Lecture # 15

Grounding and Shielding

Earth surface in electrical power engineering practice is considered as an infinite conductor with zero potential, and is capable of taking very large currents. However, the conductivity of the Earth depends on the soil characteristics, being large for moist soil and relatively smaller for hard and dry soil. Furthermore the Earth surface is regarded as an equipotential with zero potential throughout and is usually considered as a reference in power system analysis. A path must exist between the equipment and ground through a conducting medium that is usually a bonded conductor wire referred to as ground or earth wire. The equipment is thus grounded or earthed. The grounding of equipment in power system has the following functions:

1. To provide a system connection to transformer neutrals or impedances that may be connected if required so as being capable of passing the maximum ground-fault current, and that the passage of fault current should not produce any thermal or mechanical damage to the insulation of the connected equipment.
2. To provide a system for which every exposed internal and external conductive part may be connected to avoid electrocution hazard to personnel.
3. To avoid hazardous potential gradients (step or touch potentials) or transferred potentials which can occur under normal or abnormal conditions by equipotential bonding within the power system.
4. To minimize electromagnetic interference between power system components, control panels and communication systems.
5. To ensure correct operation of protective gear (including: surge protective devices).

Substation Grounding

In substations single-point grounding system is accomplished when all equipment are connected to a master bus bar which in turn is bonded to the external grounding system. The grounding system should be designed to reduce AC impedance and DC resistance. It is worth mentioning that fault levels tend to increase over the lifetime of the installation as more interconnections and generation capacity is added to the system due to growing demand. It is therefore necessary to allow sufficient margin for this increase. The standard substation short-circuit design fault duration (1 or 3 seconds) is generally considered for calculating the size of the grounding conductor. The conductor cross-section S (in mm^2) should not be less than the value determined by the following formula:

$$S = \frac{I_{SC}\sqrt{t}}{K} \qquad 2$$

Where: I_{SC} is the RMS value of fault current in amperes, t is operating time of disconnecting device, in seconds and K is a factor dependent on the material of the conductor and the insulation and the initial and final temperatures. Some values of *K* for different conductors are listed in Table (1) in accordance with IEC 364 Standard Specifications.

Table 1: Values of *K*

1	Bare copper conductors Initial temperature of conductor Maximum temperature of conductor K factor (IEC 364)	 = 30°C = 150°C or 200°C = 138 or 159	
2.	XLPE insulated copper/aluminium cable Initial temperature of conductor Maximum temperature of conductor K factor (IEC 364) copper K factor (IEC 364) aluminium	Single core = 90°C = 250°C = 176 = 116	Multicore 90°C 250°C 143 94
3	Bare steel electrode Initial temperature of conductor Maximum temperature of conductor K factor (IEC 364)	 = 30°C = 200°C = 58	

Substation grounding system usually comprise of grounded metal cage or fence around the substation equipment. The grid may be supplemented by ground rods or electrodes to assist the dispersion of ground-fault currents and further reduce the overall substation grounding resistance. Each ground point should consist of a combination of not less than two rods capable of carrying the full ultimate prospective fault current for the 1 or 3 second substation design criteria. Ground rods are usually solid copper or copper-clad steel with screw threads along its length and joints for connecting them together in order to insert them to the required depth through the soil. The resistance R_R in Ohms of the rod (footing-resistance) is calculated from the following formula:

$$R_R = \frac{\rho}{2\pi L}\left[\ln\left(\frac{8L}{d}\right) - 1\right] \qquad 3$$

Where ρ is the resistivity of soil (Ω-m) and is 1 for seawater, 10 for moist soil and is above 1000 for hard rock. *L* is length of ground rod in meters and *d* diameter of ground rod in meters. Separate high-frequency ground connections are sometimes specified for use with wave-trap equipments associated with power line carrier systems. In particular, surge arresters, current and potential transformers should have dedicated low resistance ground connections in order to ensure that current loops do not cause mal-operation of protection system. The current I_{soil} through the soil resistance R_{soil} in grounded system is given by:

$$I_{soil} = \frac{1}{2\pi}\left(\frac{\rho E_0}{R_{soil}^{\ 2}}\right) \qquad 4$$

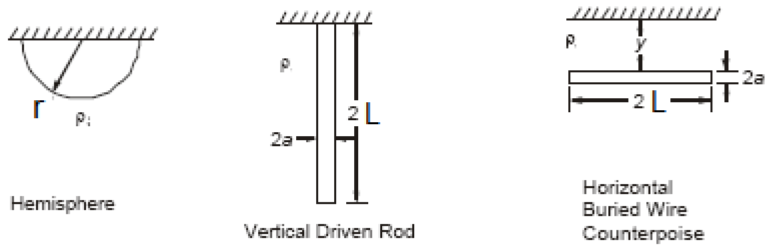
Where E_0 is the soil gradient and is usually considered as 400 kV/m for most purposes. Knowing the soil current, soil resistance and lightning or surge current I_S through the footing impedance, the tower-footing resistance can be calculated by:

$$R_F = \frac{R_{soil}}{\sqrt{1+\left(\frac{I_S}{I_{soil}}\right)}} \qquad 5$$

The tower footing resistance R_F will depend on the type of electrode configuration used and the soil resistivity. The most common types of electrode shapes used in practice are the hemisphere and long slender rods with few centimeter in diameter and about 10 to 15 meters in length, driven vertically down into the soil and connected solidly to the tower or pole footings. Sometimes ground electrodes in the form of horizontal wires, also known as the "counterpoise" having lengths of 50 to 150 meters are buried in soil where vertical ground electrodes cannot be driven. Table (2) provides the formulas for calculating the tower footing resistance and the main physical dimensions of ground electrode for various configurations.

Table 2: Earth Electrode Shapes, Dimensions and Formulas

	Electrode Shape	*Resistance*
1	Hemisphere, r	$R_F = \frac{\rho}{2\pi r}$
2	Vertical driven rod radius a, length 2L	$R_F = \frac{\rho}{2\pi L}\ln\left(\frac{2L}{a}\right)$
3	Horizontal wire. (radius a, length 2L depth y)	$R_F = \frac{\rho}{2\pi L}\ln\left(\frac{2L^2}{ay}\right)$



Cathodic reactance and soil testing should be considered during the site selection for grounding. Man-made soil additives and backfills are useful in difficult soils circumstances: they should be considered where lowering grounding impedances are difficult by conventional means. Regular physical inspections, maintenance and testing should be exercised.

Example: In a transmission line system, it is required to obtain a tower-footing resistance of 18 Ω in loosely bond soil of resistivity 100 Ω-m using the three different types of grounding electrodes configurations. Assume; *a* = 1.5 cm for rods and counterpoises and a depth 0.65 m for the counterpoise. Calculate the required dimensions.

Solution:

Given that: tower footing resistance is 18 Ω and soil resistivity is 100 Ω-m.

Vertical rod configuration:

In this case the length *L* of the rod is to be calculated using:

$$R_F = \frac{\rho}{2\pi L}\ln\left(\frac{2L}{a}\right)$$

Or

$$\ln\left(\frac{2L}{0.015}\right) = \frac{2\pi L R_F}{\rho} = \frac{2\pi \times L \times 18}{100}$$

For calculating length *L*, numerical solution is only possible, which yields: ***L* = 5.9m or 6m (approximately).**

Hemispherical electrode configuration:

In this case the radius *r* is to be calculated using: $R_F = \frac{\rho}{2\pi r}$. From which:

$$r = \frac{100}{2\pi \times 18} = \mathbf{0.88m}$$

Horizontal counterpoise:

In this case the length *L* of the rod is to be calculated using:

$$R_F = \frac{\rho}{2\pi L}\ln\left(\frac{2L^2}{ay}\right)$$

Or

$$\ln\left(\frac{2L^2}{0.015 \times 0.65}\right) = \frac{2\pi \times L \times 18}{100}$$

Numerical solution is only possible, which approximately gives: ***L* = 8.5m.**

Shielding

Power system areas such as substations and transmission lines are usually exposed to lightning strokes. It is therefore a common practice to use overhead ground wires in power system substations and all overhead transmission lines systems for protection against lightning discharge. These ground wires in all high-voltage transmission and distribution lines are used to protect the phase conductors from lightning strokes. Since ground wires run above the phase conductors, they serve as a protective "blanket" on top of phase conductors. In other words these ground wires shield the phase conductors and therefore they are also referred to as shield wires. The shield wires are made from ACSR instead of galvanized steel in order to reduce both the series resistance and inductance. These ground wires are usually electrically connected firmly to the tower-top so that they are grounded directly and therefore a ground potential (zero) is maintained at the tower-top. As a result, only the phase conductors of transmission line experiences a potential with respect to ground. In recent years Optical Ground Wire (OPGW) has been introduces as dual-purpose wires hanging above the phase conductors. OPGW serve as a medium for transmitting data and carrier communication in addition to shielding.

The shield or ground wire must be located above the phase conductors on a transmission line tower to provide protection angle of 30 degrees on either side of the transmission line tower with respect to the geometric neutral plane as shown in Figure (1). In some cases the transmission line companies uses a protection angle of 45 degrees. The protection zone should be formed to also allow the movement (swinging) of insulator string in the event of heavy winds during thunderstorm.

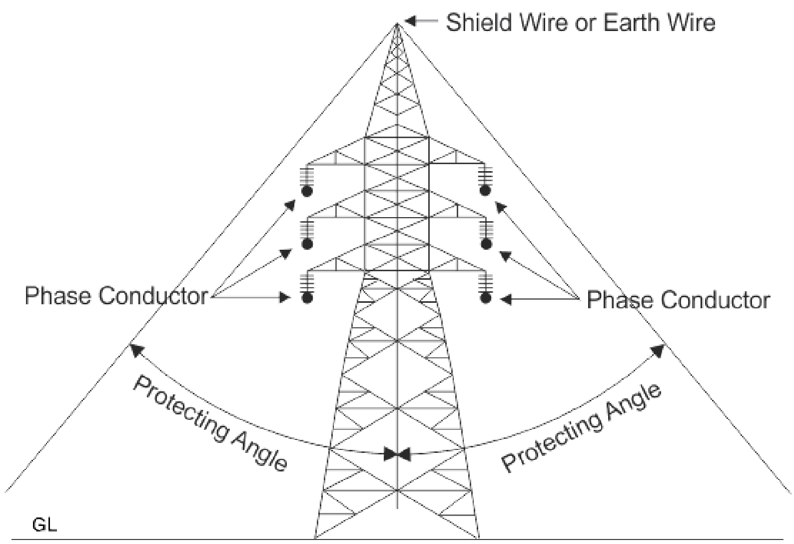


Figure 1: Shield Angle and Protection Zone

The line wires must lie within the region of protection zone provided by the shield wire. Generally a single running ground wire is used up to 132 kV lines, but in the case of EHV lines, such as 220 kV and 500 kV, two ground or shield wires are used as shown in Figure (2) in which the location of connector for ground wire is indicated. When transmitting power at higher voltages, the distance of line conductors must also increase to provide adequate clearance between the tower structure and the line conductor and also between the different phases.

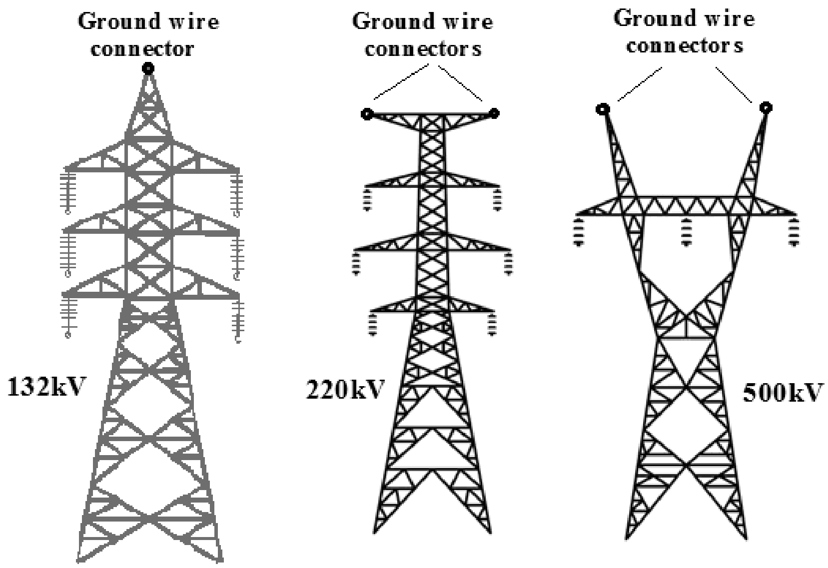


Figure 2: Transmission Line Towers with Ground Wire Location

Outdoor substations are usually shielded by a network of overhead ground wires screens hanging across the substation site or by the use of shielding towers or structures. The use of shielding towers alone tends to require tall structures in order to give adequate protection zone. The shield wire system allows lower height structures for a given protection zone coverage and the lightning current will be attenuated by increasing the number of paths to ground and thereby reducing the risk of back flashover. Often substation overhead line termination towers act as suitable support points for the shielding wire and screens. The protection zone provided by shield wires over a substation is the volume of hypothetical cone.

Back Flash or Arcing Ground

Transmission line towers carry ground wire, conductively connected to the tower top and providing shielding to the phase conductors from atmospheric lightning strokes. The top ground wire is solidly earthed at both ends over the entire length of the transmission line at the substation. However, in order to provide effective grounding, towers at specific locations are reinforced with ground electrodes (rods and counterpoises). A single counterpoise used with the tower footings has surge impedance, which falls to power-frequency resistance in the event of lightning strike on the tower. Voltage and current waves travel down the tower at about one-third the speed of light encounters this combination. At a time equal to twice the travel time, the impedance is reduced to power-frequency resistance, which is equal to total leakage impedance of the counterpoise. The surge current is grounded with little or no chance of any harmful consequences.

In the case of in-effective or faulty ground, that may be due to a broken bonding wire or rusting of ground wire contact at the footings. This may be treated equivalent to introducing an impedance Z between the tower and the ground as shown in Figure (2). In such cases the surge current is not grounded instantly and therefore induces voltage on the tower. If this total voltage exceeds the insulator flashover voltage, a flash will occur through a least possible distance, referred to as strike distance. This is called back flashover or simply a back-flash and is illustrated in Figure (3). When this occurs, half of the surge impedance of the phase conductors acts in each direction, and the primary traveling waves on the conductor in each direction give rise to induced (coupled) traveling waves on the other two phases. This may reduce the induced voltage by 30 to 40% on the insulators of phases, which were not struck by lightning and thus prevent further flashovers.

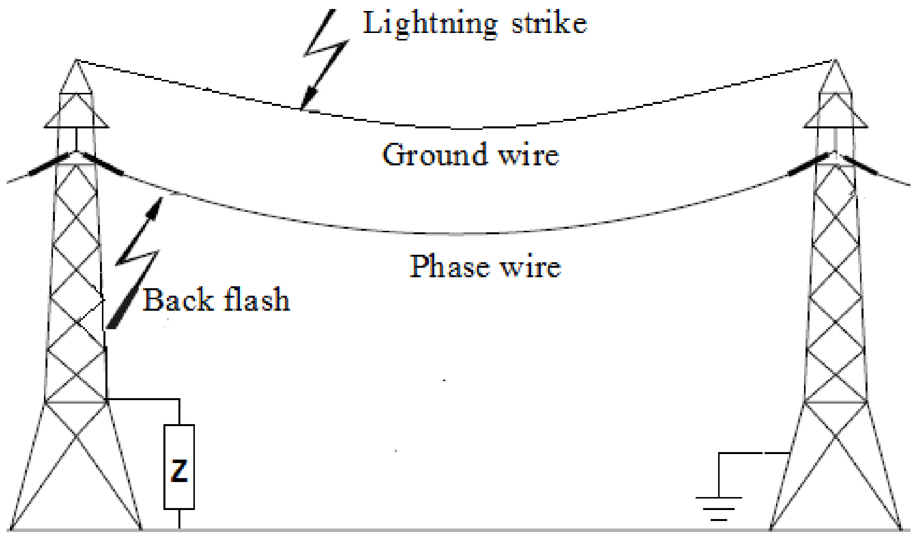


Figure 3: Illustration of Back Flash from Tower to Phase Conductor

The phenomena of back flashover can be understood on the basis of charge accumulation and building up of potential on the tower when lightning discharges on the ground wire close to the tower or the tower-top. When a lightning stroke hits the overhead ground wire, the charges flow towards the ground through the tower. Since the inclusion of impedance *Z* due to faulty ground, these charges do not effectively flow in to the ground but accumulates on the tower, thereby raising the tower potential. The rise of potential on the tower will depend on the rate of increase of the accumulation of charges on the tower, which is in turn is dependent on the wave-front time of the stroke current. If the tower potential is considerably larger, a flashover will take place between the tower and the phase conductor nearest to the tower.

The phenomena of back flash is sometimes referred to as arcing ground, since the arc builds up from a ground object (tower) and strikes the phase wire. It must be remembered that arc or flashover takes the least path-length referred to as strike distance. This path-length may be along the insulator string through air. Thus the back flashover can also strike the phase wire across the rod gap (if provided). The provision of either rod–rod electrodes or a guard ring as a coordinated gap can be useful to divert such flashovers thus protecting the string from permanent damage.