit through the grounded neutral as discussed in Section 20.4.2. These systems are protected through relays for different protective schemes and not through fuses or over-current releases as for LV. Since a relay is much more sensitive and is quicker to respond, even a small ground leakage current will be enough to actuate it and isolate the faulty circuit. The ground loop impedance in these systems are therefore kept much higher than on an LV system. Moreover, since modern relays are able to sense a current as low as 0.1 A or less, the universal practice is to have as large a ground loop impedance as possible to limit the ground leakage current, such that under no conditions will the touch and step voltages exceed the permissible tolerable levels as defined in Section 22.9.

In Chapter 20 we have analyzed the behaviour and characteristics of a system when grounded or left isolated. The ground fault factor (GFF) plays a very significant role in the selection of insulation level (BIL) and its coordination with the different equipment connected on the system. The application of a particular method of grounding would thus depend upon

- The ground protection scheme envisaged to decide on the magnitude of the ground fault current
- Criticality of the supply system, e.g. whether an immediate trip on fault is permissible
- Insulation level of the main equipment connected in the system
- Where a neutral is not available (case of a three phase three wire system) an inter-connected transformer is used to provide an artificial neutral as discussed in Section 20.9.

The grounding of a generator, for instance, which may be designed for 6.6, 11, 15 or 21 kV, and all other equipment connected in this system may be solidly grounded to have the least GFF and hence, add no extra cost to the machine for a higher level of insulation or a larger size of machine. But at such voltages the ground fault current will be excessive as noted in Section 16.13.2 to cause an extra burden to the windings of the machine or in the selection of protective devices. It is, however, noted that a few application engineers may prefer an isolated neutral system at certain installations where continuity of supply is mandatory, even on a ground fault, until an alternative arrangement is made. Examples are auxiliary drives in a power generating unit or essential drives in a process plant, essential public services railways, airports, community centres etc. At such installations, it is imperative to ensure that the generator and all the equipment connected in the system are designed for the higher GFF and a larger size or greater cost of the machines are immaterial. But the occurrence of another ground fault before clearing the first will lead to fatality and cause total damage of the faulty equipment. The ground current can now find its way through the earlier ground fault and cannot be prevented, as there is no protection available. Isolated systems are therefore generally not recommended. Instead, for such requirements, a resonance grounding system may be adopted, limiting the ground fault current to a desired low value to protect the machine from heavy fault currents and prevent the system from tripping on a ground fault. Such a system is more prevalent in overhead transmission or long distribution networks to save the whole system from an outage on a ground fault. The terminal equipment and the windings of all the machines may now be designed for a voltage corresponding to the relevant GFF.

The magnitude of the ground fault current is a matter of system design and will largely depend upon the system voltage and the ground loop impedance. The required ground impedance may be determined on the following lines, if

\[
Z_g = \frac{240}{1.5 \times I_g}
\]

Table 21.3 Maximum impedances of ground loop for protection by ground leakage relays in hazardous areas

<table>
<thead>
<tr>
<th>Current rating of circuit</th>
<th>Maximum permissible ground leakage current (I_g)</th>
<th>Recommended maximum ground loop impedance on a 240 V phase to ground circuit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amp</td>
<td>Amp</td>
<td>(Z_g)</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>32</td>
</tr>
<tr>
<td>10</td>
<td>5</td>
<td>32</td>
</tr>
<tr>
<td>15</td>
<td>5</td>
<td>32</td>
</tr>
<tr>
<td>20</td>
<td>5</td>
<td>32</td>
</tr>
<tr>
<td>30</td>
<td>5</td>
<td>32</td>
</tr>
<tr>
<td>40</td>
<td>6</td>
<td>26.7</td>
</tr>
<tr>
<td>60</td>
<td>9</td>
<td>17.8</td>
</tr>
<tr>
<td>80</td>
<td>12</td>
<td>13.3</td>
</tr>
<tr>
<td>100</td>
<td>15</td>
<td>10.7</td>
</tr>
<tr>
<td>125</td>
<td>18.7</td>
<td>8.6</td>
</tr>
<tr>
<td>150</td>
<td>22.5</td>
<td>7.1</td>
</tr>
<tr>
<td>175</td>
<td>26.2</td>
<td>6.1</td>
</tr>
<tr>
<td>200</td>
<td>30</td>
<td>5.3</td>
</tr>
<tr>
<td>300</td>
<td>45</td>
<td>3.5</td>
</tr>
<tr>
<td>400</td>
<td>60</td>
<td>2.7</td>
</tr>
</tbody>
</table>

Notes

a Highly sensitive ground leakage relays can sense a current as low as 0.1 A and less and at a much higher ground loop impedance.
b Calculated to allow at least 150% of the maximum permissible current to be on the safe side. For example, for 15A maximum ground leakage current, maximum impedance at 240 V

\[
Z_g = \frac{240}{1.5 \times 15} = 10.7 \Omega
\]

Figure 21.8 Schematic of a core-balanced CT (CBCT)
kVA = rated capacity of the supply source, which can be a generator or a transformer

\[ V_\ell = \text{system rated line voltage in volts} \]

\[ I_\ell = \text{system rated full-load line current in amperes} \]

\[ Z_g = \text{impedance of the grounded neutral circuit in ohms} \]

\[ I_g = \text{required level of the ground fault current in amperes} \]

Then

\[ Z_g = \frac{V_\ell}{\sqrt{3} \cdot I_g} \Omega \]

and

\[ I_\ell = \frac{1000 \cdot \text{kVA}}{\sqrt{3} \cdot V_\ell} \text{ Amp} \]

\( I_g \) is generally defined in terms of \( I_\ell \), such as 10–40% or 20–80% of \( I_\ell \), depending upon the protection scheme. If \( I_g \) is, say, \( n \) in units of \( I_\ell \) then

\[ Z_g = \frac{V_\ell \cdot \sqrt{3} \cdot V_\ell}{\sqrt{3} \cdot n \cdot 1000 \cdot \text{kVA}} \]

or

\[ Z_g = \frac{V_\ell^2}{n \cdot 1000 \cdot \text{kVA}} \Omega \quad (21.4) \]

From this equation one can determine the required value of neutral circuit impedance for a particular level of ground fault current. The external impedance will be \( Z_g \), less the ground impedance. In HV systems one can also determine the likely value of a ground inductor coil to achieve a near-resonance condition, to eliminate the arcing grounds, on the one hand, and facilitate a strike-free extinction of an arc by the interrupting device, on the other.

**Example 21.1**

For a 1600 kVA, 11/0.415 kV transformer, considering the LV side:

\[ Z_g = \frac{(0.415)^2 \times 1000^2}{\pi \times 1000 \times 1600} \Omega \]

For an industrial power distribution network, if the setting of the protection relay is considered to be 20% of \( I_\ell \), then

\[ Z_g = \frac{(0.415)^2 \times 1000^2}{0.2 \times 1000 \times 1600} \Omega \]

\[ = 0.54 \Omega \]

The natural zero phase sequence inductive reactance of the grounded neutral may be considered to be too small compared to this and ignored for ease of calculations. Thus the resistance \( R_g \) of the grounded neutral circuit may be considered as its impedance, i.e.

\[ l_g = \frac{0.415 \times 1000}{\sqrt{3} \times 0.54} \]

\[ = 444 \text{ Amps} \]

The impedance calculated thus will form the basis of determining the adequacy of the grounding stations provided. Probably, for such a low value of grounded neutral impedance the grounding stations may have to be more elaborate and greater in numbers (arranged in parallel). This is to ensure that at no stage will the impedance of the system increase beyond 0.54 \( \Omega \) (inclusive of the impedance of the ground). Otherwise it will render the protective scheme ineffective and allow the ground fault to persist.

The above is the case for an LV system. For an HV system, the criterion is thus the minimum exciting current required and the ground potential difference to below a dangerous level at any point on the ground circuit. The impedance of the ground circuit in such cases may be increased through a resistance or an inductor coil.

### 21.4.1 Ground fault protection of EHV systems

Protection of EHV and power generating stations calls for special considerations due to very high ground voltages and is dealt with separately in Section II, Chapter 22.

### 21.4.2 Ground fault protection of generators

This subject is dealt with in Section 16.13.2.

### 21.4.3 Ground fault protection of electronic circuits

Isolated or clean ground system is necessary for electronic circuits and serial data transmission to comply with EMC/EMI requirements. This subject is dealt with in Section 6.13.3.

### 21.5 Core-balanced current transformers (CBCTs)

These are generally employed to detect small amounts of ground leakage currents, such as in mines and other sensitive installations. They are also used to protect sensitive equipment against small ground leakages. Installations having isolated neutral or using ground resistance or impedance, to limit the ground leakage currents, may also require this type of fault detection.

A core-balanced CT is in a toroidal (circular) or rectangular form, like a conventional protection CT, except that it is designed, with a large core opening to accommodate all the \( 3-, 3 \frac{1}{2} \) or 4-core feeder cables passing through it (Figure 21.8). The basic difference between this and conventional protection CTs is the low unbalance or leakage current at which a CBCT operates. A normal protection CT would operate between its rated and accuracy limit currents, as discussed in Section 15.6.5. The important design parameter in a CBCT is its magnetizing current at the relay operating voltage, rather than the class of accuracy and accuracy limit factor.

### 21.5.1 Design parameters for a CBCT

As these CTs have to detect small to extremely feeble ground leakage currents their operating region is required to be very low, near the 'ankle point' (almost 10% of the knee point voltage) on the magnetizing curve. The design criterion is thus the minimum exciting current required at the relay operating voltage (details available from the relay manufacturer) to actuate the relay.
Consider the equivalent tripping circuit diagram of the CBCT in Figure 21.9. If

\[ R_{CT} = \text{resistance of the CBCT} \]
\[ R_L = \text{resistance of the connecting leads} \]
\[ R_r = \text{resistance of the protective relay} \]
\[ I_{re} = \text{relay operating current} \]
\[ V_r = \text{relay operating voltage at the relay current setting} \]
\[ I_p = \text{primary unbalance or ground fault current} \]
\[ = I_R + I_Y + I_B \]
\[ n = \text{turns ratio of the CBCT} \]
\[ I_{n\ell} = \text{magnetizing (leakage) or no-load current of the CBCT at the relay operating voltage} V_r \]

Then \[ V_r = I_{n\ell}(R_{CT} + R_r + R_L) \]

The primary ground fault current \[ I_p = n(I_{re} + I_{n\ell}) \]

Since on a fault the power factor is normally low, \( I_{re} \) and \( I_{n\ell} \) may be considered almost in phase, when \[ I_p = n(I_{re} + I_{n\ell}) \]

Since \( V_r \) and \( I_{n\ell} \) are interdependent parameters the optimum design is achieved when \( I_{n\ell} \) at \( V_r \) is of the same magnitude as the relay operating current, i.e. \( I_{n\ell} = I_{re} \).

For high current systems, using more than one cable in parallel, the number of CBCTs will also be the same as the number of cables, as illustrated in Figure 21.10, in which case

\[ I_p = n[I_{re} + N \cdot I_{n\ell}] \text{ for } N \text{ number of CTs} \]

All such CBCTs have to be identical in turns ratio and magnetizing characteristics to avoid circulating currents among themselves. To order a CBCT the following information will be essential:

- Minimum primary ground leakage current
- Nominal CT ratio. This may be such that on the smallest ground fault the current on the secondary is sufficient to operate the relay. Normal \( I_p = 50, 100 \text{ and } 200 \text{ A} \).
- It is recommended to be such that \( V_r = 0.1 \times \text{knee point voltage of the CBCT} \)
- Relay setting
- CT secondary current, 1A or 5A
- Minimum excitation current required at the relay operating voltage
- Knee point voltage
- Number of cables in parallel
- Limiting dimensions and internal diameter (ID) of the CT. ID will depend upon the size of the cable.

21.5.2 Insulation level

Irrespective of the system voltage, a CBCT may be designed for an insulation level of only 660 V. The cable insulation of the HV conductor is sufficient to provide the required insulation between the conductor and the CBCT.

21.5.3 Mounting of CBCTs

The following is the correct procedure for the proper mounting of these CTs:

1. It is necessary to pass all the 3, 3 1/2 or 4 cores of the cable through the core of the CBCT to detect the

![Figure 21.9](image1)

Figure 21.9 Equivalent circuit of a CBCT protection circuit

![Figure 21.10](image2)

Figure 21.10 Methods to wire a protective circuit through CBCTs

(a) Separate CBCT for each cable.
(b) Separate protective circuit for each cable.* The relay contacts are wired in series for indication, alarm or trip circuit.
unbalance or the ground leakage in 3-core cables and only ground leakage in 3½- and 4-core cables. To explain this see Figures 21.11(a) and (b). A 3-core cable will detect an unbalance in the three phases, whether this is the result of unequal loading in the three phases or a ground fault. However, 3½- or 4-core cables will detect only a ground leakage as the amount of unbalance, when it occurs, will be offset by the flow of this unbalanced current through the return path of the neutral circuit. When using only 3-core cables, the load must be almost balanced otherwise it will send wrong signals or a higher setting of the relay will become essential to account for the out-of-balance currents due to the feeders’ unequal loading.

2 In armoured cables, armouring must be removed before passing the cable through the CBCT to avoid an induced e.m.f. through the armour and the corresponding magnetizing current which may affect the performance of the CT.

3 As such CTs are required to detect small out-of-balance currents, the connecting leads should be properly terminated and must be short to contain the lead resistance as far as possible.

4 For high-rating feeders using more than one cable, there must be one CBCT for each cable. Not more than one multi-core cable must pass through such CTs. The secondary of all such parallel CTs may, however, be connected in series, across the common relay (Figure 21.10(a)). All CBCTs being used in parallel and intended for the

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**Figure 21.11** Detecting the unbalance and the ground leakage currents through a CBCT
same feeder must have identical magnetizing characteristics and calibration in order to relay identical signals. Even then small variations in the output may occur which could affect the sensitivity of a circuit using more than one CBCT. If such a reduction in sensitivity is considered detrimental to the protection of the system or the equipment, it is advisable to use a separate relay with each CBCT (Figure 21.10(b)). For a common indication, alarm or trip, the relays’ trip contacts may be wired in series.

When using only single-core cables, the same method should be adopted, as discussed above. Groups may be made of 3, 3 1/2 or 4 cores (R, Y, B or R, Y, B and N) of single-core cables, and one CBCT used in circular or rectangular form, whichever is more convenient, for each group.

Note

In an HV system it is recommended that each circuit be protected separately for a ground leakage as far as possible. This is to localize the effect of the fault and to trip only the feeder of the faulty circuit. A common protection in the incoming is not advisable, except for cost considerations, which also will be nominal for such a protection scheme compared to the cost of the main equipment. Otherwise a ground leakage in the downstream may trip the whole system, which may not be desirable. It is also possible that at the downstream, the ground leakage is very feeble due to high ground loop impedance and may not be sufficient to be detected by the common ground leakage protection provided at the incoming. It is also possible that the setting of the relay is not so low as to detect this. Thus to provide a reliable ground leakage protection for each individual circuit will be worthwhile without any serious cost implications. Such a philosophy, however, will not hold good for a system which is protected only through its incoming feeder and all the outgoing feeders are merely isolators. In this case the ground leakage protection will have to be centralized for the entire system and provided in the incoming feeder only.

21.6 Ground fault (G/F) protection schemes

A scheme for a ground fault protection will depend upon the type of system and its grounding conditions, i.e. whether the system is three-phase three-wire or three-phase four-wire. A three-wire system will require an artificial grounding while for a four-wire system the type of grounding must be known, i.e. whether it is effectively (solidly) grounded or non-effectively (impedance) grounded.

Grounding protection will depend upon the measurement of the residual quantities (V₀ or I₀) that will appear across the ground circuit in the event of a ground fault. As discussed above, in a balanced three-phase system the voltage and current phasors are 120° apart and add up to zero in the neutral circuit. In the event of an unequally distributed system or a ground fault, this balance is disturbed and the out-of-balance quantities appear across the neutral or the ground circuit respectively. The current through the ground circuit will flow only when there is a ground fault, the fault current completing its circuit through the ground path. The normal unbalanced current, due to unevenly distributed single-phase loads or unequal loading on the three phases, will flow only through the neutral circuit.

In a phase-to-phase fault, however, the system will be composed of two balanced systems, one with positive sequence and the other with negative sequence components. The phasors of these two systems individually will add up to zero, and once again, as in the above case, there will be no residual quantities through the neutral or the ground circuit, except for the transient and spillover quantities.

The ground fault current may be detected through three or four CTs, one in each phase and the fourth in the neutral circuit (Figures 21.5(a) and (b)). Through the neutral to discriminate the fault, as discussed later.

Note

In a G/F the three CTs will also measure the unbalanced load current, if any, in addition to G/F current. For an appropriate setting of the relay, therefore, it will be essential that the likely system unbalanced current be measured and the relay set in excess of this to detect a G/F. For systems feeding single-phase or unbalanced loads, prone to carrying high and widely fluctuating unbalanced neutral currents, it may be difficult to determine the likely amount of unbalance and provide a suitable setting for the G/F relay. In such cases use of four CTs or core balanced CTs would be more appropriate.

Below we discuss the more widely adopted practices to detect a ground fault, i.e.:
- Protection through a single CT
- Restricted G/F protection
- Unrestricted G/F protection
- Directional G/F protection and
- Differential G/F protection (high impedance differential protection is discussed in Section 15.6.6(1)).

21.6.1 Protection through a single CT

This is the simplest method to protect an equipment against a G/F (Figure 21.12). It can, however, be applied only at the source, which is a generator or a transformer, provided that the source has no other parallel grounding paths in the vicinity. This is to avoid sharing of the fault current and false or inadequate detection of the fault current by the relay. This scheme is therefore more functional at the main generating source, such as at the generator or the generator transformer, having a low impedance solidly grounded neutral.

![Figure 21.12 Ground fault protection through a single CT](image-url)
For any other equipment or system, such as shown in Figure 21.13, the fault current may be shared by the various grounding stations in the vicinity and the relay may not sense the real extent of the fault, even when the system is effectively grounded. A part of the fault current, may now flow through the other nearby grounding stations. Moreover, for a fault on another feeder spill currents may also pass through such relays and trip them (unwanted) when the relays are highly sensitive or have a low setting. Such a scheme will also not discriminate when required, and hence will have limitations in its application. Nevertheless, it is common practice to apply single CT protection through neutral circuits of the grounded transformers anywhere in the system, generation, transmission or distribution. Multiple groundings may cause problems, but this is taken into account at the design/planning stage.

### 21.6.2 Restricted ground fault protection

When it becomes essential to discriminate between a fault within the circuit to be protected from one outside the circuit, this scheme may be adopted. While doing so, it must be ensured that adequate ground fault protection is available to the remaining feeders, if connected on the same system.

**For a three-phase three-wire system (generally HV systems)**

The scheme for a three-phase three-wire artificially grounded system will require four CTs, identical in design parameters, turn ratio, error and magnetizing characteristics. Otherwise spill currents may occur sometimes sufficient to operate inadvertently a low-setting or highly sensitive ground fault relay. The fourth CT through the ground circuit is used with the same polarity as the three CTs of the phases. Then only would the residual current of the phase CTs fall 180° apart from that of the ground circuit CT. Such an arrangement will provide the desired discrimination, to detect the fault occurring within the protected zone. Figures 21.14(a) and (b) illustrate this discrimination through the use of the fourth CT. The residual current of the three-line CT, in a healthy condition, in the event of an unbalance in the system, is taken care of by raising the setting of the relay to account for the unbalance, as in a core-balanced CT. The fault current through the relay will flow only on a G/F occurring within the restricted zone as illustrated in Figure 21.14(a). For faults occurring outside the restricted zone, as shown in Figure 21.14(b), the fault current through the ground circuit CT will be offset by the residual current of the three-phase CTs and thus the relay will remain immune to such a fault.

![Figure 21.13](image1.png) Limitation in using a single CT for a G/F protection when the equipment has more than one parallel ground path

![Figure 21.14](image2.png) Scheme for a three-phase three-wire restricted ground fault protection for an HV system

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*Induced residual fault current through the phase CTs, $(i_t = i_r + i_y + i_b + i_g)$ is equal and falls opposite to the residual current $i$ through the ground circuit CT.

$(i_r + i_y + i_b)$ is considered zero under healthy condition.

For small unbalances the relay is set a little higher.

(b) The relay stays immune to a fault occurring outside the protected zone.
For a three-phase four-wire system (generally LV systems)

A three-phase three-wire system is generally a balanced system and has negligible unbalanced residual current through the three-phase CTs. The relay for a ground fault protection can thus be set low. The scheme discussed above is thus satisfactory for a G/F. But in three-phase four-wire LV systems, which are generally unbalanced, the above scheme poses a limitation as there may now be a substantial residual unbalanced current through the relay. For G/F protection, therefore, such a scheme will require a higher setting of the relay to avoid a trip in a healthy condition. It is possible that this setting may become sufficiently high, for highly unbalanced systems to detect an actual G/F and defeat the purpose of G/F protection. Such a situation can be averted by providing a fifth CT in the neutral circuit as shown in Figure 21.15, which obviously will have its excitation current direction opposite to the residual current of the three-phase CTs. Hence, it will offset the same, and the relay can be set low. It is therefore mandatory to use five CTs in LV systems for adequate restricted G/F protection.

Application

1 A restricted ground fault is recommended for equipment that is grounded, irrespective of its method of grounding. Unless the protection is restricted, the equipment may remain unprotected. Generally, it is an equipment protection scheme and is ideal for the protection of a generator, transformer and all similar equipment or circuits, requiring individual protection. Figure 21.16 illustrates the operation of the relay when the fault occurs within the protected zone. The scheme will prevent isolation of the equipment for faults occurring outside the restricted zone (Figure 21.17).

2 A delta-connected or an ungrounded star-connected winding should also be protected through a restricted ground fault scheme, otherwise it will remain unprotected. There is no zero sequence or residual current in such a winding to detect a ground fault. The arrangement will be similar to that for directional protection of a delta side of a transformer, as discussed later, with the use of a grounding transformer (Figures 21.18 and 21.19).

21.6.3 Unrestricted ground fault protection

The CT provided in the ground circuit is now removed and the same scheme becomes suitable for an unrestricted
Grounding theory and ground fault protection schemes

21.6.4 Directional ground fault protection

In the previous section we discussed non-directional protection of an equipment or a system. But for systems with more than one source of supply in parallel, such as a power grid, receiving power from more than one source (Figure 13.21) or an industrial load, having two or more sources of supply, one of them being a captive power source, it is possible that a fault on one may be fed by the other sources and may isolate even a healthy system, rendering the whole system unstable. Such a situation requires discrimination of a ground fault and can be prevented by the application of directional G/F protection. The primary function of a directional G/F protection is thus discrimination.

In the above situation, even an overspeeding motor on a fault elsewhere would feed back the supply source and require such protection. The protective scheme isolates the faulty source from being fed by the healthy sources. Figure 21.18 illustrates a simple power circuit provided with a directional G/F relay. In the event of a fault in system B, source B alone would isolate. Source A would not feed the fault as relay $b'$ would trip the breaker $B'$ and eliminate $I_{ga}$. The relays are necessarily set at lower settings and at lower tripping times than the non-directional GFR to isolate the faulty feeder quickly than to wait for the trip by the non-directional relay. This is to avoid a trip of the non-directional relay 'a' on system A.

A directional G/F relay basically is a power-measuring device, and is operated by the residual voltage of the system in conjunction with the residual current detected by the three CTs used for non-directional protection, as shown in Figure 21.19. To provide directional protection, therefore, a residual VT is also essential, in addition to the three residual CTs. The voltage phasor is used as a reference to establish the relative displacement of the fault current. In healthy conditions, i.e. when the current flows in the right G/F or a combined G/F and phase fault protections. It is true for a three-phase three-wire or a three-phase four-wire system. This scheme may also be arranged for a combined O/C and G/F protections as illustrated in Figures 21.5(a) and 21.5(b).

Application

This is the most common scheme in normal use for any power system with more than one feeder, connected to a common bus, such as for distribution and sub-distribution power networks, having a number of load points, controlled through a main incoming feeder. In a switchgear assembly, for instance, common protection may be provided at the incoming for a ground fault or combined O/C and G/F protections as discussed above. In such cases, a restricted G/F protection may not be appropriate or required, as the protection now needed is system ground protection, rather than individual equipment ground protection. The incomer must operate whenever a ground fault occurs at any point on the system. Moreover, for an LV system, where it may not be desirable or possible to provide individual ground protection to each feeder, such a scheme is adopted extensively.

Note

- $a$, $b$ – are non-directional GFRs
- $a'$, $b'$ – are directional GFRs
- Reverse direction current, $I_{ga}$ through relay $b'$ would trip breaker $B'$ and reduce $I_{ga}$ to zero.

Figure 21.18 System using directional ground fault relays

Figure 21.19 A typical scheme for a directional G/F protection relay
direction, $V_e = 0$ (refer to Section 15.4.3 for details), and the relay remains inoperative. The relay operates only when the current flows in the reverse direction.

**Note**
This relay may be used only under unrestricted fault conditions, with three CTs as shown. If the scheme is used under a restricted fault condition, with the fourth CT in the neutral, the directional relay will remain immune to any fault occurring outside the zone of the three CTs, as the fault current through the fourth CT will offset the residual current, detected by the three CTs (Section 21.6.3), rendering the whole scheme non-functional.

**Current polarization**
Voltage polarization depends upon the location of the relay and the location of the fault. It is possible that the residual voltage, at a particular location in the system, is not sufficient to actuate the voltage coil of the directional G/F relay. In such an event, current polarization is used to supplement voltage polarization. Current polarization is possible, provided that a star point is created on the system, even through a power transformer, if such a transformer is available in the same circuit, Figure 21.20. Else a grounding transformer may be provided as illustrated in Figure 21.21, and grounded neutral utilised, to provide the required residual current polarization, to actuate the ground fault relay.

**Note**
The two currents, residual and polarizing, are capable of operating the relay.

**21.6.5 Current setting of a ground fault relay**
1. Selection of CTs for ground fault protection particularly needs more careful consideration of the fault conditions and impedance of the ground circuit, in addition to the location of the CTs. This is due to a rather low setting of the G/F relay, 10–40% or 20–80% of the full load current or even lower, as in mines and other sensitive locations. Too low a setting may even trip a healthy system due to ground capacitance leakage currents (more so in HV circuits) or unbalanced currents through the neutral (more on LV circuits). In core balanced CTs detecting small leakage currents, it is possible that during a phase-to-phase fault there may be transient spill currents through its residual circuit, which may operate the low-set and more sensitive G/F relay, which may not be desirable. To overcome this, the time setting of the relay may be suitably adjusted so that the over-load relay will operate faster than the G/F, or slightly higher setting for the relay may be provided or time delay in the trip circuit introduced.
2. In another situation, when the ground circuit has a higher impedance than designed it may be due to poor soil conditions, dry soil beds, rocky areas, poor grounding stations or inadequate maintenance of the grounding stations. In such conditions, the ground circuit may provide a lower fault current than envisaged. Sometimes an overhead conductor may snap due to strong winds and fall on dry metallic roads, hedges and shrubs causing extremely low leakage currents, creating a hazard to life and property. This may cause an arcing ground, leading to fire hazards. For all such locations and situations, very low current settings (of the order of 5% of $I_r$ or even lower) or leakage current detection through core-balanced CTs may be adopted.
3 For circuits protected by HRC fuses for short-circuit conditions, the G/F relay must be a back-up to the fuses, and trip first on a ground fault. In other words, \( I_{t}^{2} \) (relay) < \( I_{t}^{2} \) fuses.

### 21.7 Grounding systems

Based on the protection criteria and ground fault protection schemes discussed in the previous sections and Chapter 20 we now provide a brief reference to the various types of grounding methods in vogue worldwide for installations comprising homes, buildings, HV/LV substations, industries, switchyards, power generating stations and overhead lines. The grounding schemes may vary with system voltage, type of installation, equipment to be protected, criticality of installation and exposure to human-body. It may also vary from country to country depending on their own grounding codes and statutory regulations. Here we provide only broad guidelines on basic grounding systems as practised for various types of installations. For details on application one may refer to the Standards noted under Relevant Standards.

The basic criteria of grounding are,

- protection to a human body from electric shocks and limiting the touch voltage (body leakage current) within safe limits (Section 21.1)
- protection against fire hazards.
- power supply continuity on a ground fault when desired.
- minimizing EM effects.
- protection from lightning strikes, transferred surges, switching surges and over-voltages.

The nomenclatures used for grounding systems are defined as,

- T- Connection to ground
- I- Isolation from ground.
- N- Connecting to the neutral and neutral connected to the ground.

The following are the grounding systems in practice,

1 **TN** – The supply source (usually a transformer) neutral is grounded and all metallic frames of equipment and devices operating on the system are connected to the neutral. The neutral may be connected in the following possible ways,

   - During an MV fault a current will flow through the ground electrode of the LV neutral and a power frequency voltage will appear across the LV bodies of all equipment and devices connected on the system and the remote ground.
   - During an LV phase fault (insulation fault) also the voltage between phase and body of the faulty equipment or device may exceed the phase to neutral voltage (see Section 20.1). It is therefore not a recommended system at locations contaminated with volatile gas, liquid or vapour prone to fire hazards and explosions.
   - An insulation (equipment) fault is a short circuit fault and the faulty equipment or device must be isolated quickly using HRC fuses or interrupters, short circuit releases or relays when used.
   - The system is not allowed to be used for conductors less than 10 mm² of copper or 16 mm² of aluminium.
   - The touch voltage between any two ground points should be within safe limits as discussed in Section 21.1.
   - The use of this system must be reviewed for the third harmonic quantities that this grounding system is prone to receive from other systems in the vicinity. The system therefore has limitations for electronic devices and communication circuits when connected on the system.
   - Neutral in the vicinity of metallic structures and power cables may also become a potential source of EM disturbances.
   
   Note: To overcome the above shortcomings (over-voltages during a fault) the neutrals of supply source and the LV installation may be grounded separately.

2 **TN-S** (Figure 21.23)

   - Now the neutral and the protective conductors are separate and the equipment and devices are grounded
directly with the protective ground (PG). Use of separate protective ground and neutral conductor is necessary for small feeders with conductors less than 10 mm$^2$ of copper or 16 mm$^2$ of aluminium. It is a five-wire system and preferred where quick maintenance and repair backup is available.

- Neutral is not protected and may cause a risk to life and property.
- But it is a low fault current system, the risk to fire and danger to faulty device is low.
- An MV/LV disruptive break-down in the transformer or the source of supply may cause surge transference (Section 18.5.2) and over-voltages (Section 20.1) and raise the neutral voltage and pose similar risk.
- Since neutral is grounded this scheme also allows the third harmonics to flow into the system from other sources.
- The system is suitable for loads with low level of insulation like furnaces, electronic devices and computer networks. It is a preferred system for hospitals and practised by UK and Anglo-Saxon (British) countries.

3 TN–C–S (Figure 21.24) This system is a combination of TN–C and TN–S at one installation. The neutral and the protective ground conductors of TN–S, five wire system are separate from TN–C four wire system. The TN–S therefore cannot be placed in the upstream. The point at which PG conductor separates from neutral is generally at the origin of installation.

4 TT (Figure 21.25)

- It is the simplest system and practised by most countries. The transformer or the source of supply neutral and its frame are grounded. The metallic body of loads are also connected to the ground conductor. The system is prone to over-voltages and transference of surge voltages from the MV side and suitable protection may be installed across the grounded neutral (like a surge protective device). A simpler way to achieve this is to keep source equipment separate from LV neutral rather than be inter-connected. The ground fault current, Ig is limited by the ground impedance and the faulty device is protected through a RCD (Section 21.1.2).
- The risk to fire, explosion and damage to equipment and devices is low.
- The system causes low EM disturbances.

5. IT (Figure 21.26) It is an ungrounded system or has an impedance grounded neutral. Transformer or source of supply neutral is not grounded but load metallic frames are grounded. The system is preferred where continuity of service is more essential such as at critical installations like power generating stations, process plants and crowded public places (also see Section 20.2.1). It calls for prompt fault tracking and removing and demands for efficient engineering and maintenance back up. A second fault on another phase before the first gets cleared, however, will cause a severe phase to phase fault. Provisions must be available to promptly clear the same through short-circuit protection of interrupting device of the faulty equipment. With the availability of advanced electronic diagnostic instruments, tracking the first fault and removing the same promptly even remotely is simple and in all likelihood a second fault would be rare.

- As there is no current flow during the first fault, the risk to fire, explosion or damage to equipment is low.
- Also low EM disturbances.
- In France, for instance, IT system is compulsory in hospitals, particularly operation theatres to ensure an uninterrupted power supply. With the back-up of UPS (un-interrupted power supply), this requirement may not be over emphasized, nevertheless it is a safety requirement.
21.7.1 Choice of grounding system

All grounding systems are similar and aim at achieving the same objectives as noted before. As there is no one choice with one grounding system, a power installation may therefore have a combination of these systems depending on location, type of equipment, user requirements and also local electricity authority statutory regulations. It is possible that one installation may use more than one grounding systems to satisfy different requirements for different types of loads. For example,

- Special grounding system for sensitive installations having electronic circuits, video, computers and communication network. Also see Section 6.13.3 on clean grounding.
- IT system may be preferred for critical installations not wanting an immediate shut-down. But this too has its own merits and demerits as noted above.
- TT being the most practised system worldwide for LV grounding.
- Some countries like Norway use IT System.
- Anglo-Saxon (British) countries generally use TN-C system.

All these grounding systems are practised in varying degrees by different countries. Table 21.4 gives a general over-view of the grounding practices of LV installations as adopted by some countries just for a general reference.

Most countries have drawn-up their own electricity regulations like National Electric Code (NEC) and one may refer to the same before deciding on the grounding system. For example according to NEC one may use RCD when it meets the following,

- Neutral is directly grounded.

Table 21.4 Grounding practices adopted by some countries.

<table>
<thead>
<tr>
<th>Country</th>
<th>LV grounding system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Germany</td>
<td>TT and TN-C</td>
</tr>
<tr>
<td>230/400 V</td>
<td>TT</td>
</tr>
<tr>
<td>Belgium</td>
<td>TT</td>
</tr>
<tr>
<td>230/400 V</td>
<td>TT</td>
</tr>
<tr>
<td>Spain</td>
<td>TT</td>
</tr>
<tr>
<td>230/400 V</td>
<td>TT</td>
</tr>
<tr>
<td>France</td>
<td>TT</td>
</tr>
<tr>
<td>230/415 V</td>
<td>TT and TN-C</td>
</tr>
<tr>
<td>Great Britain</td>
<td>TT and TN-C</td>
</tr>
<tr>
<td>240/400 V</td>
<td>TT</td>
</tr>
<tr>
<td>Italy</td>
<td>TT</td>
</tr>
<tr>
<td>230/400 V</td>
<td>TT</td>
</tr>
<tr>
<td>Japan</td>
<td>TT</td>
</tr>
<tr>
<td>100/200 V</td>
<td>IT</td>
</tr>
<tr>
<td>Norway</td>
<td>IT</td>
</tr>
<tr>
<td>230/400 V</td>
<td>TT</td>
</tr>
<tr>
<td>Portugal</td>
<td>TN-C and TN-S, IT and impedance grounded IT in process industries.</td>
</tr>
<tr>
<td>USA</td>
<td>120/240 V</td>
</tr>
</tbody>
</table>

Source: Cahier Technique Merlin Gerin n°173.

Similarly various parts of IEC 60364 provide solutions to grounding of various types of installations and locations such as bath tubs, shower basins, swimming pools, sauna heaters, construction and demolition sites, installations at agriculture and horticulture premises, data processing equipment, caravan parks and caravans etc. Similarly for hospitals, schools, navy, mines and work sites.

For brevity we limit our discussions to the above. For implementation of these systems one may refer to the various parts of IEC 60364, NEC and references 3–6 provided in the Further Reading.

21.7.2 Protection from lightning strikes, transferred surges and over-voltages

Limiting potential rise in the LV ground circuit due to lightning surges, surge transferences and over-voltages caused by faults on MV side is an important requirement for all LV ground systems. Some remedial measures are noted below,

- To protect from direct lightning strikes a lightning arrester can be installed at the top most point of the building and grounded separately.
- To protect from transferred surges (Section 18.5.2) a surge protective device (SPD) (Section 17.13) can be installed across the neutral and ground on the LV side of the transformer as marked in Figure 21.25. It should be at the origin of the supply source and not near the receiving point as far as possible.

Note

SPDs wherever installed must be grounded separately to prevent ground potential rise while clearing the surge.

- To protect from over-voltages due to faults on the MV side (Section 20.1) many countries practise to keep the substation LV ground circuit and neutral / ground of LV system separate to prevent MV side over-voltage raise the voltage of the LV network during a fault on the MV side, unless LV is also impedance grounded and its ground impedance is enough to absorb the over-voltage. The usual practice to accomplish this is to have an IT system with impedance grounding on the MV side to limit the zero sequence fault currents in the MV system. IEC 60364-4-424 prescribes the limiting voltage on the LV system as,

\[ \frac{V_r}{\sqrt{3}} + 250 \text{ V for more than } 5 \text{ s.} \]

\[ \frac{V_r}{\sqrt{3}} + 1200 \text{ V for less than } 3 \text{ s.} \]

In IT system the phase-N voltage, \( \frac{V_r}{\sqrt{3}} \) rises to \( V_r \) on a ground fault. LV equipment and devices must be suitable to withstand the same.

To study more on the effects of transferred surges and over-voltages on various LV ground systems refer to IEC 60364 and its various parts and the literatures noted at references 3–6 under Further Reading. Above more emphasis is provided on LV installations but similar parameters will apply for MV and HV installations also.
### Relevant Standards

<table>
<thead>
<tr>
<th>IEC</th>
<th>Title</th>
<th>IS</th>
<th>BS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>BS IEC 60050-195/1998</td>
</tr>
<tr>
<td>60364-1 to 7</td>
<td>Electrical installation of buildings – code of practice.</td>
<td>732/2000</td>
<td>BS 7671/2001</td>
</tr>
<tr>
<td>60898/1995</td>
<td>Electrical accessories – Circuit breakers for over current protection for household and similar installations.</td>
<td>8828/2001</td>
<td>BS EN 60898/2003 –</td>
</tr>
<tr>
<td>61008/2002</td>
<td>Residual current operated circuit breakers.</td>
<td>12640-1-2000</td>
<td>–</td>
</tr>
<tr>
<td>61008-1/2002</td>
<td>Residual current operated circuit breakers, without integral over current protection – General rules.</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>61009-1/2003</td>
<td>Residual current operated circuit breakers, with integral over current protection – General rules.</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>61543/2005</td>
<td>Residual current operated protective devices (RCDs) for household and similar use-Electromagnetic compatibility.</td>
<td>–</td>
<td>BSEN 61543/2006 –</td>
</tr>
<tr>
<td></td>
<td>Specification for grounding transformers.</td>
<td>3151/2001</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Code of practice for undesirable static electricity.</td>
<td>7689/2000</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>General requirements for residual current operated protective devices.</td>
<td>12640-2-2001</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Circuit breakers with integral over current protection.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Related US Standards ANSI/NEMA and IEEE

<table>
<thead>
<tr>
<th>Standard</th>
<th>Description</th>
<th>IS</th>
<th>BS</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANSI-C37.16/2000</td>
<td>Low voltage power circuit breakers – preferred ratings and application recommendations.</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

### Notes

1. In the table of relevant Standards while the latest editions of the Standards are provided, it is possible that revised editions have become available or some of them are even withdrawn. With the advances in technology and/or its application, the upgrading of Standards is a continuous process by different Standards organizations. It is therefore advisable that for more authentic references, one may consult the relevant organizations for the latest version of a Standard.

2. Some of the BS or IS Standards mentioned against IEC may not be identical.

3. The year noted against each Standard may also refer to the year it was last reaffirmed and not necessarily the year of publication.

### List of formulae used

#### Current passing through a human body

\[
I_b = \sqrt{\frac{S_b}{t_b}} 
\]  
(21.1)

- \(I_b\) = r.m.s value of the leakage current through the body in Amperes (A)
- \(S_b\) = shock energy in watt-seconds (Ws)
- \(t_b\) = duration of leakage current in seconds (s)

#### Safe currents through a human body

(i) for a 50 kg body

\[
I_b(50 \text{ kg}) = \frac{0.116}{\sqrt{I_b}} 
\]  
(21.2)

(ii) for a 70 kg body
\[ I_b(70 \text{ kg}) = 0.157 \frac{1}{\sqrt{70}} \] (21.3)

**Selecting a ground fault protection scheme**

\[ Z_g = \frac{V_1^2}{n \cdot 1000 \cdot \text{kVA}} \Omega \] (21.4)

- kVA = rated capacity of the supply source
- \( V_1 \) = system rated line voltage in volts
- \( I_r \) = system rated full load line current in Amperes
- \( n \) = unit of \( I_r \)
- \( Z_g \) = impedance of the grounded neutral circuit in Ohms
- \( I_g \) = required level of the ground fault current in Amperes

**Further Reading**