Effective Methods For Power Systems Grounding

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Abstract –This paper primarily focuses on the classification of grounding based on rated voltage of the faulty system. The importance of a good grounding design with illustrations is also described. Useful grounding information can be obtained from IEEE standard 80 and the Green Book.

Key-words – Grounding, classifications, characteristics, design, rated voltage, fault current, equipotential.

1. Introduction

The two primary reasons for grounding are:

1. Protection and Safety
2. Reference Voltage

Fig 1 shows different grounding symbols. A signal ground is used as a reference voltage, chassis ground is required to assuage electrostatic voltages and earth ground is used to drain fault currents. Both chassis and earth grounds are serve the purpose of protection and safety of humans as well as appliances.

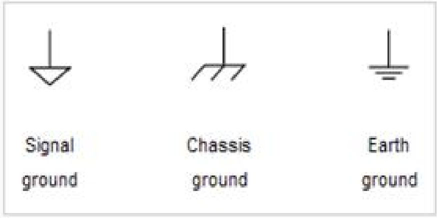


Fig 1 Ground Symbols

Power systems grounding include both chassis and earth grounds. Since the topic is very vast, the paper is confined to earth grounds.

Objective of any power system grounding is to provide a low impedance path for current to drain into the ground at the point of fault with the least clearing time. However there could be situations where obtaining a low impedance path would not be an economical solution. Hence we have to modify our grounding design to best fit the situation.

It will be worth comparing the following two definitions:

1. NESC (National Electrical Safety Code) provides the definition for an effectively grounded system as, "An effectively grounded system is intentionally connected to earth through a ground connection or connections of sufficiently low impedance and having sufficient current carrying capacity to limit the buildup of voltages to levels below that which may result in undue hazard to persons or to connected equipment" [1].
2. The Green Book (IEEE Standard 142) states - effective grounding is achieved when:

$$3X_1 > X_o \quad (1)$$
$$R_o < X_1^2 \quad (2)$$

Where, R_o is zero sequence resistance, X_o is zero sequence reactance and X_1 is positive sequence reactance.

The grounding design for a whole system or circuit is different from grounding methods for single equipment such as a generator or any household appliance. For instance, the grounding design for a skyscraper would depend on grounding grids where as a generator in the skyscraper could be individually grounded. Fig 2 shows several generators and transformers individually grounded.

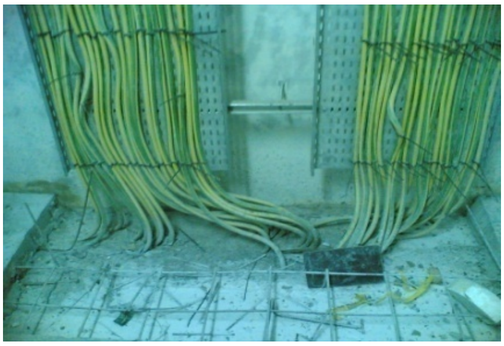


Fig 2 Solid Ground

This paper explains advantages of a good grounding design and most common methods used for grounding power systems. Effort is made to classify and compare several grounding designs. The latter part of this paper provides a general algorithm for designing of grounding power systems. In most cases, to best serve the purpose of a grounding system, the design should be 'situation specific'.

2. Importance of good grounding design

A good grounding system requires a high current capacity path with relatively low impedance at the fundamental frequency so that voltages developed under high fault current conditions are not hazardous. It is very easy to makes a low impedance connection to ground. However problems arise as soon as equipments are connected to it. This could be other near by grounded systems and usually by the equipment of installation itself.

Following are a few examples to consolidate the above:

1. Fig 3 shows chassis of several computers looped together to a common ground. In the figure, the transmission line is connected to the service entrance panel which is connected to the subpanel. Note that not all the loops in the figure are safe. It is considered safe only for those loops in which the chassis are connected to the same ground. In other words, those chassis that are looped between the two panels are unsafe since the panels are grounded separately. This may severely damage the equipments connected to the sub panel. This is because, if at any instant there is any fault on chassis C then the short circuit caused in the system could draw high currents. Now, in the positive cycle of the AC, let the current flow from the Subpanel to the Service entrance. Thus the short circuit current would be drained through the ground in the service entrance. But during the negative cycle of the AC, the short circuit current drawn from the service entrance will be greater than the circuit ratings of all equipments used in the subpanel. Therefore the short circuit current drained through the Subpanel ground will damage all appliances connected to the Subpanel.

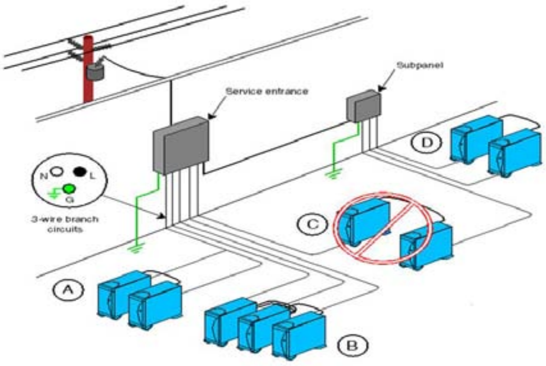


Fig 3 Faulty Ground Connections

2. In transmission line towers, earth wires are used to dissipate the current induced on the lines due to lightning. Adequate distance or gaps should be provided between the arms of the tower lines and the earth wire, to ensure prevention of "Back flashover". Back flashover is the arcing between earth wire and a single phase wire. Note that here the earth wire is the transmission tower itself [2].

Fig 4 Transmission Line Towers

3. Another example would be, in designing of grounding system care should be taken to avoid parallel paths. In following figure we can see that, the fault current I_F in first case is equal to the maximum grid current I_G. However in the second case, the total fault current, I_F at the point of fault is the sum of the currents I_G and I_e. In other words, ground rods or grids should not be connected parallel to the ground instead they should be connected in series or the ground rod should be individually connected to the ground through an earth pit [3].

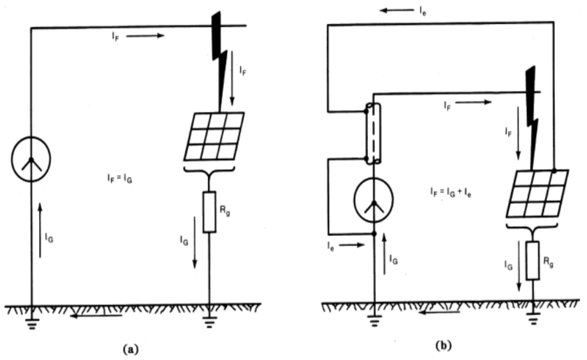


Fig 5 Equipotential silhouettes of a grounding grid with or without ground rods

3. Classification of grounding systems

Design of grounding system could vary greatly depending on situation, application and geography of the site. For instance, if the system to be grounded is of high voltage then low impedance grounding could lead to potential hazards relating to fire. The geography of the site is considered since the soil resistivity could alter the impedance of the grounding system.

Classification of grounding systems (fig 6) could be evasive. Here the focus is on classification of grounding systems with respect to the operating voltage of the system.

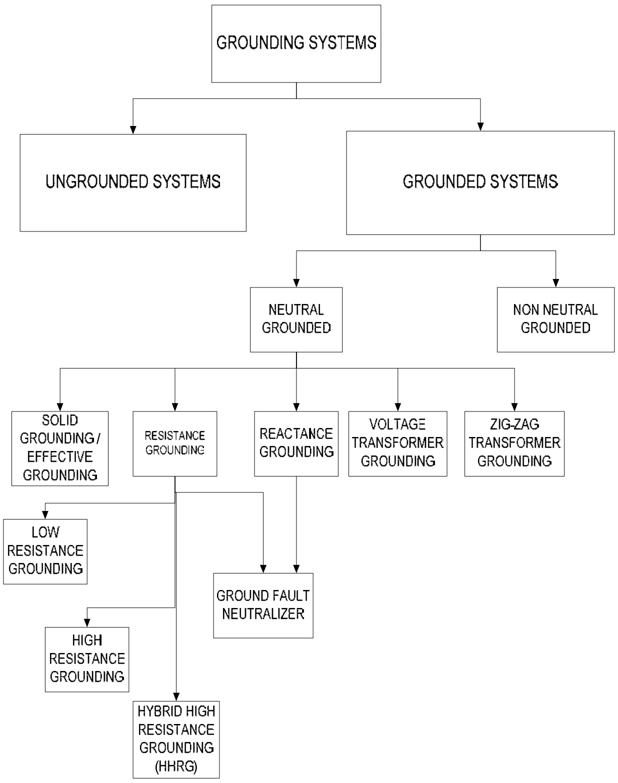


Fig 6 Classifications of Grounding Systems

3.1 Ungrounded Systems

They were thought to be the most stable grounded type of systems because only when there is a ground, there is a low potential. Hence the fault current would be very high in such situations. To avoid such high fault currents ungrounded systems where thought to be good. Also effects of harmonics on an ungrounded system can be ignored due to the fact that since the system is ungrounded the harmonics would eventually die out within the system itself. Finally, for an ungrounded system there is no source of interference from other grounded systems. However, ungrounded systems are very poor in protecting transient overvoltage. Due to these voltages there could be faults beginning from one part of the circuit and propagating throughout the circuit. In these cases the insulation of the conductors would gradually deteriorate and would break down eventually. Such faults would go unnoticed until they occur. Thus we switch over to grounded systems.

3.2 Grounded Systems

There are basically two ways to ground a system. Neutral Grounding is the most common method. It could be used to ground an entire system and it could also be used to ground particular equipments like generators, transformers etc [4]. These methods are usually employed at a power generation station or a substation. Neutral grounding primarily focuses on grounding system ELV systems and EHV systems. Non neutral grounding methods are those used for grounding systems not solely involved to power generation or distribution. The groundings of buildings, substations and the utility grid as a whole could be considered as non-neutral grounding. These types of grounding are primarily focused on medium voltage and low voltage systems. They could also vary according to the regions or countries in which they are installed.

Fig 7 shows grounding systems involving impedances. Apart from the impedances involved, circuit breakers are also shown in combination with grounding. It is interesting to note that the grounding conductor is never tripped. In most cases the breakers trip only the live conductors and not the neutral or earth conductors. A neutral conductor should not be tripped alone. If tripped it should be tripped along with the live conductors.

3.3 Solid Grounding

Solid grounding systems are those that are directly grounded with no impedance. Generally, generators are preferred with this type of ground for providing fast clearing time of high fault currents. It could be attributed to the idea that a fault at the power source would be drained instantaneously at the source itself [Fig 2].

3.4 Low Resistance Grounding

A resistance grounded system is one in which resistance is added along the grounding conductor to keep faults currents within limits. The objective of limiting the fault current here is primarily focused on protecting the insulation of the grounding conductor. Recent suggestions indicate preference for low resistance grounding of generators than solid grounding, to give the system better reliability against overvoltage and harmonics. Resistance grounded systems are best suited for voltages below 150 Volts.

3.5 High Resistance Grounding

Similar to low resistance grounding but differs in the value of resistance. Here the value of resistance is comparatively higher. This would violate the objective of grounding. Low impedance is vital in the sense that current should always choose the grounding conductor to flow at the point of fault. Adding a high resistance would not serve this purpose and is contradictory to the assertion above. But this method of grounding is preferred for limiting of fault currents for medium voltage systems typically in the range of 150 to 600 Volts. Occurrence of arc formation is highly unlikely for voltages below 150 volts and even if an arc is formed, it cannot be sustained [5].

Typical High Resistance Grounding Systems are found in petroleum and chemical industries. Here arc suppressions and prevention of arcs are very important due to presence of highly inflammable substances. A notable disadvantage of high resistance grounding is the amount of time required to drain out the fault current is relatively more than in low resistance or solidly grounding systems.

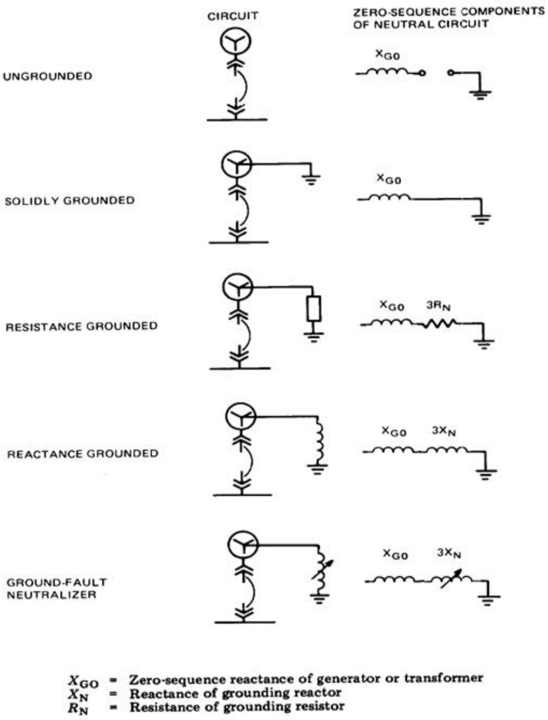


Fig 7 Grounding Systems involving impedances

3.6 Hybrid High Resistance Grounding

There are essentially two reasons for preferring a hybrid grounding system:

1. The fault clearing time in a high resistance grounding scheme is higher than in low resistance grounding schemes.
2. Advantage of a low resistance grounding scheme was mentioned above. However this very boon to low resistance grounded system is a limitation too. This is because when several generators and/or transformers are grounded simultaneously the equivalent impedance of the system would be lower, since all these impedances are in parallel, see fig 8. This could result in a very high increase of fault current of the system in the order of 1000 Amperes. An alternative solution to this could be to provide a neutral bus for multiple power sources and ground the neutral bus through a resistance, see fig 9 [6]. For these reasons the best solution would be to combine the two grounding schemes – a hybrid of low resistance grounding and high resistance grounding. HHRG systems are best suitable in medium voltage applications around 1 to 20 kV [7] [8].

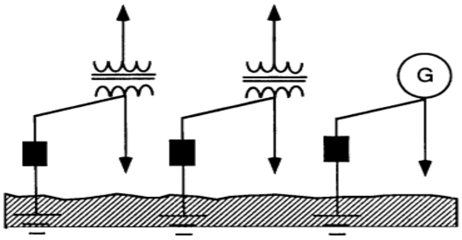


Fig 8 Individually Grounding Power Sources

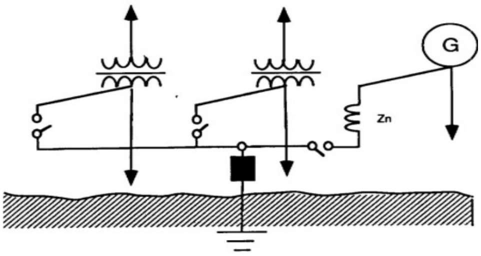


Fig 9 Grounding Several Power Sources through a neutral bus.

Fig 10 shows an application of such a grounding scheme installed in a paper mill involving 13.8 kV generators [9].

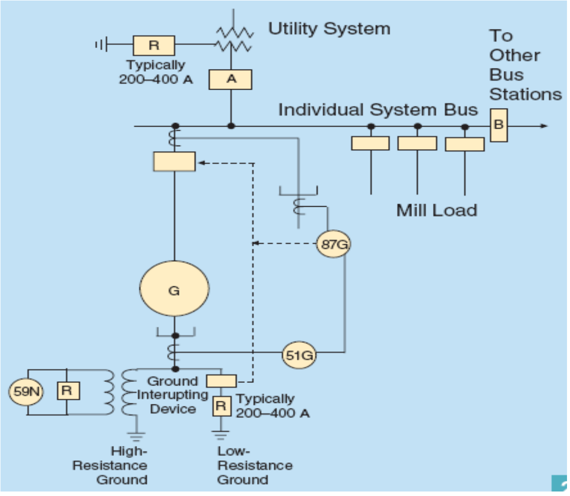


Fig 10 Hybrid High Resistance Grounding Systems

3.7 Ground Fault Neutralizer

Also called Peterson's Coil, this is primarily used for suppressing arcs caused in the grounding conductor with the help of back EMFs of the inductor. Hence they are also known as Peterson's Arc Suppression Coil Grounding. This could be used in parallel with a capacitor to short the high frequency harmonics in the system, see fig 11. Harmonics is generally introduced into a system due to electronic devices such as silicon controlled rectifiers (SCRs) used in HVDC transmission lines, variable frequency drives and also due to interference from radio signals.

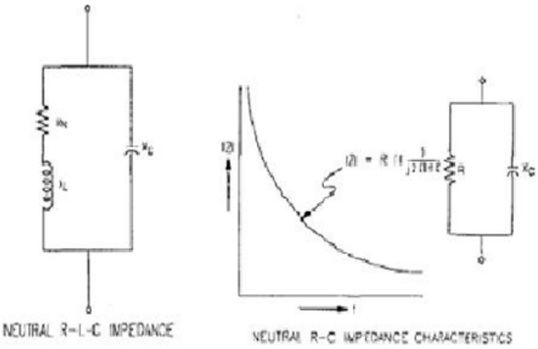


Fig 11 Grounding for high frequency harmonics

Still another form of classification grounded systems that we could think of could be: Impedance and Non Impedance grounded systems. In such a classification non impedance grounded system would be a solidly grounded system and grounding systems involving impedance would be resistance and reactance grounded systems. A typical application of this grounding could be found in aircrafts where the power generated is at 400Hz compared to the normal 50Hz. This is because; the generator size reduces drastically as the frequency increases as evident from the formula below:

$$EMF = NAIB\sin\theta \ (3);$$
$$\theta = \omega t \ (4);$$
$$\omega = 2\pi f \ (5).$$

Where N is the number of turns, A is the area of rotating coil, I is the current flowing through the coil, B is the magnetic field, θ is the angle between normal of the coil plain and magnetic field, t is the time and ω is the angular frequency of the coil.

Table 1 summarizes the above mentioned grounding schemes which would provide better understanding.

Table 1 Grounding Systems: Comparison

	METHODS OF SYSTEM GROUNDING			
Characteristics	**Ungrounded**	**Solid**	**Low Resistance**	**High Resistance**
Susceptible to transient voltage	Worst	good	good	Best
Under fault conditions (Line-Ground) increase of voltage stress	Poor	best	good	Poor
Arc Fault Damage	Worst	poor	good	Best
Personnel Safety	Worst	poor	good	Best
Reliability	Worst	good	better	Best
Economics - Maintenance	Worst	poor	poor	Best

Plant Continues to Operate Under Single Line-Ground Fault	Fair	poor	poor	Best
Ease of locating ground faults (least time)	Worst	good	better	Best
System Coordination	not possible	good	better	Best
Upgrade of ground system	Worst	good	better	Best
Two voltage levels on same system	not possible	possible	not possible	Best
Reduction in number of faults	Worst	better	good	not possible
Initial fault current into ground system	Best	worst	good	better
Potential Flashover to ground	Poor	worst	good	Best

3.8 Voltage Transformer Grounding

In systems where either the primary or secondary windings of the transformer utilize a delta configuration, there is no convenient neutral point connection available as opposed to a star configuration. Hence voltage transformer grounding is used to ground the delta side of the power or distribution transformer, see fig 12.

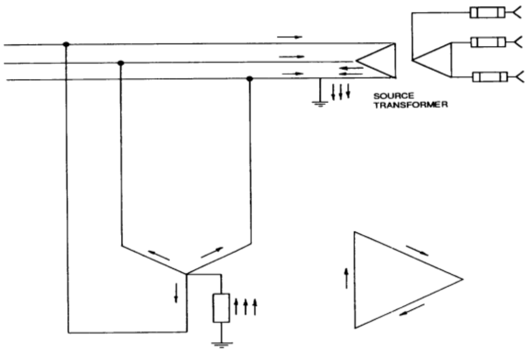


Fig 12 Neutral Ground for star connection

Such grounding transformers are applicable for voltages in the range of 20 kV to 33 kV. Though such grounding methods could be used for lower voltages it could prove costly and is usually avoided. Another advantage of such a system is, since the rated voltage of the system is high any other type of grounding would lead to arcs and very high fault currents. A step down transformer grounding would help to reduce the voltage and then solid or resistance ground the neutral point of the star grounded voltage transformer, thereby limiting fault current values as well as arcs [10].

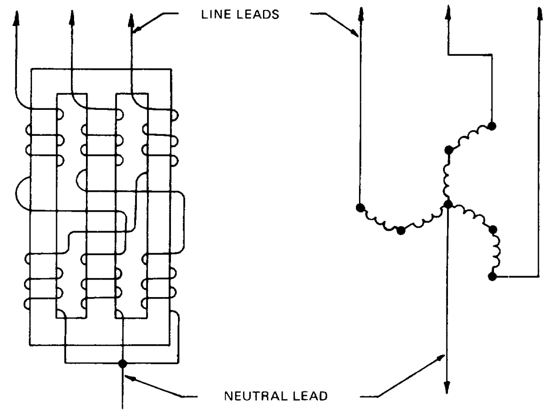
3.9 Zig Zag Transformer

The name zig-zag originates from the zig-zag windings of the transformer. There is no secondary winding in such a transformer. Its sole purpose is to ground systems of very high voltages that are above 33 kV. The most vital benefit of such a grounding transformer is that, it provides a divided path for fault current to flow. The fault current is equally divided on all the three conductors and thus limiting the high fault currents see fig 13.

The types of grounding transformers mentioned above could be used in combination with circuit breakers. Care should be taken when installing transformers in combination with breakers. The rating of the breaker should not exceed the transformer rating. These breakers serve the purpose of protecting the grounding transformer in case of fault currents exceeding the transformer ratings [10].

3.10 Other Types of Grounding (Non-Neutral)

For grounding a delta configuration two methods could be used. The following methods are used for are useful for low voltage systems (600 Volts or below), see fig 14.



(a) (b)

Fig 13 (a) zig-zag transformer (b) star configuration

3.10.1 Corner of the Delta Systems

In the past transformers with delta connected secondaries, have been ungrounded. Grounding of one phase corner of the delta grounding has been to convert a ungrounded system to a grounded sytem. A phase to ground fault could be easily located. It is the cheapest method of converting an ungrounded delta system to a grounded system.

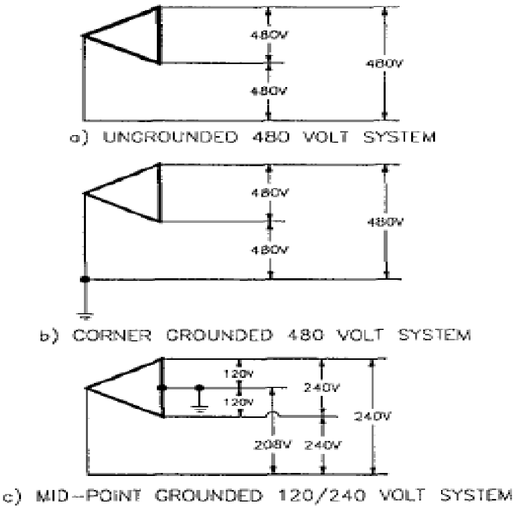


Fig 14 Non-neutral Grounded Systems

3.10.2 Grounding of a Delta System on one of the phases at midpoint.

In situations where three single phase transformers are connected in delta, the midpoint, if available, is grounded. With this method it is possible to gain some of the advantages of neutral grounding by grounding the midpoint of one phase. This method does not provide all advantages of neutral grounded system and is not recommended for voltages over 240 Volts. However it facilitates fast tripping for phase to ground faults and effectively controls, overvoltage to safe levels [10].

Still other types include TT, IT, TN-C, TN-S and TN-C-S system where T stands for earth, I for isolated, C for combined, S for separate and N for neutral These systems are explained in IEEE Standard 142 (Green Book) and in BS 7671 (British Standard).

4. Design Calculation for Power Systems Grounding

The following problem should best summarize the above mentioned methods for grounding any system. Although the power system in consideration is a substation this method could be generally applied to all power systems.

Case 1: Design a square ground mesh.

The data obtained or measured are as follows:
Fault duration, $t_f = 0.5$s
Positive sequence equivalent system impedance, $Z_1 = 4.0 + j10.0\ \Omega$ (115 kV side)
Zero sequence equivalent system impedance $Z_0 = 10.0 + j40.0\ \Omega$ (115 kV side)
Current division factor, $S_f = 0.6$
Line-to-line voltage at worst-fault location = 115,000V
Soil resistivity, $\rho = 400\Omega$-m
Crushed rock resistivity (wet), $\rho_s = 2500\ \Omega$-m
Thickness of crushed rock surfacing, $h_s = 0.102$m
Depth of grid burial, h = 0.5 m
Available grounding area, A = 63 m × 84 m
Transformer impedance, (Z_1 and Z_0) = 0.034 + j1.014 Ω (13 kV)
Z = 9% at 15 MVA, 115/13 kV

Step 1: Field Data

Given area, A = 63m x 84m (5292 m^2) ≈ 70m x 70m (4900 m^2) {for an initial design}.

Step 2: Conductor Size

$I_f \approx 3$ x (symmetrical fault current) = $3I_o$ = 3180 A; X/R ratio = 3.33

$$I_0 = \frac{E}{3R_f + R_1 + R_2 + R_0 + j(X_1 + X_2 + X_0)} \quad (6)$$

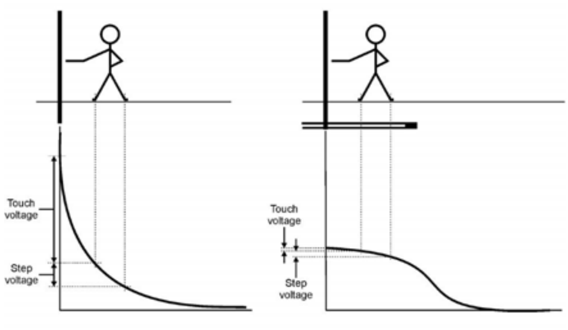
For the 13kv bus fault, the 115kV equivalent fault impedances must be transferred to the 13kV side of the transformer.

$Z_1 = (13/115)^2(4+ j10) + 0.034 + j1.014 = 0.085 + j1.142$.
$Z_2 = 0.034 + j1.014$.
$|3I_o|$ = 6814A {Hence this value is used for conductor sizing}; X/R ratio = 16.2
D_f is found for a given X/R ratio and fault duration, $t_f = 0.5$s (say), then decrement factor, $D_f \approx 1$.
$A_{kcmil} = I \times K_f \times tc^{(1/2)}$ (7)
$A_{kcmil} = 6814 \times 7.06 \times 0.5^{(1/2)} = 34.02$ kcmil
$A_{mm2} = 17.06 = \pi d^2/4$; diameter of the conductor, d = 4.7mm

Step 3: Touch and Step Criteria

In shock situations, the voltage across the human body in contact with the system is calculated. The grounding system designed should not allow any voltage to build across the human body and the ground above this calculated voltage. It is found to be a function of the weight of the person. For instance a person weighing 70kg can tolerate more voltage than a person of 50kg. Also the tolerable voltage across hand to hand or hand to foot (Fig 15) is found to be greater than the tolerable voltage across leg to leg. We can write the tolerable voltage:

$$E_{\text{hand to foot}} > E_{\text{hand to hand}} > E_{\text{foot to foot}}$$



Step and touch voltages

Fig 15

The tolerable voltage between the large part of body in contact with system and foot, hand to foot, hand to hand and foot to foot are called mesh, touch, metal and step voltages respectively. Hence the above relation can be rewritten as:

$$E_{mesh} > E_{touch} > E_{metal} > E_{step}$$

The tolerable potential difference across the body is greatest in mesh or touch voltages because to build up the PD substantially, it has to overcome the electrical activity of the heart.

Another potential that should be taken into consideration during the design is transferred potential. This potential is a result of ground potential rise (fig 16) at the point of fault compared to a remote ground. Hence the potential from substations connected through the grid could be transferred to the point of fault [11].

$$K = \frac{\rho - \rho_s}{\rho + \rho_s} \qquad (8) \qquad\qquad C_s = 1 - \frac{0.09\left(1 - \frac{\rho}{\rho_s}\right)}{2h_s + 0.09} \qquad (9)$$

$$K = \frac{400 - 2500}{400 + 2500} = -0.72 \qquad\qquad C_s = 1 - \frac{0.09\left(1 - \frac{400}{2500}\right)}{2(0.102) + 0.09}$$

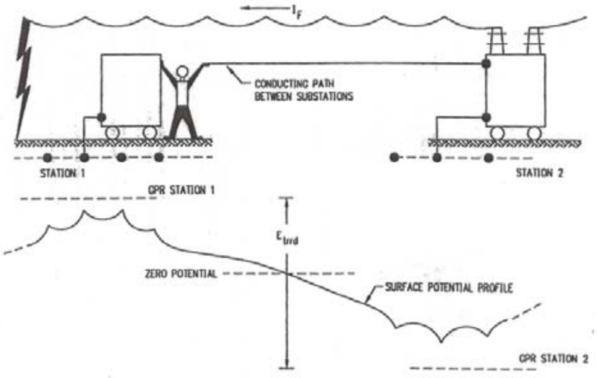


Fig 16 Ground Potential Rise during transferred voltages

$E_{step70} = (1000 + 6C_s\rho_s)\ 0.157 / t_s$ (10)
$E_{step70} = [(1000 + 6(0.74)2500)]0.157/0.5 = 2686.6\ V$
$E_{step50} = (1000 + 1.5C_s\rho_s)\ 0.157 / t_s$ (11)
$E_{step50} = [(1000 + 1.5(0.74)2500)]0.157/0.5 = 838.2\ V$
Where; C_s = Surface Layer Derating Factor
ρ_s = Surface Layer Resistivity Ω-m

Step 4: Initial Design
Layout of the ground mat, G_{mat}; A = 70 x 70m
Grid spacing, D = 7m
Grid burial depth, h = 0.5m
Total length of buried conductor, L_T = 2x11x70

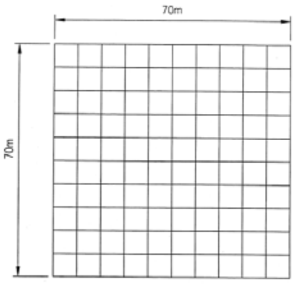


Fig 17 Ground Mat – Initial design

Step 5: Determination of Grid Resistance

$$R_g = \rho\left[\frac{1}{L_T} + \frac{1}{\sqrt{20A}}\left(1 + \frac{1}{1 + h\sqrt{20/A}}\right)\right] \qquad (12)$$

$$R_g = 400\left[\frac{1}{1540} + \frac{1}{\sqrt{20 \cdot 4900}}\left(1 + \frac{1}{1 + 0.5\sqrt{20/4900}}\right)\right] = 2.78\ \Omega \qquad (13)$$

Step 6: Grid Current
Maximum Grid Current, $I_G = D_f \times I_g$ (14)
$I_G = D_f \times S_f \times 3I_o$ (15)
I_G = 1x0.6x3180 = 1908A

Step 7: Ground Potential Rise
GPR = $I_G \times R_g$ (16)
GPR = 1908 x 2.78 = 5304V
GPR = 5304 > $E_{touch70}$ = 832.2V
This is not desirable.

Step 8: Mesh Voltage

$$E_m = \frac{\rho \cdot I_G \cdot K_m \cdot K_i}{L_C + L_R} \qquad (17)$$

$$E_m = \frac{400 \cdot 1908 \cdot 0.89 \cdot 2.272}{1540} = 1002.1\ V$$

Step 9: Comparing mesh and touch voltages
E_m = 1002.1V > E_{touch} = 832.2V. From fig 15 this is not desirable. Hence the design needs to be modified [3].

Case 2: Square grid with ground rods

Generally there are 2 ways to modify the grid design to meet tolerable touch voltage requirements.

1. Reduce GPR to a value below the tolerable touch voltage or to a value low enough to result in a value of E_m below the tolerable touch voltage.

2. Reduce the available ground fault current. Reducing the available ground fault current is usually difficult or impractical to achieve, so the grid is modified by changing any or all of the following: grid conductor spacing, total conductor length, grid depth, addition of ground rods, etc. in this design 20 ground rods will be added to the grid in case 1, along the perimeter of the grid as shown in fig 18.

Using this design, recalculating steps 5 through 9, we find that $E_m = 747.4 < E_{touch} = 838.2$. Since this is desirable we proceed to step 10 to find that $E_s = 548.9V < E_{step} = 2686.6$. Therefore no modification required and we can proceed to step 12 for the detailed design. At this point, all equipment pigtails, additional ground rods for surge arresters etc should be added to complete the grid design details [3].

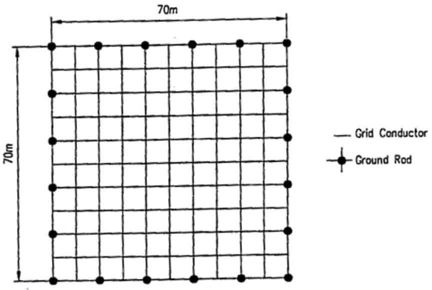


Fig 20 Modified Grid Design

5 Conclusion

Finally it would be worth mentioning the effect of laying a thin layer of material across the whole surface of the substation. This is done so that the varying soil resistivity does not affect the ground loop impedance at the time of fault. The thin layer of material has very high resistivity compared to that of the soil beneath it. This would not only provide a high impedance to ground for humans at the time of shock and thereby limiting the current through the body. The system ground could be directly connected to the soil beneath the layer. It also helps reduce current densities residing on the top layer of the soil in case of soil layer with higher resistivity on the surface than below. In other words it helps in draining current faster from the thin surface layer to the soil beneath by not allowing current to accumulate on the top surface and hence reducing current density on the top layer.

Reclosure of switchgears such as isolator and circuit breakers are another important aspect of power systems. Reclosure after a ground fault is common in modern operating practice. In such circumstances, a person might be subjected to the first shock without permanent injury. Next, a single instantaneous automatic reclosure could result in a second shock, initiated within less than 0.33s from the start of the first. It is this second shock, occurring after a relatively short interval of time before the person has recovered, that can cause a serious accident and may prove to be fatal. With manual reclosure, the possibility of exposure to a second shock can be reduced because the reclosing time interval may be substantially greater. The cumulative effect of the two or more closely spaced shocks has not been thoroughly evaluated but a reasonable allowance can be made by using them as a sum of individual shocks as the time of a single exposure (lumped model).

All power systems from generation to transmission ending with the distribution of electricity require grounding protection. Not only does a power system require grounding, even electronic sensitive equipments require grounding for both protections against static electricity as well as for ground reference.

There is still a wide variety of grounding methods employed. The classifications discussed in this report depend on the rated voltage of the system. Grounding is also very important for both reliability and stability of power systems.

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