# 20

# Temporary over-voltages and system grounding

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## 20.1 Theory of over-voltages

A three-phase balanced system has all the three phasors of voltage and current 120° apart, as illustrated in Figure 20.1(a) for a conventional anti-clockwise rotation. These phasors are known as positive sequence components. During a fault, this balance is disturbed and the system becomes unbalanced being composed of two balanced components, one positive and the other negative sequence (Figures 20.1(a) and (b)). For a description of the effects of these components, refer to (Section 12.2(v)). During a ground fault, zero phase sequence components also appear, which are single phasor components and combine three equal phasors in phase, as shown in Figure 20.1(c). This is the residual voltage,  $V_{\rm g}$ , that appears across the ground circuit, i.e. between the neutral and the ground as illustrated in Figure 20.12. This voltage is responsible for a fault current,  $I_g \cdot I_g$  will flow through the grounded neutral when it is a three-phase four-wire neutral grounded system, as shown in Figure 20.12. It will also flow through a three-phase three-wire artificially grounded system when it is grounded through a neutral grounding transformer (Section 20.9) as illustrated in Figures 20.17 and 20.18. In a three-phase three-wire system, which has neither its own grounded neutral nor an artificially created grounded neutral, there will be no direct ground fault current. But charging currents through the ground leakage capacitances, particularly on an HV system, may still exist, as illustrated in Figures 20.2-20.4.

These currents may develop dangerous over-voltages across the healthy phases, under certain ground circuit impedance conditions, as discussed in Section 20.2.1(1). It is thus possible to encounter a ground fault, even when the system is not grounded, the fault current finding its return path through the ground leakage capacitances. While an LV system, in view of a far too low ground voltage,  $V_g$  (equal to line voltage, Section 20.2.1(1)), as compared to high ground capacitive leakage reactance,  $X_{cg}$ , would cause a near open circuit ( $V_g/X_{cg}$  being too meagre) and stay immune, leaving the grounded conductor floating at  $V_g = V_\ell$ .



Figure 20.1 Phasor representation of an unbalanced power system on a ground fault



Figure 20.2 An ungrounded or isolated neutral system (circuit completing through the ground leakage capacitances)



Figure 20.3 Case of ground fault within the load



Figure 20.4 Case of a ground fault on a power system on the load side

# 20.2 Analysis of ungrounded and grounded systems

This is related more to an HV system.

#### 20.2.1 Analysis of an ungrounded system

This is common to

- A three-phase three-wire, star connected isolated neutral system,
- A delta connected system, or
- A three-phase four-wire, ungrounded system.

An ungrounded a.c. system is more often subject to overvoltages. The reason is that even when the system is not connected to ground, it makes a ground connection through the coupling of the leakage ground capacitances, as illustrated in Figure 20.2. For all purposes these capacitances may be regarded as equal and uniformly distributed, providing a balanced system. In the event of a ground fault, this circuit is closed as shown and a capacitive current,  $I'_{g}$  flows back to the healthy phases via these capacitances  $C_g$ , Analysing the circuit of Figure 20.2, the following may be derived:

If  $C_{\rm g}$  = electrostatic or leakage capacitance to the ground per phase, providing the return path to the fault current  $I_g$ , in the event of a ground fault on the system. This current will be capacitive in nature.  $X_{cg}$  = ground capacitive reactance per phase

$$= \frac{1}{2\pi f \cdot C_{\rm g}}$$

Under transient conditions, f becomes surge frequency,  $f_{\rm s}$  and

$$X_{\rm cg}$$
 becomes,  $\frac{1}{2\pi f_{\rm s}\cdot C_{\rm g}}$ 

where

$$f_{\rm s} = \frac{1}{2\pi \sqrt{L \cdot C_{\rm g}}}$$

L being the inductance of the circuit.

- If  $I_g$  = ground fault current  $V_g$  = ground potential, which is the same as zero sequence voltage or residual voltage
  - $V_{\ell}$  = line voltage and

$$V_{\rm p}$$
 = phase voltage

then on a ground fault, say, in phase R, the voltage across this phase will reduce to zero, while the ground potential across the healthy phases will rise to  $V_{\ell}$  from a zero level earlier. It will cause a fault current  $I'_{g}$  in the healthy phases also, through the ground leakage capacitances such that  $I'_{\rm g} = V_{\rm I} / X_{\rm cg}$  (assuming the ground circuit has no other impedance) and the ground fault current through the grounded circuit,

$$I_{g} = \overline{I_{Y}} + \overline{I_{B}}$$
$$= \overline{I'_{g}} + \overline{I'_{g}}$$
 (both phasors being 60° apart)

 $= \sqrt{I'_g{}^2 + I'_g{}^2 + 2 \cdot I'_g \cdot I'_g \cdot \cos \cdot 60^\circ}$  (as in Section 15.4.3)

$$= \sqrt{(I_{g}^{\prime 2} + I_{g}^{\prime 2} + I_{g}^{\prime 2})}$$

=  $\sqrt{3} \cdot I'_{g}$  (but this current may not be enough to trip a protective relay)

The voltage across the healthy phases is now  $\sqrt{3}$  times or 73% more than the phase to neutral voltage under healthy conditions (voltage across healthy phases =  $\sqrt{3} V_g$  (on a ground fault  $V_g = V_\ell$ )).

Under certain line to ground impedance conditions, when the ground circuit may also contain some inductive reactance, the voltage of the healthy phases may rise further, much above the system voltage, due to resonance and ferro-resonance effects discussed hereafter. All this in turn may tend to swing the system to an unstable state. It may also cause arcing grounds\* at the supporting insulators, leading to voltage surges, travelling in both directions along the line, and may be enough to cause damage to the line insulators and the terminal equipment.

The magnitude of over-voltage will depend upon the actual inductive reactance introduced through the ground circuit. The unintentional introduction of an impedance into the ground leakage capacitive circuit is generally a result of a ground fault in the main equipment such as a generator, a transformer, or an induction motor and when one or more of their phase windings form a part of the ground circuit, as illustrated in Figure 20.3. Under such conditions, they will introduce their own inductive or resistive impedances or a combination of them into the ground circuit and alter the parameters of the ground capacitive circuit. Figure 20.5 illustrates the system of Figure 20.2, drawn simply on a single phase basis. The current through the ground circuit will be zero when the system is healthy, the ground leakage capacitances finding no return path (Figure 20.6). It is not necessary that the equipment itself should develop a ground fault and then only its impedance will be inducted into the ground circuit. It may be introduced into the circuit even when there is a line or a system ground fault, as illustrated in Figure 20.4. The ground circuit may give rise to dangerous voltages in the healthy phases, as analysed below.

#### (1) When the external impedance is a resistance or a capacitive reactance

Referring to Figure 20.5, if  $Z'_{g}$  is the external impedance introduced into the natural leakage ground circuit, as a consequence of a ground fault, as shown in Figures 20.3

<sup>\*</sup>Arcing grounds: This occurs during a temporary ground fault on an ungrounded HV system. It causes an arc between the line conductor and the ground, which may be direct or through the flashover of the line insulators, due to over-voltage. The ground leakage capacitors that may be considered as charged with the line voltage are discharged to the ground on developing a ground fault. The supply voltage would charge them again and so the process will repeat until the fault exists. The repeated discharges and charges of ground capacitors during the fault produce arcs and are termed arcing grounds, giving rise to voltage surges.



 $Z'_{g}$  = Additional ground impedance (*R*,  $X_{c}$  or  $X_{L}$ )

Figure 20.5 Equivalent ground circuit representing the power system of Figure 20.2



On a healthy system the ground leakage capacitances find no return path and therefore do not activate. They do so when there is a ground fault as illustrated in Figures 20.3 and 20.4



and 20.4, then the voltage across the impedance  $Z'_g$  can be determined as follows:

#### When the impedance is a resistive reactance

The peak voltage  $V'_{g(max)}$  across R will be

$$V'_{\rm g(max)} = \frac{R}{\sqrt{R^2 + X_{\rm cg}^2}} \cdot \sqrt{2} \cdot V_{\ell}$$
 (20.1)

Computing values of  $V'_{g(max)}$  by approximating, in terms of circuit resistance *R* and ground capacitive reactance  $X_{cg}$ , when

$$R = 0, \ V'_{g(max)} = 0$$

$$R = \frac{1}{2} X_{cg}, \ V'_{g(max)} = \frac{1/2}{\sqrt{(1/4 + 1)}} \cdot \sqrt{2} V_{\ell} = 45\% \text{ of } \sqrt{2} V_{\ell}$$

$$R = X_{cg}, \ V'_{g max} = \frac{1}{\sqrt{2}} \cdot \sqrt{2} V_{\ell} \approx 71\% \text{ of } \sqrt{2} V_{\ell}$$

$$R = 1 \cdot 5X_{cg}, \ V'_{g max} = \frac{1 \cdot 5}{\sqrt{3 \cdot 25}} \cdot \sqrt{2} V_{\ell} \approx 83\% \text{ of } \sqrt{2} V_{\ell}$$

$$R = 2X_{cg}, \ V'_{g max} = \frac{2}{\sqrt{2}} \cdot \sqrt{2} V_{\ell} \approx 89\% \text{ of } \sqrt{2} V_{\ell}$$

 $R = 2X_{cg}, V'_{g \max} = \frac{2}{\sqrt{5}} \cdot \sqrt{2} V_{\ell} \simeq 89\% \text{ of } \sqrt{2} V_{\ell}$ 

As *R* approaches infinity;  $V'_{g(max)}$  will tend to approach  $\sqrt{2}V_{\ell}$ .



**Figure 20.7** Influence of external impedance  $Z'_{g}$  in the ground circuit on the system voltage in the event of ground fault in an ungrounded system

The variation in  $V'_{g max}$  with the variation in resistive reactance, R, in the ground circuit, is shown in Figure 20.7, curve 1.

Inference

Irrespective of the value of the external resistance (*R*) in the ground circuit, the maximum voltage the healthy phases may have to sustain will not exceed  $\sqrt{2}V_{\ell}$ , in the event of a ground fault on an ungrounded system.

#### When the impedance is a capacitive reactance

Referring to Figure 20.5, the peak voltage  $V'_{g}$  across  $X_{c}$  will be

$$V'_{g \max} = \frac{X_c}{X_c + X_{cg}} \cdot \sqrt{2} V_\ell$$
(20.2)

Computing  $V'_{g \max}$  along similar lines to those above, i.e. when

$$X_{c} = 0, \quad V'_{g \max} = 0$$

$$X_{c} = \frac{1}{2} X_{cg}, \quad V'_{g \max} = \frac{\frac{1}{2}}{\frac{1}{2} + 1} \cdot \sqrt{2} V_{\ell} = 33.3\% \text{ of } \sqrt{2} V_{\ell}$$

$$X_{c} = X_{cg}, \quad V'_{g \max} = \frac{1}{2} \cdot \sqrt{2} V_{\ell} = 50\% \text{ of } \sqrt{2} V_{\ell}$$

$$X_{c} = 1 \cdot 5 X_{cg}, \quad V'_{g \max} = \frac{1 \cdot 5}{2 \cdot 5} \cdot \sqrt{2} V_{\ell} = 60\% \text{ of } \sqrt{2} V_{\ell}$$

$$X_{c} = 2X_{cg}, \quad V'_{g \max} = \frac{2}{3} \cdot \sqrt{2} V_{\ell} = 66.7\% \text{ of } \sqrt{2} V_{\ell}$$

As  $X_c$  approaches infinity,  $V'_{g \max}$  will tend to approach  $\sqrt{2} V_{\ell}$ . The variation in  $V'_{g \max}$  with the variation in capacitive reactance,  $X_c$ , in the ground circuit is shown in Figure 20.7, curve 2.

#### Inference

This is same as for resistive impedance. In these two cases, when the external impedance is resistive or capacitive, there is no excessive voltage rise across the healthy phases of the system beyond  $\sqrt{2} V_{\ell}$ . The voltage developed across the ground capacitance,  $X_{cg}$ , and the external impedance R or  $X_c$  is shared in the ratio of their own values, the sum total of which will remain constant at  $\sqrt{2} V_{\ell}$ .

# (2) When the external impedance is an inductive reactance

Now the situation is different, as resonance and ferroresonance effects in the series inductive-capacitive circuits may cause dangerous over-voltages.

#### (i) Resonance effect

Referring to Figure 20.5, the peak voltage  $V'_{g}$  across  $X_{L}$  will be

$$V'_{g \max} = \frac{X_{\rm L}}{X_{\rm cg} - X_{\rm L}} \cdot \sqrt{2} V_{\ell}$$
(20.3)

Computing  $V_{g}'$  along similar lines to those for resistive impedance,

i.e when  $X_{\rm L} = 0$   $V'_{\rm g max} = 0$ 

$$X_{\rm L} = \frac{1}{2} X_{\rm cg} \quad V'_{\rm g\,max} = \frac{\frac{1}{2}}{1 - \frac{1}{2}} \cdot \sqrt{2} \, V_{\ell} = \sqrt{2} \, V_{\ell}$$

 $X_{\rm L} = X_{\rm cg},$   $V'_{\rm g max}$  will tend to approach infinity

This is known as a resonating condition. It is, however, seen that in view of some in-built impedance in the ground circuit it will tend to attenuate the alarmingly rising voltage  $V'_{g \text{ max}}$ , to oscillate at around 8 to 10 times  $\sqrt{2} V_{\ell}$ . This voltage will tend to raise the ground potential substantially, depending upon the value of the external impedance  $X_{\text{L}}$ . It will also raise the ground potential of the healthy phases, which may cause arcing grounds and become dangerous to the line insulators and the terminal equipment. This is known as the resonance effect of the inductive reactance.

When

$$X_{\rm L} = 1.5 X_{\rm cg}, \quad V'_{\rm g\,max} = \frac{1.5}{0.5} \cdot \sqrt{2} \, V_{\ell} = 3 \cdot \sqrt{2} \, V_{\ell}$$
$$X_{\rm L} = 2 X_{\rm cg}, \qquad V'_{\rm g\,max} = 2 \cdot \sqrt{2} \, V_{\ell}$$
$$X_{\rm L} = 3 \, X_{\rm cg}, \qquad V'_{\rm g\,max} = \frac{3}{2} \cdot \sqrt{2} \, V_{\ell} = 1.5 \cdot \sqrt{2} \, V_{\ell}$$

As  $X_{\rm L}$  approaches infinity,  $V'_{\rm g max}$ , will tend to approach

 $\sqrt{2} V_{\ell}$ . This variation in  $V'_{g \text{ max}}$ , with the variation in inductive reactance,  $X_{L}$ , is also shown in Figure 20.7.

The inductive reactance,  $X_L$ , will tend to offset the ground capacitive reactance  $X_{cg}$  and diminish the denominator to a certain value of  $X_L$ , say, until it completely offsets the content of  $X_{cg}$  ( $X_L = X_{cg}$ ). At higher ratios, when  $X_L > 3X_{cg}$ , the denominator will rise more rapidly than the numerator and will tend to attenuate the  $V'_{g max}$ , as with R and  $X'_c$ , but at a slightly higher value of  $V'_{g max}$  (Figure 20.7, curve 3).

#### (ii) Ferro-resonance effect

The above analysis of over-voltages in the healthy phases of an ungrounded system in the event of a ground fault on one of the phases was based on the assumption that the inductive reactance of the electromagnetic circuit, i.e. the magnetic core of the connected equipment (which may be a transformer or an induction motor) was linear over its entire range of operation. But this may not always be true. It is also possible that some components such as a CT or a CVT, may have their magnetic core gradually saturated\* during normal operation, under certain circuitconditions and resonate with the ground capacitive reactance  $X_{cg}$ . This may lead to a high voltage in a healthy system, even when there is no ground fault, the ground circuit becoming completed through the grounded neutral of such a device (Figure 20.8).

The phenomenon of saturation of the magnetic core of such a device during normal operation and its resonance with the ground capacitive reactance,  $X_{cg}$ , is known as ferro-resonance. It would have the same effect on the healthy phases/system as in (i) above.

The inductive reactance of the magnetic circuit on saturation may fall to a much lower value than the linear

\*Saturation of transformers also produces high currents, rich in harmonics.



During saturation  $X_{\rm L} \simeq X_{\rm cg}$  leading to the phenomenon of ferro-resonance

Figure 20.8 Case of a ferro-resonance in a residual VT leading to overvoltages even in a healthy system

inductive reactance of the magnetic core, as a consequence of design requirements, and lead to a condition of low  $X_{\rm L}$  to  $X_{\rm cg}$  ratio (say  $X_{\rm L} \approx 1.5$  to  $2X_{\rm cg}$ ) in curve 3 of Figure 20.7. Under such a condition, the voltage across  $X_{\rm L}$  will tend to oscillate automatically between certain overvoltage limits. The effective  $X_{\rm L}$  is seen to match the ground capacitive reactance  $X_{\rm cg}$  such that it helps to damp the over-voltages across the healthy phases, to oscillate at around two to three times  $\sqrt{2} V_{\ell}$ .

Such a situation may also arise in electromagnetic equipment, which is subject to a varying system voltage during normal operation. One example is a residual voltage transformer (RVT) (Section 15.4.3) which is required to detect an unbalance (zero sequence) or a ground fault in the primary circuit and may reach early saturation. A similar situation is also possible in a measuring CT and even a protection CT, as both may saturate at a certain level of fault current in the primary. The same situation would arise in a CVT (Chapter 15). Such devices (CTs, RVTs and CVTs) are generally grounded as a safety requirement, and may give rise to such a situation during normal operation, even in a healthy system.

## 20.3 The necessity for grounding an electrical system

An ungrounded system, in the event of a ground fault, is subject to an over-voltage, as noted in Section 20.2.1. It is prone to cause yet higher voltages in the healthy phases when its ground circuit becomes inductive, as discussed above. The over-voltage may damage the supporting insulators and the terminal equipment. Should a system be left ungrounded? This aspect must be viewed with the above phenomena in mind. It may also cause arcing grounds and prove fatal to a human body coming into contact with the faulty equipment or the conductor. Assuming that a total power system, from its generating station to the far end LV distribution network (Figure 13.21) is left ungrounded and a ground fault occurs somewhere on the LV side, the fault current through the human body will find a return path through the grounding capacitances, no matter how feeble it may be. This current may be dangerous to a human for which even 10 mA is fatal, as discussed in Section 21.1.1.

Generally, neutral grounding should be adopted in principle to avoid generation of over-voltages and to eliminate the phenomenon of arcing grounds. Even a solidly grounded system, with a very low resistive reactance, can avoid such over-voltages as the fault current on a ground fault will find its return path through the shortest solid ground conductor, having a low resistance, rather than through the ground capacitances, which have a relatively much higher capacitive reactance. (See Figure 20.12.)

Below we briefly discuss the criteria and theory of selecting a grounding system to achieve a desired level of fault current to suit a predetermined ground fault protection scheme, i.e. type of grounding and grounding impedance to suit the system voltage, type of installation, and location of installation.

### 20.4 Analysis of a grounded system

Consider Figure 20.12 again, when the neutral *N* is solidly grounded. Also refer to Figure 20.1. If

- $V_{\ell}$  = line voltage
- $Z_{\ell}$  = positive sequence impedance This is measured between phase to phase or phase to neutral, depending upon the availability of the neutral. The test current is kept at the rated value for the equipment or the system under test. For the

$$Z_{\ell} = \frac{V_{\rm I}}{\sqrt{3} \cdot I_{\rm r}}$$

 $Z_2$  = negative sequence impedance.

system shown in Figure 20.9(a).

The same way as above, but now a negative sequence voltage is applied (by interchanging one of the phases of the source of supply)

 $Z_0$  = zero phase sequence or residual impedance. This is measured between the three-phase terminals of a star winding shorted together and the neutral (Figure 20.9(b)) and is calculated by

$$Z_0 = 3 \cdot \frac{V_{\ell}}{\sqrt{3}} \cdot \frac{1}{I_r} \text{ or } 3 \cdot \frac{V}{\sqrt{3} \cdot I}$$

where

 $\frac{V}{\sqrt{3}}$  = test voltage and *I* = test current, to be around the currentcarrying capacity of the neutral.

Also 
$$Z_0 = 3\overline{R_0} + 3\overline{X_0}$$

where

- $R_0$  = zero phase sequence or residual resistance, and
- $X_0$  = zero phase sequence or residual reactance
- $Z_{\rm g}$  = total impedance through the ground circuit
- $I_{g}$  = ground fault current, zero sequence current or residual current through the ground circuit



Figure 20.9 Measuring system impedances

 $V_{\rm g}$  = ground potential, which is the same as the zero sequence voltage or residual voltage. In a ground fault, it would remain at  $V_{\ell}/\sqrt{3}$  unlike at  $V_{\ell}$  in an ungrounded system (Section 20.2).

The residual voltage may also be measured by a residual voltage transformer (RVT) (Figure 20.10). Refer to Section 15.4.3 for more details.

Then the total impedance through the ground circuit

$$Z_{\rm g} = \overline{Z}_1 + \overline{Z}_2 + \overline{Z}_0$$

(For approximate values at design stage see Table 13.6.) and the fault current through ground circuit

$$I_{g} = \frac{3V_{g}}{Z_{g}}$$
  
or 
$$I_{g} = \frac{3 \cdot V_{\ell}}{\sqrt{3} \cdot Z_{g}}$$

The residual current may also be measured by a three-CT method as illustrated in Figure 20.11.



Figure 20.10 Detecting a ground fault in an isolated neutral system



Figure 20.11 Measuring the residual current

When some extra impedance R,  $X_C$ ,  $X_L$  or a combination of these is introduced into the ground circuit it will become possible to alter the magnitude and the characteristic of the ground circuit current,  $I_g$ , to suit an already designed ground fault protection scheme as discussed below.

A three-phase four-wire system may be grounded in the following ways:

- 1 Solid neutral grounding system or
- 2 Impedance neutral grounding system

# 20.4.1 Solid neutral grounding system (also known as effectively grounded system)

We have already discussed a solid neutral grounding system in Section 20.3. The residual voltage or the ground potential rises to the phase voltage  $V_{\ell}/\sqrt{3}$  and does not alter the voltage of the healthy phases. To analyse this system, we have redrawn the circuit of Figure 20.2 in Figure 20.12, grounding the neutral solidly. The impedance to ground,  $Z_g$ , through the neutral circuit will be extremely small and resistive in nature, compared to the ground capacitive reactance  $X_{cg}$  i.e.  $Z_g << X_{cg}$ , and will share most of the fault current. The current through the ground leakage capacitances may be ignored to derive an easy inference. The effectiveness of grounding and its impedance will play the most decisive role in determining the fault current and the most appropriate protection.

#### 20.4.2 Impedance neutral grounding system

Consider the system shown in Figure 20.12 and introduce some impedance  $Z_g$  in its neutral circuit as shown in Figure 20.13. Now it is possible to vary the magnitude and characteristic of the fault current through the neutral circuit.

- If  $I_g$  = ground fault current and
  - $I'_{g}$  = fault current through the healthy phases due to neutral impedance  $Z_{g}$

then current through the neutral circuit, as a result of impedance  $Z_g$ ,



Figure 20.12 A solid neutral grounding system



 $Z_{q}$  = Tapped reactor or arc suppression coil

Figure 20.13 An impedance grounding neutral system

$$= \overline{I'_g} + \overline{I'_g}$$
$$= \sqrt{3} \cdot I'_g$$

If  $I''_g$  = fault current through the healthy phases due to ground capacitive reactance  $X_{cg}$ , then the current through the ground capacitive reactances

$$= \overline{I_g''} + \overline{I_g''}$$
$$= \sqrt{3} \cdot I_z''$$

And the total ground fault current

$$I_{\rm g} = \sqrt{3} \cdot I_{\rm g}' + \sqrt{3} \cdot I_{\rm g}''$$

The value of  $I_g$  can thus be varied in magnitude and phase displacement to suit a particular location of installation or protective scheme by introducing suitable R and  $X_L$  into the neutral circuit. When the impedance is inductive, the fault current  $I'_g$  will also be inductive and will offset the ground capacitive current  $I''_g$ . In such a grounding, the main purpose is to offset the fault current as much as possible to immunize the system from the hazards of an arcing ground. This is achieved by providing an inductor coil, also known as an arc suppression coil, of a suitable value in the neutral circuit.

# 20.5 Arc suppression coil or ground fault neutralizer

This is also known as a Petersen coil, named after its inventor. With an inductive reactance,  $X_L$ , in the ground circuit the ground fault current can be substantially neutralized by tuning the inductor correctly. A small residual ground current however, will still flow through the ground circuit as a result of its own resistance, insulator leakage and corona effect. In all likelihood, it would be sufficient to operate the protective scheme. Since the

fault current is now nearly in phase with the voltage of the healthy phases, it will prevent the interrupting device from causing a restrike while interrupting the fault (Section 17.7.2(iii)). Such an arrangement is more appropriate for systems that are above 15 kV and are subject to frequent ground faults, for example an overhead transmission line or a long distribution system.

With such a system the possibility of an arcing ground is almost eliminated and it is now possible even to allow the ground fault condition to prevail until it can be conveniently repaired. Now it will cause no harm to a human operator, supporting insulators or the terminal equipment. On long-distance transmission or distribution networks such a situation may rather be desirable to prevent the system from tripping instantly until at least the off-peak periods or until the supply is restored through an alternative source. The process of finding the fault and its repair may be allowed to take a little longer.

A neutral grounding reactor (NGR) is also desirable to achieve auto-reclosing of a faulty phase during a onepole opening as a result of a fault of a transient nature on this phase (Section 24.9.1). The reactance grounding will limit the high unbalanced capacitive currents through the healthy phases to ground and prevent an unbalance and so also an unwanted trip as illustrated in Figure 20.14. Referring to Figure 20.14, a ground fault of a transient nature on phase B would cause the two line breakers b and b' to trip and result in heavy ground fault current through the capacitive coupling of the healthy phases, eventually also tripping the breakers of the healthy phases. The NGR would neutralize such currents and prevent an unwanted trip, achieve the desired auto reclosing and improve system transient stability. For such a situation to arise it is tuned to a zero p.f. to achieve a near-resonant condition so that the fault current,  $I_g$ , is almost zero, and the capacitive current is substantially offset by the power frequency inductor current, i.e.

$$X_{\rm L} \simeq \frac{X_{\rm cg}}{3}$$



Figure 20.14 A ground fault neutralizer

where the total ground capacitive reactance

$$= \frac{1}{\left(\frac{1}{X_{cg}} + \frac{1}{X_{cg}} + \frac{1}{X_{cg}}\right)} = \frac{X_{cg}}{3}$$

If L = inductor coil inductance in henry

 $C_{\rm g}$  = ground capacitance per phase in farad and

f = system frequency in Hz

then

$$2\pi \cdot f \cdot L \approx \frac{1}{3(2\pi \cdot f \cdot C_g)}$$
  
or  $L \approx \frac{1}{3(2\pi f)^2 \cdot C_g}$  henry (20.4)

It is likely that for reasons of system disturbances, frequency fluctuations and switching of a few sections of the system, both  $X_L$  and  $X_{cg}$  may vary in actual operation and upset the resonance condition, leading to transient over-voltages. To overcome this, the inductor coil may be made variable (the setting of which may be altered automatically) through a motor-driven tap changer to achieve the tuning again. If the ground fault persists the inductor coil may be rated continuously rather than for a short-time and for the full fault current that the coil may have to carry.

To overcome the generation of over-voltages across the inductor coil (Section 20.2.1(2)) its inductance, *L*, is generally selected high, so that the resonance condition with the ground capacitors,  $C_g$ , occurs near the natural frequency of the system (50 or 60 Hz) and the voltage developed across the inductor coil,  $V'_g$ , may oscillate only at around  $V_\ell/\sqrt{3}$ . Generally, the Petersen coil neutralizer is a high-reactance grounding and is also termed resonant grounding, free from over-voltages and restrikes. Accordingly the voltages developed across the Petersen coil

$$V'_{\rm g} = \frac{X_{\rm L}}{X_{\rm cg} - X_{\rm L}} \cdot \frac{V_{\ell}}{\sqrt{3}} \le \frac{V_{\ell}}{\sqrt{3}} \quad (X_{\rm L} >> X_{\rm cg})$$

The voltage developed would thus oscillate around the normal voltage and fall in phase with the fault current to achieve a near-strike-free interruption of the interrupting device on a ground fault.

Note

- 1 As in IEC 60071-1,2 a higher insulation level (BIL) will be necessary for all insulators and terminal equipment when the ground fault persists for more than 8 hours per 24 hours or a total of more than 125 hours during a year.
- 2 Because of likely de-tuning and generation of over-voltages, this system is seldom in practice.

Sometimes such a situation may arise on its own, even on a normally grounded system, not intended for ground current neutralizing. It can happen when an overhead line snaps due to a storm, wind or any other factor and falls on trees, hedges or dry metalled roads and remains energized in the absence of a proper return path and cause a low leakage current, insufficient to trip the protective circuit. This is a situation not really desirable on a normally grounded system, as it may lead to an ungrounded system and may develop over-voltages.

## 20.6 Ground fault factor (GFF)

This is an important indicator that shows the grounding condition of a system and helps to determine the most appropriate ground fault protective scheme as well as the insulation level for that system. It is defined as the ratio of the highest voltage to ground,  $V_g$  (r.m.s.), of the healthy phase or phases during a ground fault to the corresponding power frequency phase voltage  $V_\ell/\sqrt{3}$ , when the system was healthy. Refer to Figure 20.15.

:. Ground fault factor (GFF) = 
$$\frac{V_g}{V_\ell/\sqrt{3}}$$
 (20.5)

which is usually more than 1.

It is also established that in an effectively grounded system the voltage to ground,  $V_{\rm g}$ , of the healthy phases does not exceed 80% of the line-to-line voltage  $V_{\ell}$  and consequently the GFF does not exceed  $0.8 \times \sqrt{3}$ , i.e 1.4. The system may be considered as effectively grounded when

• 
$$\frac{X_0}{X_+}$$
 = between 0 and 3, and

• 
$$\frac{R_0}{X_+}$$
 = between 0 and 1



R & Y - Healthy phases

B - Faulty phase

 $V_{\rm q}$  – (rms) value of ground voltage measured on fault

Figure 20.15 Determining the ground fault factor

where

 $X_0$  = zero sequence reactance

 $R_0$  = zero sequence resistance

 $X_{+}$  = positive sequence reactance

To achieve the desired conditions of grounding, the following are the generally adopted grounding practices.

#### 20.6.1 An ungrounded or isolated neutral system

When the system is totally isolated from the ground circuit, except through indicating, measuring or protective devices, which are normally grounded and possess a high impedance to ground, the ground fault factor

$$\text{GFF} = \frac{V_\ell}{V_\ell / \sqrt{3}} = 1.732$$

This may become higher, depending upon the circuit's conditions (for example, the ferro-resonance effect, Section 20.2.1.(2)).

Note

An isolated neutral is a condition of grounding system, where as an isolated ground (Section 6.13.3) is a method of shielding of signals in electronic circuits

#### 20.6.2 A grounded neutral system

When the system is grounded through its neutral, either solidly, through a resistance or through an arc suppression coil (inductor), it becomes a grounded neutral system. This type of system grounding may be classified as follows:

- Effectively grounded
- Non-effectively grounded and
- Resonant grounded systems.

For detailed schemes in practice see Section 21.7.

#### Effectively grounded system

This is to achieve a higher level of fault current to obtain a quicker tripping on fault. It is obtained when the system has a ground fault factor not exceeding  $1.4 (V_g \le 0.8V_\ell)$ , as noted above. A solidly grounded system will provide effective grounding (see TN systems of grounding, Section 21.7). This system will reduce the transient oscillations and allow a current sufficient to select a ground fault protection scheme. It is normally applicable to an LV system.

#### Non-effectively grounded system

An impedance grounded system will fall into this category (see TT system of grounding, Section 21.7). The GFF may now exceed 1.4 ( $V_g > 0.8V_\ell$ ).

#### Resonant grounded system

When the system is grounded through an arc suppression coil (reactor) so that during a single phase to ground fault, the power frequency inductive current passing through the inductor coil would almost offset the power frequency leakage capacitive component of the ground fault current. However, such a situation is not allowed to persist for more than 8 hours in any 24 hours or for a total of 125 hours during a year. If it is more, a higher level of insulation (BIL) will become necessary for all insulators and terminal equipment. The ground fault factor in this case may also exceed 1.4. This basically falls in the category of ungrounded system (see IT system of grounding, Section 21.7).

When the system parameters  $R_0$ ,  $X_0$  and  $X_1$  are known, the value of GFF may be determined more accurately by the use of Figure 20.16, which has been established for different grounding conditions, i.e. for different values of  $R_0$ ,  $X_0$  and  $X_1$ .

## 20.7 Magnitude of temporary overvoltages

At a particular location this can be obtained by multiplying the peak system phase to ground voltage by the ground fault factor at that location. For example, for a 6.6 kV nominal voltage system, having an isolated neutral (ungrounded system), the maximum temporary overvoltage during a ground fault may rise to

$$V_{\rm ph}({\rm peak}) \times {\rm GFF}$$
  
where  $V_{\rm ph}({\rm peak}) = \sqrt{2} \times \frac{6.6}{\sqrt{3}} \, {\rm kV} = 1 \, {\rm p.u.}$   
and  ${\rm GFF} = \sqrt{3}$  for an ungrounded system  
 $\therefore$  Temporary over-voltage = 1 p.u.  $\times \sqrt{3}$   
 $= \sqrt{3} \, {\rm p.u.}$ 

# 20.8 Insulation co-ordination

For non-effectively grounded systems, having a GFF of more than 1.4, a higher level of insulation (BIL) will be



 $R_0$  = Zero sequence resistance

 $X_0$  = Zero sequence reactance

 $X_1$  = Positive sequence reactance

**Figure 20.16** Relationship between  $R_0/X_1$  and  $X_0/X_1$  to determine the values of ground fault factor  $k_0$  based on IEC

essential for all equipment being used on the system to withstand a higher level of a one-minute power frequency voltage test as well as an impulse voltage withstand test if such levels (Lists I, II and III) are prescribed in the relevant Standards. If not, then it may be assumed, that the prescribed test values take account of such an eventuality. Refer to Tables 11.6, 14.1, 14.3(a), 32.1(a), 13.2 and 13.3 for more details.

## 20.9 Artificial neutral grounding of a three-phase three-wire system

In the previous section we have discussed the theory of providing a ground fault protection when a neutral was already available on the system. This could be utilized for a solid or an impedance grounding to achieve the required level of fault current on a ground fault, and meet the requirement of the protection scheme or the stability of the system. Here we discuss circuits which do not have a neutral as a matter of system design, such as for the purpose of transmission and long HV distribution, where the power is transmitted on a delta circuit to economize on the initial cost. Such as from the generating station through a generator transformer where the transformer can be  $Y/\Delta$ , say, 15.75/400 kV. In such a case, when grounding is required on the delta side of the transformer, this is possible by creating an artificial neutral point. The basic need for such a provision, where a neutral does not exist, may be necessary, primarily to achieve the following:

To reduce the high-voltage transient oscillations in an 1 isolated neutral system and to prevent the voltage of the healthy phases from rising beyond their line to neutral voltage, as far as possible. Prolonged existence of over-

voltages may have a tendency to cause a short-circuit from line to ground, even in the healthy phases.

- 2 A ground fault protection scheme that is easy to handle, clear the fault quickly and prevent it from spreading.
- 3 To eliminate prolonged arcing grounds as a matter of safety to human lives. A live conductor falling on ground will remain live if not grounded and cause an arcing through ground leakage capacitances. It may generate excessive heat and become a hazard to life and property.
- 4 On higher voltage systems, due to ground leakage capacitances, the voltage of the two healthy phases may increase to twice the voltage, similar to double charging, when switching a capacitor unit (Section 23.5.1).
- 5 Electrostatic induction may take place on overhead power-carrying systems, through charged clouds, dust, rain, fog and sleet and due to changes in the altitudes of lines. If these induced charges are not freed through grounding, they will continue to rise gradually and accumulate on the system. This is called floating potential and may result in a breakdown of the system insulation or the terminal equipment.

If the above are not taken into account the devices and components used on the system may have to be selected or braced for a higher system voltage, say, up to twice the rated voltage or even more. The over-voltage condition may almost be the same as for ungrounded capacitor switching (Section 23.5.1(ii)).

#### Neutral grounding transformers

The artificial neutral point on the delta side can be created by providing an inter-connected star neutral, also known as a zig-zag transformer. It can also be provided through a star-delta transformer. Both arrangements are illustrated in Figures 20.17 and 20.18 respectively. Such transformers are of a standard core type, with only a single winding on



Figure 20.17 3¢ inter-connected star-neutral grounding transformer

the grounding transformer



Figure 20.18 3¢ Star/delta neutral grounding transformer

each transformer limb, split into two halves as shown. The total winding arrangement is like a 1:1 autotransformer, with the provision of altering the ground impedance, similar to that in a normal ground circuit, as discussed above. The additional resistance or impedance, as required in the ground circuit, may be provided either by inserting it between the neutral point and the ground or in the three individual phases as shown in Figures 20.17 and 20.18.

The rating of the auxiliary transformer can be shorttime, sufficient to feed the fault current and its own noload losses for, say, 30 seconds or so, according to the maximum tripping time of the protective scheme. The normal rating of such transformers is generally between 5 and 100 kVA, sufficient to carry the full ground fault current. The winding is designed for line-to-line system voltage.

#### Note

The magnetic core is designed so that it will not saturate during

normal operation to avoid a ferro-resonance condition. The knee point voltage is kept at about 1.3 times the system line voltage.

# Residual voltage transformer (star/open delta transformer)

This is not a method of providing an artificial neutral, as in the previous case, but to detect an unbalance or residual voltage (zero sequence voltage) in a three-phase threewire or a three-phase four-wire ungrounded system. The residual or zero sequence voltage that may appear across the open delta will be the reflection of an unbalance or a ground fault in the system (Figure 20.10). Also refer to Section 15.4.3 for more details.

# 20.10 Grounding of generators

Refer to Section 16.13.2.

#### **Relevant Standards**

IEC	Title	IS	BS	
60071-1/1993	Insulation coordination phase to earth – Principles and rules. Insulation coordination phase to phase – Principles and rules.	2165-1/2001, 2165-2/2001	BS EN 60071-1/1997	-
60071-2/1996	Insulation coordination – Application guide.	3716/2001	BS EN 60071-2/1997	-
	<b>Relevant US Standards ANSI/NEMA</b>	and IEEE		
ANSI/IEEE-131	3.1/1996 Insulation coordination – Definitions, princ	iples and rules.		

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

#### Analysis of an ungrounded system

#### When the external impedance is resistive

$$V'_{g(max)} = \frac{R}{\sqrt{R^2 + X_{cg}^2}} \cdot \sqrt{2} \cdot V_1$$
(20.1)

 $V'_{g}$  = voltage across the external resistance R

R = external resistance

 $X_{c\sigma}$  = ground capacitive reactance

 $V_{\ell}$  = line voltage

#### When the external impedance is capacitive

$$V'_{g \max} = \frac{X_{c}}{X_{c} + X_{cg}} \cdot \sqrt{2}V_{1}$$
 (20.2)

 $V'_{\rm g}$  = voltage across  $X_{\rm c}$ 

 $X_{\rm c}$  = external capacitive reactance

#### When the external impedance is inductive

$$V'_{g \max} = \frac{X_{\rm L}}{X_{\rm cg} - X_{\rm L}} \cdot \sqrt{2} V_{\ell}$$
 (20.3)

#### $X_{\rm L}$ = external reactance

#### Arc suppression coil or ground fault neutralizer

To substantially offset the capacitive current by the power frequency inductor current

$$L \simeq \frac{1}{3(2\pi f)^2 \cdot C_{\rm g}} \text{ henry}$$
(20.4)

L = inductor coil inductance in henry

 $C_{\rm g}$  = ground capacitance per phase in farad and f = system frequency in Hz

#### **Ground fault factor**

$$GFF = \frac{V_g}{V_1/\sqrt{3}}$$
(20.5)

 $V_{\rm g}$  = highest voltage to ground (r.m.s)

# **Further Reading**

- Kaufmann, R.H. and Halberg, M.M., 'System over-voltages, causes and protective measures'.
- Lythall, R.T., *The J & P Switchgear Book*, Butterworths (on balanced and unbalanced components).