UTM
UNIVERSITI TEKNOLOGI MALAYSIA

Earthing

Chapter 4

Contents

4.1 Fundamentals of earthing

4.1.1 Introduction-Background on Earthing

- BENJAMIN FRANKLIN (1706-1790)

Benjamin Franklin founded the flying-kite experiment in the effort to prove lightning is an electrical natural phenomenon. The experimental set-up: An electric Kite, Silken String which was conducting, waxed string not conducting, a key and his finger to feel the tantalizing effect of electrical discharge where the charges being induced by the presence of thunderclouds. Benjamin introduced the first lightning rod placed on the roof of building. **The rod was connected to down conductor which subsequently connected to the ground terminal**. This might have muted from the electric kite experience.

- NIKOLA TESLA(1856-1943)

Invented telephone repeater, rotating magnetic field principle, polyphase alternating-current system, induction motor, alternating-current power transmission, tesla coil transformer, wireless communication and more than 700 other patents. **Tesla grounded the transformer tank to ground to protect personnel from the consequent of short-circuit fault in the transformer to the ground.**

Introduction-cont.

- **Protection** of electrical power networks and building structures from lightning strikes can be realized by means of lightning **earthing** system. Also hazards of **step voltage, touch voltage and transferred voltage** can be reduced by providing good and **effective earthing system**. These voltages are there due to discharging from the system to the earth terminal network.
- For a transmission line, when lightning strike the tower, a sudden rise of earth potential on it can cause **backflashover** or sideflashover. This phenomenon may result in line outages due to flashover between line to line or line to the **earthed** tower. It is proven that the **rate of backflashover** is very much dependent on the **tower footing resistance** and that this backflashover increases remarkably with increasing footing resistances.

Introduction-cont.

- Also, during the **current penetration to ground via earth terminal network** can cause a spread of potential starting from point of strike of the lightning or fault current. Thus, the provision of a good earth connection will reduce the likelihood of blackflashover as well as reduce the **spread of dangerous voltages around the earth point.**
- **An earthed metallic sheath of an underground cable, the neutral of a PME system or an earth wire in a transmission line may provide a low resistance path from a fault back to the system neutral.** A system is satisfactorily earthed if the protective gear operates to remove danger in the event of a fault to any metalwork having a continuous metallic connection to the system neutral.
- With some overhead lines, because of **high soil resistivity**, it may not be possible economically to attain a sufficiently low resistance fault path and the operation of **overcurrent protection may be slowed down** or inhibited.

4.1.2 Safety Ground

- Safety ground is meant to ensure that persons working with electrical equipment will not be exposed to the danger of **electrical shocks**

- Safety of operating personnel requires grounding of all **exposed metal** parts of power equipment

- There is no simple relation between the **resistance of the ground system** as a whole and the **maximum shock current** to which a person might be **exposed**

- Thus a **low station ground resistance is not itself a guarantee of safety**

Safety Ground

- Range of tolerable currents
  - Effects of an electric current depend on its **duration**, **magnitude**, and **frequency**
  - Human beings are **most vulnerable** to current with frequencies of **50 to 60 Hz**
  - Human body can tolerate slightly **larger currents** at **25 Hz** and approximately **5x larger direct currents** and still **larger** currents at **3 to 10 kHz**
  - Currents of **1 to 6 mA**, often termed **'let-go currents'** – do not impair a person's ability to control his/her muscles
  - **9 to 25 mA** – may be **quite painful** and can make it **hard to release energized objects** grasped by the hand
  - **Larger currents**- **uncontrollable muscular contractions** could make breathing difficult
  - **100mA range- ventricular fibrillation, stoppage of the heart, or inhibition of respiration** might occur and cause severe injury or death
  - $I = f(t^{-1/2})$
  - High speed **clearing** of ground faults is crucial

Safety Ground

- Range of tolerable currents – cont.
  - One's body should not be a part of an electrical circuit
  - Means of reducing hazard:
    - **Grounding**
    - **Isolation**
    - **Guarding**
    - **Insulation and Double insulation**
    - Shock limitation
    - Isolation transformers
    - Employ high-frequency and DC

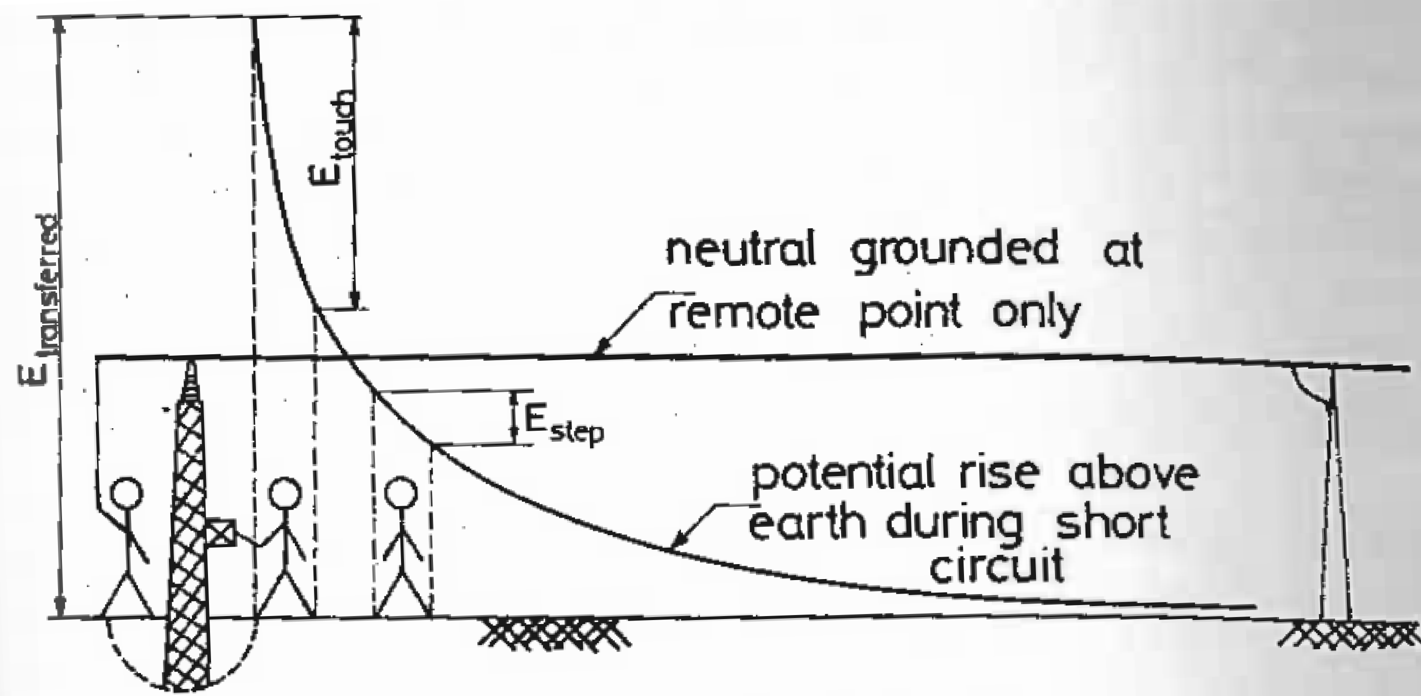


Fig. 13.7 Step, touch, and transferred voltages near a grounded structure.

- Tolerable step, touch, and transferred voltages
  - Using the magnitude of the tolerable body current and the approximate circuit constants, its is possible to calculate the **tolerable potential difference between possible points** of contact
  - The **step voltage** increases the closer one gets to the site of a ground fault or to the grounding point
  - If the **enclosure of grounded equipment** in which an earth fault has occurred **is touched** by a person, he or she will be subjected to a **potential** termed a **'touch voltage'**
  - When a **person standing** within the station areas **touches a conductor grounded** at a **remote point** or when a person standing at a remote point touches a conductor connected to the station ground grid, he or she is subjected to a **transferred potential.** The **shock voltage** in this case may be equal to the full voltage rise of the ground grid under fault conditions
  - The **tolerable step and touch voltages** with duration t_s for persons weighing 50 to 70 kg could be estimated in terms of **t**, **soil homogeneity, and ground resistivity** (Eqns 13.22 and 13.23 Khalifa)

4.2 Earthing system and soil structure

- **Correlation between Resistivity and Resistance**

Equation for unit length resistance:

$$\frac{R}{l} = \frac{\rho}{A}$$

where $\rho$is the resistivity of the material (Ω.m)

A is the **cross-sectional area of the strap** in consistent unit (m^3)

For example, for a hemispherical electrode,

$$R = \frac{\rho}{2\pi a}$$

where:

ρ	is resistivity of material
a	radius of hemispherical electrode
R	is resistance of the buried electrode

Soil Resistivity

- The soil resistivity is also known as the **earth resistivity** and it is measured in **ohm-metre** per cubic centimetre of the sample of earth.

  In **non-homogeneous ground**, the resistivity is the **geometrical mean of the various materials** making up the mass of earth to the depth of the measurement.

- **Soil Resistivity Factor** - Factors affecting soil resistivity are as follows:
  i. Soil **type** and **nature** of soil
  ii. **Concentration** and composition of the **dissolved substances** in the immediate neighborhood
  iii. **Temperature** of the soil
  iv. **Moisture** content of the soil
  v. **Water** content
  vi. **Ion** concentration

- The resistivity of soil depends on the amount of **salts dissolved** in its moisture.
- A small quantity of dissolved salts can reduce the resistivity very remarkably
- Different salts gave different effects on the sol resistivity, which explains why the resistivities of apparently similar soils from different locations vary considerably
- The distribution of **grain size** has an effect on the manner in which the moisture is held.
- The finer the grading, the lower will thus be the resistivity
- It is reasonable to assume that higher pressures resulting in a more compact body of earth will result in lower values of resistivity

- The value of **resistance to ground of an electrode system** is the **resistance between the electrode system** and **another 'infinitely large' electrode in the ground at infinite spacing**
- The **soil resistivity** is a deterministic factor in evaluating the ground resistance. It is an electrophysical property
- The soil resistivity depends on **the type of soil**, **its moisture content**, and **dissolved salts.**
- There are effects of **grain size** and its distribution and effects of **temperature** and **pressure**
- **Homogeneous** soil is seldom met, particularly when large areas are involved.
- In most cases, there are several **layers of different soils**.

- For **nonhomogeneous soil**, an apparent resistivity is defined for an equivalent homogeneous soil, representing the prevailing resistivity values from a certain depth downward
- The **moisture content of the soil reduces its resistivity**
- As the moisture content varies with seasons, the resistivity varies accordingly
- The grounding system should therefore be installed nearest to the **permanent water level**, if possible, to minimize the effect of **seasonal variations** on soil resistivity.
- As water resistivity has a larger temperature coefficient, **the soil resistivity increases as the temperature is decreased**, with a discontinuity at the freezing point.

- **Effect of the Type of Soil**

Table 4.1: Typical **Resistivity Value** of Some Soils (From Tagg, 1964)

NO.	TYPE OF SOIL	RESISTIVITY (Ω.cm)
1	Loam, Garden Soil, etc	500-50,000
2	Clays	800-5,000
3	Clay, Sand and Gravel Mixtures	4,000-25,000
4	Sand and Gravel	6,000-10,000
5	Slates, Shale, Sandstone, etc	1,000-50,000
6	Crystalline Rocks	20,000-1,000,000

- **Effect of the Type of Soil**

Table 4.2: Typical **Resistivity Value** of Some Soils (From Ryder, 1952)

NO.	TYPE OF SOIL	RESISTIVITY (Ω.cm)
1	Clay	2,000-6,00
2	Sandy Clay	8,000-20,000
3	Marsh, peat	15,000-30,000
4	Sand	25,000-50,000
5	Rock	Up to 1,000,000

- **Effect of Moisture**

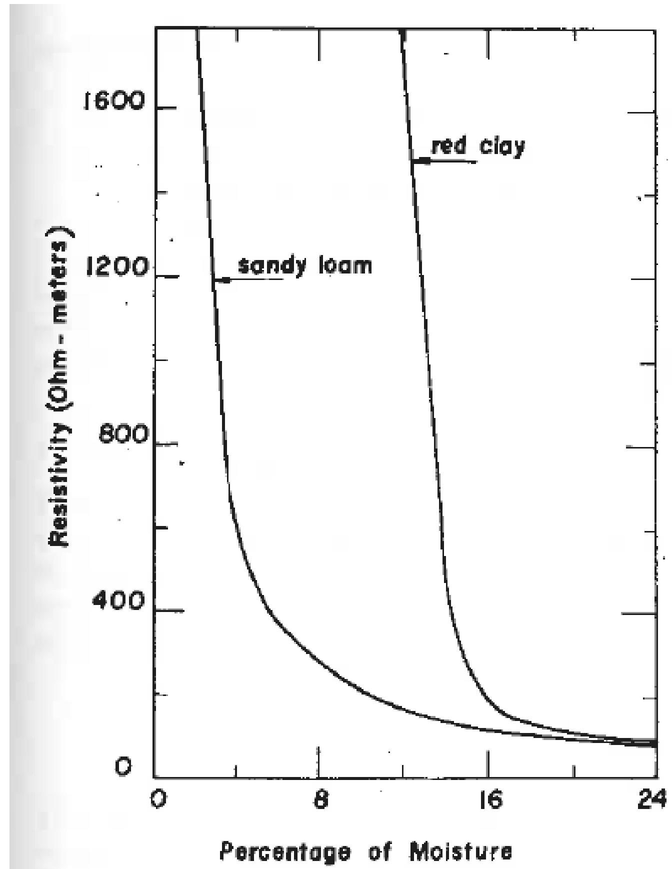


Figure 1: Variation of soil resistivity versus moisture (From Khalifa, 1990)

- **Effect of Moisture**

Table 3: Moisture Content and Resistivity (From Ryder, 1952)

Moisture Content By Weight (%)	Resistivity (Ω/cm^3)	
	Top Soil	Sandy Loam
0.0	$1,000 \times 10^6$	$1,000 \times 10^6$
2.5	250,000	150,000
5.0	165,000	43,000
10.0	53,000	18,000
15.0	19,000	10,500
20.2	12,000	6,300
30.0	6,400	4,200

- **Effect of Dissolved Salts in the Water**

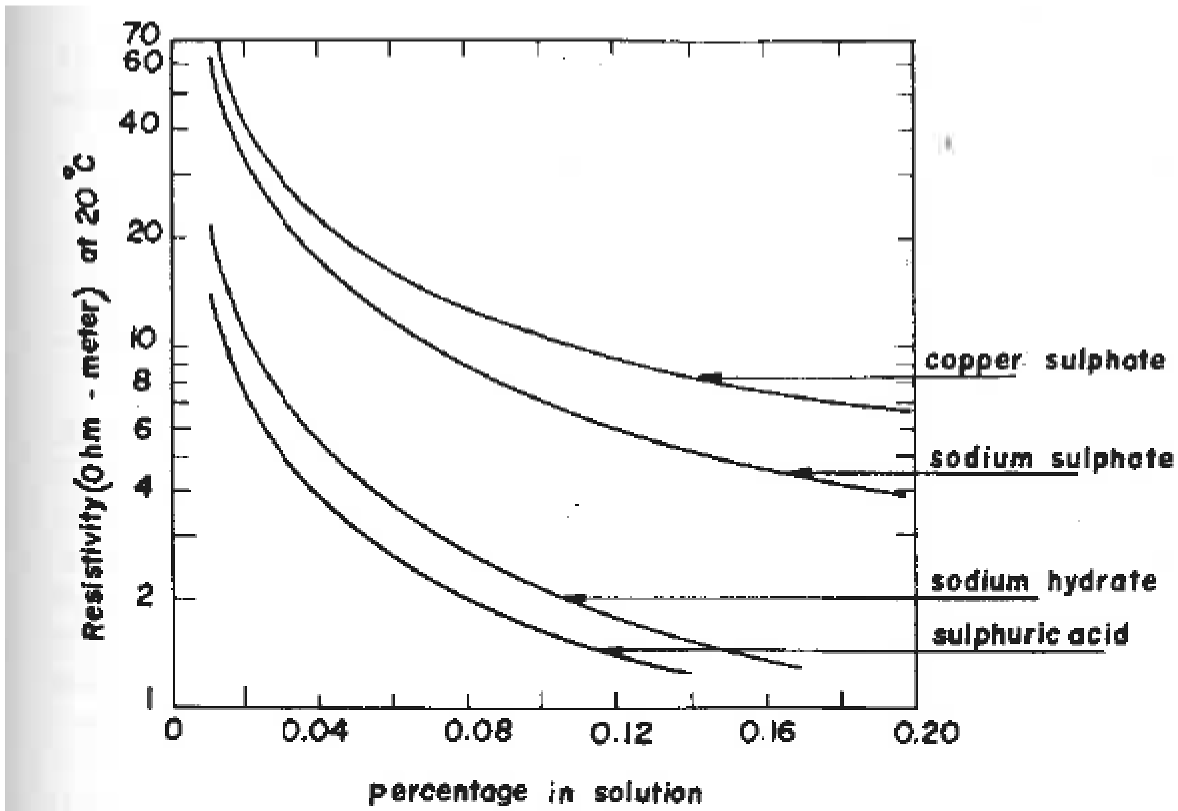


Figure 2: Resistivities of Different Solution (From Khalifa, 1990)

- **Frequency Effect of Current into the Ground**

Equation for unit length resistance:

$$\frac{R}{l} = \frac{\rho}{A}$$

where ρ is the resistivity of the material (Ω.m)

A is the **cross-sectional area of the strap** in consistent unit (m^3)

Unit length capacitance can be calculated from equation

$$C = \frac{\varepsilon_r l}{18.\, ln\left(\frac{4l}{d}\right)} \times 10^{-9}$$

where:

- C is capacitance of the conductor (Farad)
- ε_r is the constant permittivity 8.854 x 10^{-9}
- l is length of conductor/rod (m)
- d is diameter of conductor/rod (m)

The **inductance** of rod can be calculated from:

$$L = 2l.\, ln\frac{4l}{d} \times 10^{-3}$$

where:

L is inductance of conductor (H)

l is the length of conductor (m)

d is the diameter of conductor (m)

The effect of the **resistive** elements of the grounding circuit will predominate at **very low frequency**.

At certain frequency, the magnitude of the **inductive reactance** equals the magnitude of the **capacitive reactance** and the circuit undergoes **resonant**.

- **Current Characteristics**

<u>Direct Current (DC)</u>

For a given load, direct current (DC) is a steady flow of current in one direction only.

Equation **V = IR** is applicable to DC circuits.

<u>Alternating Current</u>

Alternating current (AC) is continually changing magnitude and direction.

Equation **V = IR also applicable to AC circuits only when the AC circuit contains a pure resistance load**.

4.3 Resistance of earthing systems

Resistance of a grounding point electrode

- The simplest possible electrode is the hemisphere

$$R = \frac{\rho}{2\pi a}$$

where:

ρ	is resistivity of soil
a	radius of hemispherical electrode
R	is resistance of the buried electrode

- Exercise: Prove the above equation.

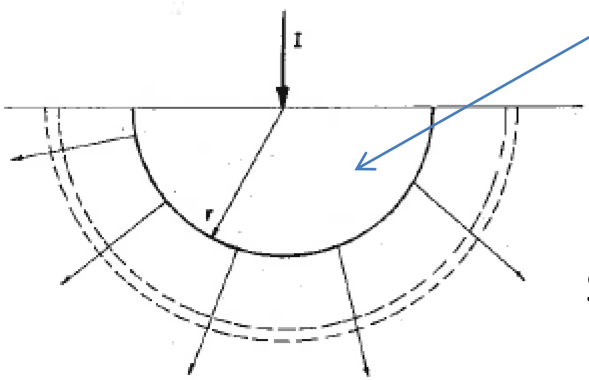
Exercise: Prove the above equation.

Hint: 1. Consider infinitesimal increment in resistance given by dR

(consider the resistance of the skin of half of a football)

2. Integrate from r=a to r=infinity

Hemispherical electrode with radius a



Soil with a resistivity ρ

Resistance of driven rods

- The driven rod is one of the simplest and most economical form of electrodes
- Its ground resistance could be calculated if its shape is approximated to that of an ellipsoid of revolution having a major axis equal to twice the rod's length and a minor axis equal to its diameter d, then

$$R = \frac{\rho}{2\pi L} ln\left(\frac{4L}{d}\right)$$

- If the rod is taken as cylindrical with a hemispherical end, the analytical relation for R takes the form

$$R = \frac{\rho}{2\pi L} ln\left(\frac{2L}{d}\right)$$

- If, however, the rod is assumed as carrying current uniformly along its length, the formula becomes

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

Table - approximate formulas for the resistance of electrodes with various shapes

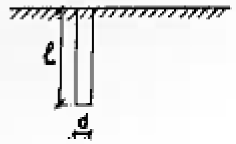
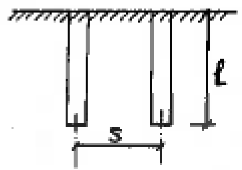
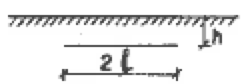
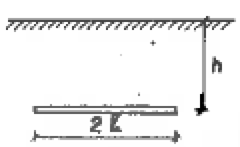
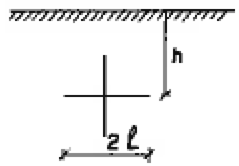
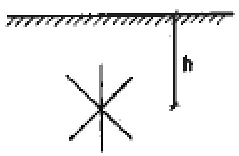
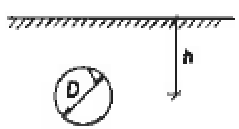
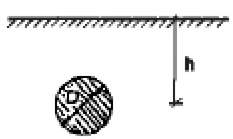
	Ground rod	$R = \frac{\rho}{2\pi\ell}\left[\ln\left(\frac{8\ell}{d}\right) - 1\right]$
	Two ground rods $S > \ell$	$R = \frac{\rho}{4\pi\ell}\left[\ln\left(\frac{8\ell}{d}\right) - 1\right] + \frac{\rho}{4\pi S}\left(1 - \frac{\ell^2}{3S^2}\right)$
	$S < \ell$	$R = \frac{\rho}{4\pi\ell}\left(\ln\frac{32\ell^2}{dS} - 2 + \frac{S}{2\ell} - \frac{S^2}{16\ell^2}\right)$
	Horizontal wire	$R = \frac{\rho}{4\pi\ell}\left(\ln\frac{16\ell^2}{dh} - 2 + \frac{h}{\ell} - \frac{h^2}{4\ell^2}\right)$
	Horizontal strip (section a by b)	$R = \frac{\rho}{4\pi\ell}\left[\ln\frac{8\ell^2}{ah} + \frac{a^2 - \pi ab}{2(a+b)^2} - 1 + \frac{h}{\ell} - \frac{h^2}{4\ell^2}\right]$

Table - approximate formulas for the resistance of electrodes with various shapes

	Four-point star	$R = \frac{\rho}{8\pi \ell}\left(\ln \frac{4\ell^2}{dh} + 2.9 - 2.14\frac{h}{\ell} + 2.6\frac{h^2}{\ell^2}\right)$
	Six-point star	$R = \frac{\rho}{12\pi \ell}\left(\ln \frac{4\ell^2}{dh} + 6.85 - 6.26\frac{h}{\ell} + 7\frac{h^2}{\ell^2}\right)$
	Ring of wire	$R = \frac{\rho}{2\pi^2 D} \ln \frac{16D^2}{dh}$
	Horizontal round plate	$R = \frac{\rho}{4D} + \frac{\rho}{8\pi h}\left(1 - 0.036\frac{D^2}{h^2}\right)$
	Vertical round plate	$R = \frac{\rho}{4D} + \frac{\rho}{8\pi h}\left(1 + 0.018\frac{D^2}{h^2}\right)$

Formulas for Calculation of Resistances to Ground

	Hemisphere radius a	$R = \frac{\rho}{2\pi a}$
	One ground rod length L, radius a	$R = \frac{\rho}{2\pi L}\left(\ln\frac{4L}{a} - 1\right)$
	Two ground rods $s > L$; spacing s	$R = \frac{\rho}{4\pi L}\left(\ln\frac{4L}{a} - 1\right) + \frac{\rho}{4\pi s}\left(1 - \frac{L^2}{3s^2} + \frac{2L^4}{5s^4}\cdots\right)$
	Two ground rods $s < L$; spacing s	$R = \frac{\rho}{4\pi L}\left(\ln\frac{4L}{a} + \ln\frac{4L}{s} - 2 + \frac{s}{2L} - \frac{s^2}{16L^2} + \frac{s^4}{512L^4}\cdots\right)$
	Buried horizontal wire length $2L$, depth $s/2$	$R = \frac{\rho}{4\pi L}\left(\ln\frac{4L}{a} + \ln\frac{4L}{s} - 2 + \frac{s}{2L} - \frac{s^2}{16L^2} + \frac{s^4}{512L^4}\cdots\right)$
	Right-angle turn of wire length of arm L, depth $s/2$	$R = \frac{\rho}{4\pi L}\left(\ln\frac{2L}{a} + \ln\frac{2L}{s} - 0.2373 + 0.2146\frac{s}{L} + 0.1035\frac{s^2}{L^2} - 0.0424\frac{s^4}{L^4}\cdots\right)$
	Three-point star length of arm L, depth $s/2$	$R = \frac{\rho}{6\pi L}\left(\ln\frac{2L}{a} + \ln\frac{2L}{s} + 1.071 - 0.209\frac{s}{L} + 0.238\frac{s^2}{L^2} - 0.054\frac{s^4}{L^4}\cdots\right)$
	Four-point star length of arm L, depth $s/2$	$R = \frac{\rho}{8\pi L}\left(\ln\frac{2L}{a} + \ln\frac{2L}{s} + 2.912 - 1.071\frac{s}{L} + 0.645\frac{s^2}{L^2} - 0.145\frac{s^4}{L^4}\cdots\right)$
	Six-point star length of arm L, depth $s/2$	$R = \frac{\rho}{12\pi L}\left(\ln\frac{2L}{a} + \ln\frac{2L}{s} + 6.851 - 3.128\frac{s}{L} + 1.758\frac{s^2}{L^2} - 0.490\frac{s^4}{L^4}\cdots\right)$
	Eight-point star length of arm L, depth $s/2$	$R = \frac{\rho}{16\pi L}\left(\ln\frac{2L}{a} + \ln\frac{2L}{s} + 10.98 - 5.51\frac{s}{L} + 3.26\frac{s^2}{L^2} - 1.17\frac{s^4}{L^4}\cdots\right)$
	Ring of wire diameter of ring D, diameter of wire d, depth $s/2$	$R = \frac{\rho}{2\pi^2 D}\left(\ln\frac{8D}{d} + \ln\frac{4D}{s}\right)$
	Buried horizontal strip length $2L$, section a by b, depth $s/2$, $b < a/8$	$R = \frac{\rho}{4\pi L}\left(\ln\frac{4L}{a} + \frac{a^2 - \pi ab}{2(a+b)^2} + \ln\frac{4L}{s} - 1 + \frac{s}{2L} - \frac{s^2}{16L^2} + \frac{s^4}{512L^4}\cdots\right)$
	Buried horizontal round plate radius a, depth $s/2$	$R = \frac{\rho}{8a} + \frac{\rho}{4\pi s}\left(1 - \frac{7}{12}\frac{a^2}{s^2} + \frac{33}{40}\frac{a^4}{s^4}\cdots\right)$
	Buried vertical round plate radius a, depth $s/2$	$R = \frac{\rho}{8a} + \frac{\rho}{4\pi s}\left(1 + \frac{7}{24}\frac{a^2}{s^2} + \frac{99}{320}\frac{a^4}{s^4}\cdots\right)$

Resistance of driven rods

- The resistance of a **single** rod is in general not sufficiently low, and it is necessary to use a number of rods connected in **parallel**
- They should be **driven as far apart as possible** so as to **minimise the overlap** among their areas of influence
- In practice, this is very difficult, so it becomes necessary to determine the **net reduction in the total resistance** by connecting rods in parallel
- One of the approximate methods is to **replace a rod by a hemispherical electrode having the same resistance**
- The method assumes that each equivalent hemisphere carries the same charge
- Evaluating their average potential and total charge, the capacitance and hence the resistance of the system can be calculated

Resistance of driven rods

- The resistance of **rods in parallel** is thus found to exceed (1/n) of that a single rod because of their **mutual screening**

- The screening coefficient **η** for n electrodes in parallel is defined as

  η = resistance of one electrode/n(resistance on n electrodes in parallel)

- It is difficult to determine the value of η for complicated systems and usually it is listed in tables obtained by calculations and measurements

Grounding grids

- A common method for obtaining a low ground resistance at high voltage substations is to use **interconnected ground grids**
- A typical grid system for a substation would comprise 4/0 (11.684mm diameter) bare solid copper conductors buried at depth of from 30 to 60 cm, spaced in a grid pattern of about 3 to 10 m.
- At each junction, the conductors are securely bonded together
- Such a grid not only effectively ground the equipment, but has the added advantage of controlling the voltage gradients at the surface of the earth to values safe for human contact.
- Ground rods may be connected to the grid for further reduction in the ground resistance when the upper layer of soil is of much higher resistivity than that of the soil underneath

Resistance to ground and Mesh voltages of grounding grids

- The resistance to ground determines the maximum potential rise of the grounding system under a ground fault.
- An equation for grid resistance can be derived (eg eqn 13.8 in Khalifa)

$$R = \frac{\rho}{L}\left(ln\frac{2L}{\sqrt{dh}} + K_1\frac{L}{\sqrt{A}} - K_2\right)$$

L total length of all conductors

A area of grid d grid conductor diameter

K1 and K2 factors which are functions of length-to-width ratio of the area

- For practical design purposes various approximate formulas based on the similarity of a grid and a round plate of equal area have been proposed (Table 13.2)
- **The mesh voltage** represents the maximum touch voltage to which a person can be exposed at the substation

Scale models of grounding grids

- Scale model tests with an electrolytic tank are very useful for determining the ground resistance and surface potential distributions during ground faults in complex grounding arrangements where accurate analytical calculations are hardly possible

- By measuring the voltage applied to the model and the current flowing through the electrolyte between the model grid and the return electrode, the effective grid resistance could be evaluated

4.4 Impulse impedance of grounding systems

– The impulse impedance of a grounding system is necessary for determining its performance while discharging impulse currents to ground, as in the case of lightning and transient ground faults.

Performance of driven rods

An equivalent circuit of a driven rod under impulse is shown below

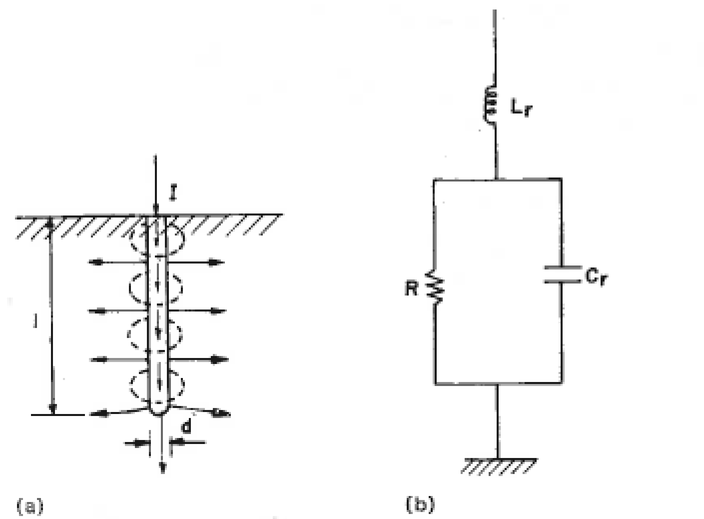


Fig. 13.6 (a) Impulse current spreading from a driven rod. Its magnetic field is also represented. (b) Equivalent circuit for a driven rod under impulse.

- The current in the electrode and ground forms a magnetic field
- It is highest where the current is most concentrated (ie at the top).
- At high frequencies of about 1 MHz the ground will draw a considerable capacitive current in addition to its conductive current.
- The total current flows through the self-inductance of the electrode
- At low frequencies, the inductance and capacitance of the electrode can be safely neglected
- Whereas at extremely high frequencies the ground would be represented by a distributed network

Performance of grounding grids

- Ground wires of considerable length are usually buried as counterpoises along transmission lines near high-voltage substations for lightning protection

- Formulas for the resistance of the wires are given such as in 13.14 Khalifa.

- Naturally, the impulse impedance is initially higher than the power-frequency impedance, but decreases with time to the steady-state value at a rate depending on the circuit and wave parameters

- The inductance of the grid is the governing factor contributing to its impulse impedance.

4.5 Earthing System Design

4.5.1 Review

- **Fundamentals of Grounding system**
  - Ensure safety, provides protection
  - Installed in high or low voltage substations
- **Reasons for grounding system**
  - To limit voltage imposed by:
    - Lightning, line surges, unintentional contact with higher voltage lines
    - Stabilize voltage to ground – during normal operations
- **Basic concepts**
  - Ground: connection between electrical circuit/equipment to the earth.
  - Grounding conductor: connecting equipment/circuit to the grounding electrodes.
  - Ground electrode: provides a way for grounding current to dissipate into earth.
  - Ground resistance: Resistance between ground rod and earth.

- **Accidental electrocution circuit parameters:**
  - Current and voltage causes damage in electrocution. Current does most of damage.
  - Voltage is pressure that causes current to flow and thus causes explosion.

4.5.2 Substation Ground Design

Introduction

- The **ground of a substation is very important,** as it provides the **ground connection for the system neutral,** the **discharge path for surge arresters,** and ensures **safety to operating personnel.**
- It also provides a **low-resistance path to ground to minimise the rise in ground potential.**
- The ground-potential rise depends on **fault-current** magnitude and the **resistance** of the grounding system
- Low-resistance substation grounds are difficult to obtain in desert and rocky areas. In such cases, the use of **grids** will provide the most convenient means of obtaining a suitable ground connection.
- Many utilities add **ground rods** for further reduction of the resistance. The **size of the grid** and the **number and length of driven rods** depend on the substation **size**, the **nature of the soil**, and the **ground resistance desired**.

- The practical design of a grid requires inspecting the layout plan of equipment and structures.
- The grid system usually extends over the entire substation yard and sometimes several meters beyond.

- To **equalize** all **ground potentials** around the station, the various ground **cables** or **buses** in the yard and in the substation building should be **bonded together** by heavy multiple connections and tied into the main station ground.

- It is also necessary to adjust the **total length** of **buried conductors**, including cross connections and rods, to be at, least equal to those required to keep local potential differences within **acceptable** limits.

Ground Conductor Size

- The ground conductor should have low impedance and should carry prospective fault currents without fusing or getting damaged, taking into account future expansion of the connected power system. The size of ground conductor is given somewhere else. (Eqn 13.7 Khalifa)

$$a = I\sqrt{\frac{76t}{\ln(\frac{234 + T_m}{234 + Ta})}}$$

where

a is copper cross section

t is the fault duration (s)

T_m is

T_a is the ambient temperature

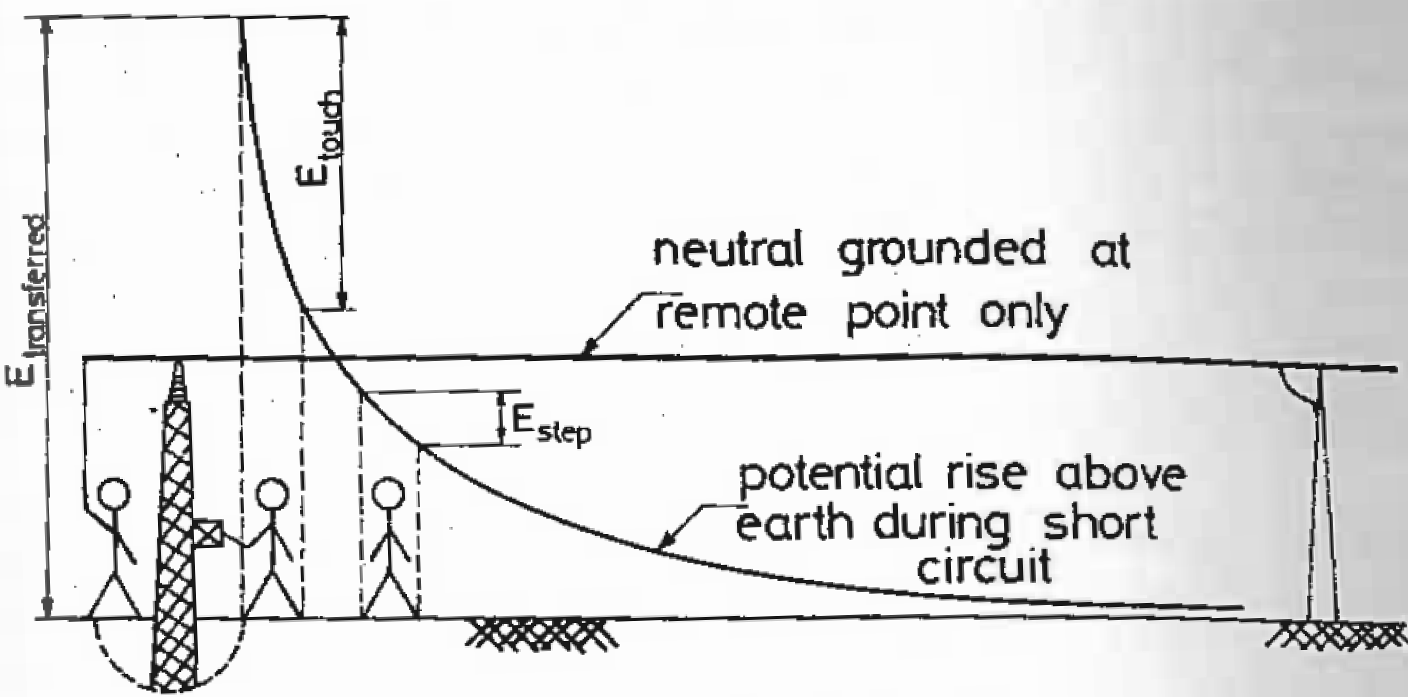


Fig. 13.7 Step, touch, and transferred voltages near a grounded structure.

Ground Conductor Length

Conductor Length required for gradient control

$$E_{step} = K_s K_i \rho \ \frac{1}{L} \qquad \text{(Eqn. 13.16 Khalifa)}$$

$$K_s = \frac{1}{\pi}\left(\frac{1}{2h} + \frac{1}{S+h} + \frac{1}{2S} + \frac{1}{3S} + \ \ldots\right)$$

where

K_s is the coefficient that takes into account the effect of conductor number

S is spacing

h is depth of burial

Conductor Length required for gradient control

The tolerable step voltage with duration t_s, E_{step}, which is the voltage between any two points on the ground surface that can be touched simultaneously by the feet is

$$E_{step} = \frac{165 + \rho_s}{\sqrt{t}}$$

where ρ_s is the resistivity of ground beneath the feet [in ohm.m], taking its surface treatment into account

- The tolerable touch voltage, E_{touch}, which is the voltage between any two point on the grounds where a person may stand and any point that can be touched simultaneously by either hand is

$$E_{touch} = \frac{165 + 0.25\rho_s}{\sqrt{t}}$$

Conductor Length required for gradient control

- Equating E_{mesh} to the maximum value of E_{touch} yields the approximate length of buried conductor required to keep voltage within safe limits

$$\frac{K_m K_i \rho I}{L} = \frac{165 + 0.25\rho_s}{\sqrt{t}}$$

The approximate length of buried conductor required to keep voltage within safe limits is thus

$$L = \frac{K_m K_i \rho I \sqrt{t}}{165 + 0.25\rho_s}$$

4.5.3 Grounding of Gas-Insulated Substations

- The main difference between GIS and conventional substations is their **enclosures**. Under faults, these **enclosures** carry **induced currents** of significant magnitude.
- The currents must be **confined to specific paths**

Grounding of enclosures

- The following requirements should be met to minimize the undesirable effects caused by circulating currents
  1. All metallic enclosures should normally operate at ground voltage level
  2. No significant voltage differences should exist between individual enclosure sections
  3. The supporting structures and any part of the grounding system must not be influenced by the flow of induced currents

4. Precautions should be taken to prevent excessive currents being induced into adjacent frames and structures
5. As GIS substations have limited space, reinforced-concrete foundations may cause irregularities in a current discharge path. The use of simple monolithic slab reinforced by steel serves as an auxiliary grounding device. The reinforcing bars in the foundations can act as additional ground electrodes

Touch voltages for GIS

- The enclosures of GIS should be properly designed and adequately grounded so as to limit the potential difference between individual sections within the allowable limit of 65 to 130 V during faults
- The analysis if GIS grounding includes estimation of the permissible touch voltage
- Dangerous touch and step voltages within the GIS area are drastically reduced by complete bonding and grounding of the GIS enclosures, and by using grounded conductive platforms connected to the GIS structures

4.5.4 Transmission-line tower Grounding

- To design and operate a transmission system with a low-outage rating and safety to the maintenance personnel as well as the public, it is necessary to have a suitable grounding system
- This can be furnished by overhead ground wires, counterpoise, and by earthing tower bodies and foundations
- The degree to which low tower footing resistance can be met depends on local soil conditions
- The method used to reduce the equivalent footing resistance and the degree to which this is carried out is a matter of economics
- Experiences indicates that some means of reducing the footing resistance to an equivalent of 10 Ω, as measured within the ground wires removed, is more economical than adding extra insulation
- Unfortunately, improved grounding cannot be economically effective in the event of direct lightning strokes to phase conductors

- The importance of having low tower footing resistance in this case is in avoiding a high rate of back flashovers and thereby improving the conditions for successful fault suppression by ground-fault neutralizers

- Ground wires are so located as to shield the line conductors adequately from direct lightning strokes

- With underground cables the situation is different.

- Dangerous voltages to earth may result from insulation failure, charges due to electrostatic induction, flow of currents through the sheath, or from the voltage rise during faults discharging to the station ground system to which the sheaths are connected

4.5.5 Design Procedures

Basic Grounding System Design

- The basic grounding system design consists of:

  i. Grounding electrode system
  ii. Grounding electrode conductor
  iii. Grounded and main bonding jumper
  iv. Equipment grounding conductor
  v. Equipment and enclosure grounding and bonding
  vi. Ground fault protective equipment

Ground Electrode Design

- Grounding electrode provides a path, which is a way in or out to flow into the ground.

- The responsibilities are to maintain good contact with earth, provide many paths into earth for flow or fault current and to drain leakage and static currents into the ground.

- Types of Earth Electrode System
  - Driven pipe or rod (ground rod)
  - Buried metal strip, wire and cables
  - Buried metal plate

- The Ground Rod
  - Is of ferrous or non–ferrous material
  - Better current dissipation with length of rod
  - Performance depends on earth and soil characteristics, mainly resistance
  - Surrounded by layers of earth (closer layer, higher resistance)
  - Can be driven vertically or horizontally into ground
  - If one rod doesn't provide low enough resistance extra rods can be driven in

- **Guidance in Types of Conductor Used**

MATERIAL	IN OPEN AIR	IN SOIL	IN CONCRETE
Copper	Solid, stranded or as coating	Solid, stranded or as coating	Do not use
Hot Galvanized steel	Solid or stranded	Solid	Solid
Stainless steel	Solid or stranded	Solid	Do not use
Aluminum	Solid pr stranded	Do not use	Do not use
Lead	Solid or as coating	Solid or as coating	Do not use

- **Guidance in Types of Conductor Used**

MATERIAL	RESISTANCE	INCREASED BY	ELECTROLYTIC WITH
Copper	Against many materials	Concentrated chlorides, sulphur and organic materials	-
Hot Galvanized Steel	Good in acid soils	-	Copper
Stainless Steel	Against many materials	Water with dissolved chlorides	-
Aluminum	-	Basic agents	Copper
Lead	High concentrations sulphates	Acid Soils	Copper

Joint Selection

i. Basic rule of connecting /joining the rod to the rod conductor:

- Connection should be accessible
- Made to assume an effective grounding path

ii. Connection between the grounding electrodes and the conductor need not be accessible when:

- Concrete encased grounding electrode
- Driven grounding electrode
- Buried grounding electrode

iii. During a joint connection points are:

- No dependency on solder
- Ground clamps compatible with material clamp to not more than 1 conductor per clamp
- Clamps listed for more than 1 conductor permitted to have more than 1 conductor

iv. Installation on the Ground Rod

- Little surface disturbance is firstly needed
- Diameter of rod is a major effort in installing effort
- Installation methods include manual and mechanical driving and drilling
- If the rod length increases, diameter should increase to ensure that the rod has sufficient mechanical strength

4.6 Standard Requirements for Earth-Termination Systems

4.6.1 **Introduction**

When dealing with the dispersion of the lightning current (high frequency behaviour) into the ground, whilst minimizing any potentially dangerous overvoltages, the shape and dimensions of the earth-termination system are the important criteria.

In general, a low earthing resistance (if possible lower than 10 Ω when measured at low frequency) is recommended.

From the viewpoint of lightning protection, a single integrated structure earth-termination system is preferable and is suitable for all purposes (i.e. lightning protection, power systems and telecommunication systems).

Earth-termination systems shall be bonded in accordance with the requirements of the lightning equipotential bonding.

- The earthing system, sometimes simply called '**earthing**', is the **total set of measures used to connect an electrically conductive part to earth**.
- The earthing system is an essential part of power networks at both **high- and low-voltage levels.**
- A **good earthing system** is required for:
  1. **Protection** of **buildings** and **installations** against **lightning**
  2. **Safety** of human and animal life by **limiting touch** and **step voltages** to **safe** values
  3. **Electromagnetic compatibility (EMC)** i.e. **limitation of** electromagnetic disturbances
  4. **Correct operation** of the **electricity supply network** and to ensure **good power quality.**

- All these functions are provided by a **single earthing system** that has to be designed to fulfil all the requirements.

- Some elements of an earthing system may be provided to fulfil a specific purpose, but are nevertheless part of one single earthing system.

- **Standards require all earthing measures within an installation to be bonded together, forming one system.**

4.6.2 Electrical properties of the ground

- The electrical properties of the ground are characterised by the **earth resistivity ρ.** In spite of the relatively simple definition of ρ given above, the determination of its value is often a complicated task for two main **reasons**:

  1. The **ground** does **not** have a **homogenous** structure, but is formed of layers of different materials
  2. The **resistivity** of a given type of ground **varies widely** (Table 1) and is very dependent on moisture content.

- The calculation of the earthing resistance requires a good knowledge of the **soil properties**, particularly of its resistivity ρ. Thus, the large variation in the value of ρ is a problem.
- In many practical situations, a **homogenous** ground structure will be **assumed** with an **average value of ρ,** which must be estimated on the basis of **soil analysis or by measurement.**

- **There are established techniques for measuring earth resistivity.**

- One important point is that the **current distribution in the soil layers used during measurement** should simulate that for the final installation.
- Consequently, **measurements must always be interpreted carefully.**

- Where no information is available about the value of ρ it is usually **assumed ρ = 100 Ωm.**

- However, as Table 1 indicates, the real value can be very different, so acceptance testing of the final installation, together with an assessment of likely variations due to weather conditions and over lifetime, must be undertaken.

Table 1: Ground resistivity, ρ for various kinds of the soil and concrete

TYPE OF GROUND	Ground resistivity, ρ [Ωm]	
	Range of values	Average value
Boggy ground	2 - 50	30
Adobe clay	2 - 200	40
Silt and sand-clay ground, humus	20 - 260	100
Sand and sandy ground	50 - 3,000	200 (moist)
Peat	> 1,200	200
Gravel (moist)	50 - 3,000	1,000 (moist)
Stony and rocky ground	100 - 8,000	2,000
Concrete: 1 part cement + 3 parts sand	50 - 300	150
1 part cement + 5 parts gravel	100 - 8,000	400

- The other problem in determining soil resistivity is the **moisture content**, which can change over a wide range, depending on geographical location and **weather conditions**, from a low percentage for desert regions up to about 80% for swampy regions. The earth resistivity depends significantly on this parameter.

- Figure 2 illustrates the relationship between **resistivity** and **humidity** for **clay**. One can see here that, for humidity values higher than 30%, changes of ρ are very slow and not significant. However, when the ground is dry, i.e. values of h lower than 20%, the resistivity increases very rapidly.

- In regions with temperate climate, for example in European countries, the earthing resistance changes according to the **season** of the year, due to dependence of the **soil humidity** on the earth resistivity.
- For **Europe**, this dependence has an approximate **sine form**, where the **maximum** value of earthing resistance occurs in **February** and the **minimum** value in **August**. The average value occurs in May and November.

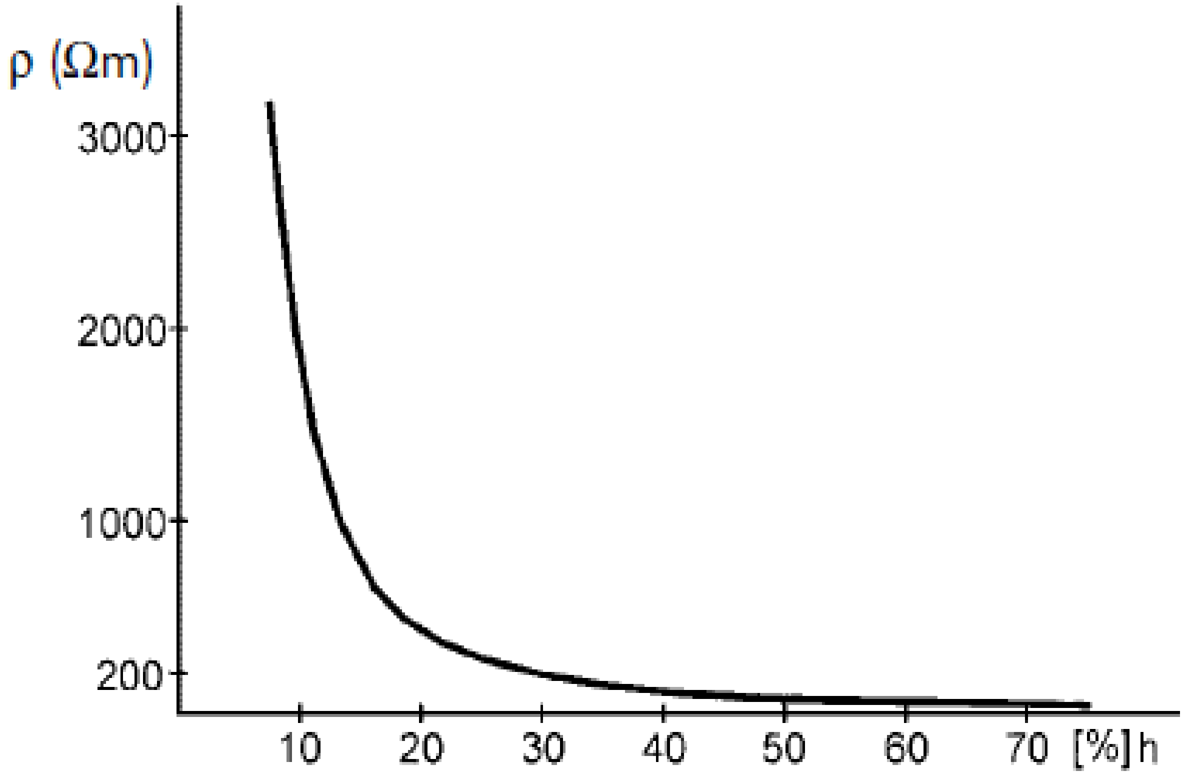


Figure 2: Earth resistivity, ρ of clay as function of soil humidity, h

- The amplitude in February is approximately 30% larger than average, while in August it is about 30% smaller than the average.

- It must be remembered that the effect of freezing is similar to that of drying – the resistivity increases significantly.

- For these reasons the calculations of earth resistance and the planning of electrodes can be performed up to a limited level of accuracy.

- The **electrical properties of earthing** depend essentially on **two parameters**:

  Earthing resistance

  Configuration of the earth electrode

- **Earthing resistance** determines the relation between **earth voltage V_E** and the **earth current** value.
- The **configuration of the earth electrode** determines the **potential distribution on the earth surface**, which occurs as a result of current flow in the earth.
- The **potential distribution on the earth surface** is an important consideration in **assessing** the **degree of protection against electric shock** **because it determines the touch and step potentials.**

- The **earthing resistance** has **two** components:

  - **Dissipation resistance R_D**, which is the **resistance of the earth between the earth electrode and the reference earth**.

  - **Resistance R_L of the metal parts** of the earth **electrode** and of the **earthing conductor**.

- The resistance R_L is usually **much smaller** than the dissipation resistance R_D.
- Thus, usually the earthing resistance is estimated to be equal to the dissipation resistance R_D.
- In the literature, '**earthing resistance**' usually refers to the **dissipation resistance**.

4.6.3 Earthing resistance and potential distribution

- In **AC circuits** one must consider essentially the **impedance** of an **earthing Z_E**, which is the impedance between the **earthing system** **and** the **reference earth** at a given **operating frequency**.
- The **reactance** of the earthing system is the reactance of the **earthing conductor** and of **metal parts** of the **earth electrode**.
- At **low frequencies** - the supply frequency and associated harmonics - **reactance** is usually **negligible** in comparison to earthing resistance, **but must be taken into account** for **high frequencies** such as **lightning transients**.
- Thus, for low frequencies, it is assumed that the earthing impedance Z_E is equal the **dissipation resistance R_D**, which is in turn assumed to be approximately equal to the **earthing resistance, R**:

$$Z_E \approx R_D \approx R \qquad (1)$$

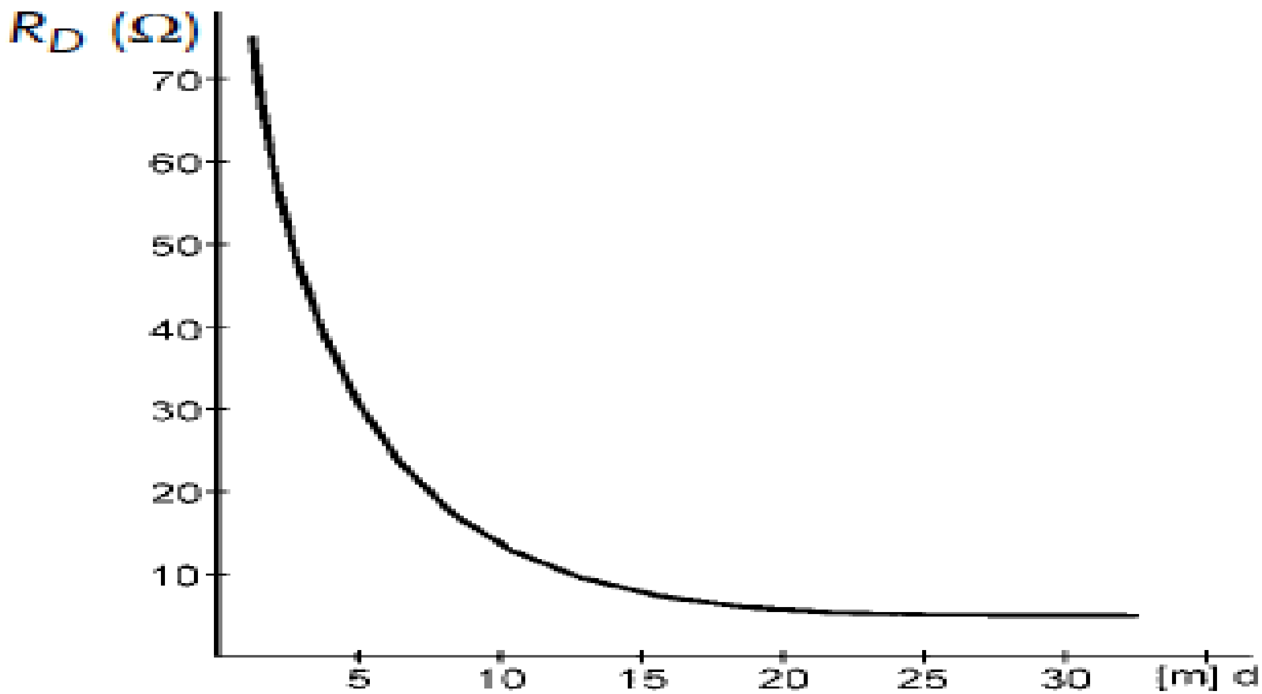
- The earthing resistance R of an earth electrode depends on the **earth resistivity ρ** as well as the **electrode geometry.**

- In order to achieve **low** values of **R** the **current density** flowing from the electrode metal to earth should be **low**, i.e. the **volume** of earth through which the current flows is as **large** as possible. Once the current flows from metal to earth it spreads out, reducing current density.

- If the electrode is physically small, e.g. a **point**, this effect is large, but is very much reduced for a **plate** where spreading is only effective at the **edges**.
- This means that **rod, pipe, or wire electrodes** have a much **lower dissipation resistance** than, for example, a plate electrode with the **same surface area**.
- Moreover, it is well documented in literature that **DC and AC induced corrosion increases with current density**. **Low current density extends electrode life.**

- The calculation of earthing resistance is usually performed under the assumptions that the ground is boundless and of uniform structure with a given value of resistivity.
- It is possible to determine exact equations for earthing resistance but, in practice, their usefulness is very limited, especially in the case of complex and meshed earth electrodes where the mathematical relations become very complicated.
- Furthermore, even a **small inaccuracy in the value of the resistivity** has a **significant influence** on the **actual earthing resistance** of **meshed earth electrodes** and it is often very difficult to determine the earth resistivity with the accuracy required.
- Because of this, **exact theoretical equations of earthing resistance** are usually **used only for simple structures** of earth electrodes in order to illustrate the <u>**relationship**</u> between the **earth voltages, earth potential distribution** and the **earth current.**
- For extended and meshed earth electrodes, approximations of earth resistance are used.

Figure 4 - Example of dissipation resistance of a progressively longer rod earth electrode RD as a function of the depth d

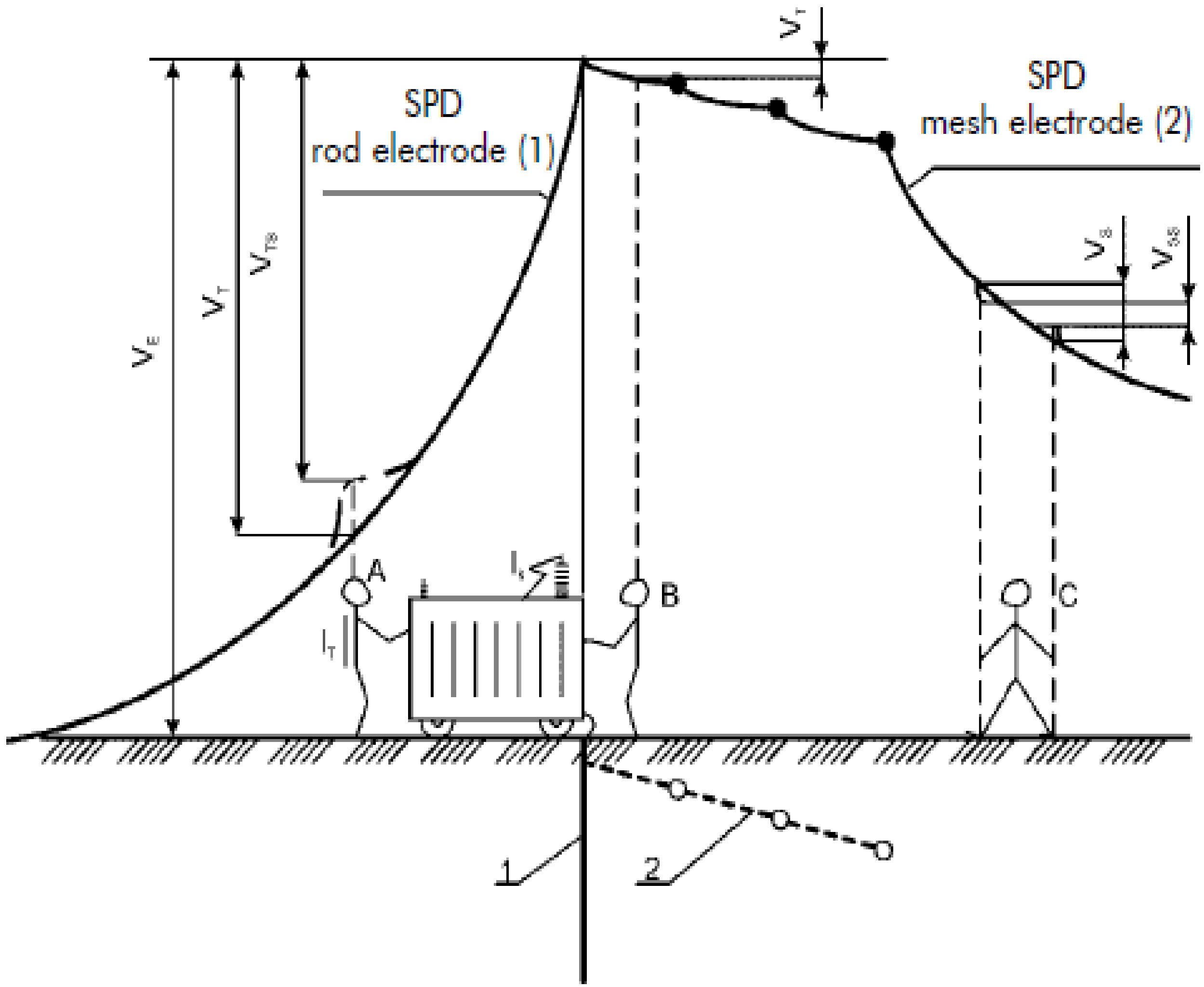


- One can distinguish **several types of earth electrodes** including:
  1. **Simple surface earth electrodes** in the form of **horizontally** placed **strip** or **wire**, either as a **single ended strip or a ring**
  2. **Meshed electrodes,** constructed as a **grid** placed **horizontally** at **shallow depth**
  3. **Cable with exposed metal sheath or armour** which behaves similarly to a strip-type earth electrode
  4. **Foundation earth electrodes** formed from **conductive structural parts embedded in concrete foundation** providing a large area contact with the earth.
  5. **Rod electrodes** which can consist of a **pipe**, **rod**, etc. and are **driven** or **buried** to **a depth greater than 1 m** and usually from **3 m to 30 m** or more.

- **Homework: State advantages and disadvantages of Foundation Earth Electrodes (see Standard IEC 62305 Part III)**

- The **first four arrangements** are **surface earth electrodes**, which usually consist of **strip wire or band arranged as radial, ring or meshed electrodes**, or a **combination of these embedded at shallow depths of up to about 1 m.**
- An important **advantage** of these constructions is the **favourable surface potential distribution.**
- **Rod electrodes** belong to so called **deep earth electrodes**; the advantage of these is that they **pass through soil layers of different conductivity** and are particularly useful in places where the **shallow layers have poor conductivity.**
- In this way it is easy to **obtain** an **expected electrode resistance** (Figure 4).
- Another advantage of rod electrodes is that they **can be installed in places where there is a limited surface area available to install the electrode**.
- However, **surface potential distribution of rod electrodes is unfavourable**, **so in practice a combination of rod and surface earth electrodes are also used, in order to obtain both a good resistance and desirable surface potential distribution.**

Figure 5 - Comparison of earth surface potential distribution (SPD) during the current flow in the earthing system, for two earth electrode constructions

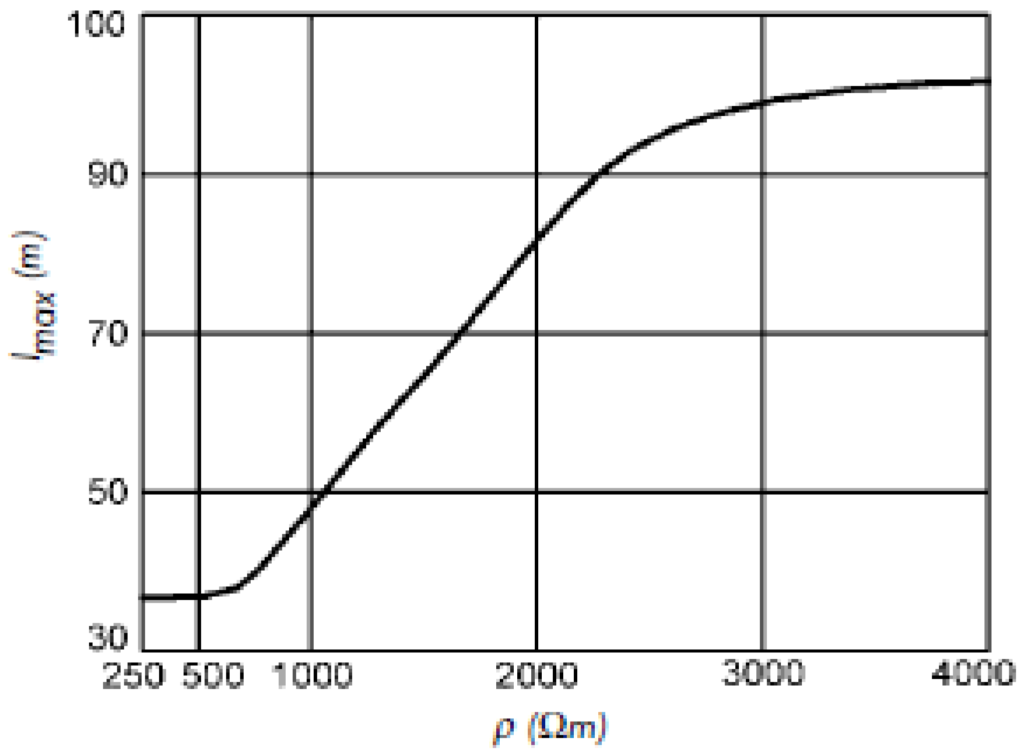


- Figure 5 shows the situation for a rod electrode while the right-hand side shows that for a meshed electrode.
- The rod electrode (1) has a low resistance but most unfavourable potential distribution while the meshed electrode (2) has a much flatter earth potential profile.
- The touch potential (person A) is considerably larger for the rod electrode (1) than for the meshed one (2), (person B).
- Step potentials (person C) are also less dangerous in case of the meshed electrode.

- When a meshed earth is not possible, a ring electrode provides an intermediate solution combining reasonable cost with reasonable safety.
- The earthing resistance determines the value of earthing voltage, whereas the configuration of the earth electrode has significant influence on the potential distribution on the earth surface.

- Naturally, the configuration also influences the earthing resistance – a meshed electrode contacts a larger volume of earth – so both resistance and configuration need to be considered together.
- Note that, because meshed electrode systems cover large areas it is not practical to bury them deeply, so they are more susceptible to changes in soil moisture content.
- Improved stability of resistance can be achieved by including a number of long vertical rods in the mesh.
- Meshed electrodes increase the surface area that experiences a voltage rise as the result of current flow to the earth electrode.
- Over the area of the mesh an 'equipotential' exists, but at the periphery of the electrode there is a potential gradient as shown in Figure 6a.
- Although there is no touch potential – because the mesh extends beyond any metal structure by more than one metre – dangerous step voltages can occur.
- This situation can arise, for example, in the earthing system of a substation.
- In order to avoid this phenomenon, the outer elements of the meshed earth electrode should be placed at a greater depth than the rest of the grid (Figure 6).

Figure 7: Maximal length l_{max} of lightning earth electrodes as a function of earth resistivity, ρ



- **Earthing resistance** and **earth surface potential distribution** are the main parameters characterising electrical properties of the earthing system.
- Electrical parameters of the earthing system depend on both **soil properties and earth electrode geometry.**
- Soil properties are characterised by **earth resistivity**, which changes over a wide range from a few Ωm up to few thousand Ωm, depending on the type of ground and its structure, as well as its humidity. As a result, it is difficult to calculate an exact value of earthing resistance.
- All relationships describing earthing resistance are derived with the assumption that the ground has a homogenous structure and constant resistivity.
- Ideally, the earth surface potential should be flat in the area around the earth electrode.

- Earthing is important for protection against electric shock, and is characterised by **touch and step voltages**.
- **Rod electrodes** have a most **unfavourable surface potential distribution**, while **meshed electrodes have a much flatter distribution**.
- The **behaviour of the earthing system** for **high transient currents** should be considered.
- **Very high current values diminish earthing resistance** due to the **strong electric field between the earth electrode and the soil**, while **fast current changes increase earthing impedance** due to earth electrode inductance.
- The earthing impedance is, in this case, a superposition of both these events.

4.6.4 Earth-Termination Systems

For earth-termination systems, electrodes can be laid vertically or horizontally. Depending on either horizontal or vertical positioning, the minimum length of electrode for each protection class is specified (see Fig. 3 below).

Earth-termination system (Standard 62305 p249 part 3)

- The LPS designer and the LPS installer should select **suitable types of earth electrodes** and should **locate them at safe distances from entrances and exits of a structure** **and** from the **external conductive parts in the soil**.

- The LPS designer and the LPS installer should make special provisions for protection against **dangerous step voltages** in the vicinity of the earth-termination networks if they are installed in areas accessible to the public (see Clause 8).

Types of earth electrode arrangements

Type A arrangement

- This type of arrangement comprises **horizontal or vertical earth electrodes** installed outside the structure to be protected **connected to each down-conductor** or **foundation earth electrodes <u>not forming a closed loop.</u>**
- The type A earth-termination system is suitable for **low structures** (for example family houses), **existing structures** or an **LPS with rods or stretched wires or for an isolated LPS**.
- This type of arrangement comprises **horizontal** or **vertical** **earth electrodes** **connected to each down-conductor**.
- Where there is a <u>**ring**</u> conductor, which interconnects the down-conductors, **in contact with the soil** the earth electrode arrangement is <u>still</u> classified as type A if the <u>ring conductor is in contact with the soil</u> **for less than 80 % of its length**.
- In a type A arrangement the **minimum number of earth electrodes** should be **one for each down-conductor** and **at least two for the whole LPS.**

Types of earth electrode arrangements

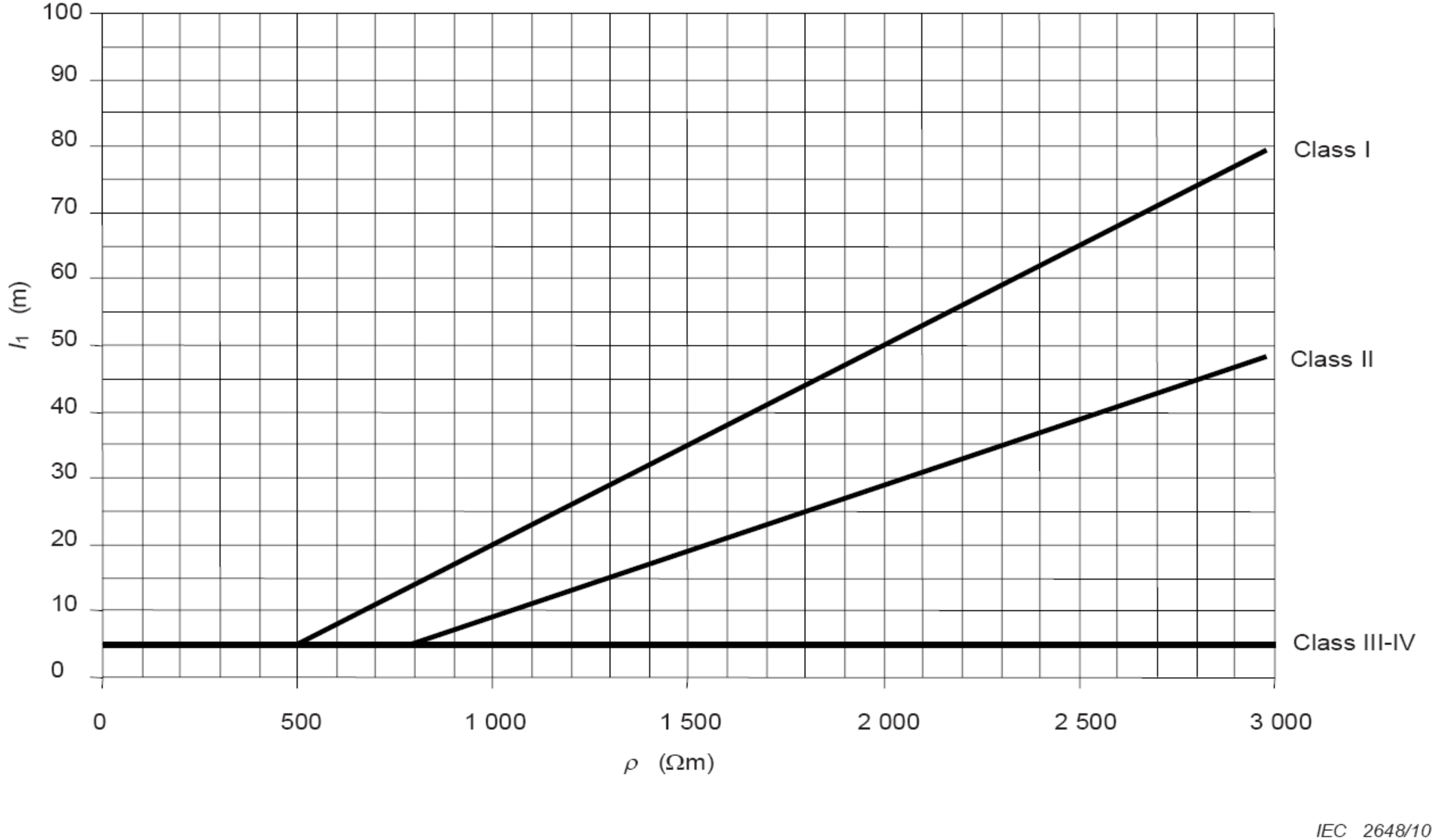
Type A arrangement

- The **minimum length** of each earth electrode at the base of each down-conductor is

  – l_1 for **horizontal** electrodes, or
  – 0.5 l_1 for **vertical** (or inclined) electrodes,

  where l_1 is the minimum length of horizontal electrodes shown in the relevant part of Figure 3.

- The earth electrodes (type A arrangement) shall be installed at a depth of upper end at least 0.5 m and distributed as uniformly as possible to minimize electrical coupling effects in the earth.



NOTE Classes III and IV are independent of soil resistivity.

Figure 3 – Minimum length l_1 of each earth electrode according to the class of LPS

Types of earth electrode arrangements

Type B arrangement

- This type of arrangement comprises either **a ring conductor** external to the structure to be protected, **in contact with the soil for at least 80 % of its total length**, or **a foundation earth electrode forming a closed loop**. Such earth electrodes may also be meshed.

- The type B earth-termination system is **preferred for meshed air-termination systems** and for **LPS with several down-conductors**.

- It is recommended that the number of electrodes shall be not less than the number of the down-conductors, with a minimum of two.
- The additional electrodes should be connected to the ring earth electrode at points where the down-conductors are connected and, for as many as possible, equidistantly.

Types of earth electrode arrangements

Type B arrangement

- For the **ring** earth electrode (or foundation earth electrode), the **mean radius r_e** of the **area enclosed by the ring** earth electrode (or foundation earth electrode) shall be **not less than** the value l_1:

  $$r_e \geq l_1$$

  where l_1 is represented in Figure 3 according to LPS class I, II, III and IV.

- The ring earth electrode (type B arrangement) should preferably be buried at a depth of at least 0.5 m and at a distance of about 1 m away from the external walls.

Types of earth electrode arrangements

- Earth electrodes shall be installed in such a way as to allow inspection during construction.
- The embedded depth and the type of earth electrodes shall be such as to minimize the effects of corrosion, soil drying and freezing and thereby stabilize the conventional earth resistance.
- It is recommended that the upper part of a vertical earth electrode equal to the depth of freezing soil should not be regarded as being effective under frost conditions.
- For **bare solid rock**, only the type B earthing arrangement is recommended.
- For structures with extensive electronic systems or with high risk of fire, type B earthing arrangement is preferable.

Installation of Electrodes

The earth electrodes (type A arrangement) shall be installed at a depth of upper end at least 0.5 m and distributed as uniformly as possible to minimize electrical coupling effects in the earth.

The ring earth electrode (type B arrangement) should preferably be buried at a depth of at least 0.5 m and at a distance of about 1 m away from the external walls.

Inspection must be possible. Burial depth is as to minimize corrosion, soil drying and freezing. For bare solid rock, a type B earthing arrangement is recommended. So does a structure with extensive electronic systems or with high risk of fire.

Natural Earth Electrodes

Interconnected reinforcing steel in concrete foundations or other suitable underground metal structures can be used as an earth electrode.

Special care shall be exercised at the interconnections to prevent mechanical splitting of the concrete.

Consideration of mechanical stress due to high current, long-term increase in earthing resistance etc. should be made.

Protection measures against touch voltages

In certain conditions, the vicinity of the down-conductors of an LPS, may be hazardous to life even if the LPS has been designed and constructed according to the above-mentioned requirements.

The hazard Is reduced to a tolerable level if one of the following conditions is fulfilled:

a) under normal operation conditions there are no persons within 3 m from the downconductors;

b) a system of at least 10 down-conductors is employed;

c) the contact resistance of the surface layer of the soil, within 3 m of the down-conductor, is not less than 100 kΩ.

If none of these conditions is fulfilled, protection measures shall be adopted against injury to living beings due to touch voltages as follows:

– insulation of the exposed down-conductor is provided giving a 100 kV, 1.2/50 μs impulse withstand voltage, e.g. at least 3 mm cross-linked polyethylene;

– physical restrictions and/or warning notices to minimize the probability of down-conductors being touched.

Protection measures against step voltages

In certain conditions, the vicinity of the down-conductors may be hazardous to life.

The hazard is reduced to a tolerable level if one of the following conditions is fulfilled:

a) under normal operation conditions there are no persons within 3 m from the downconductors;

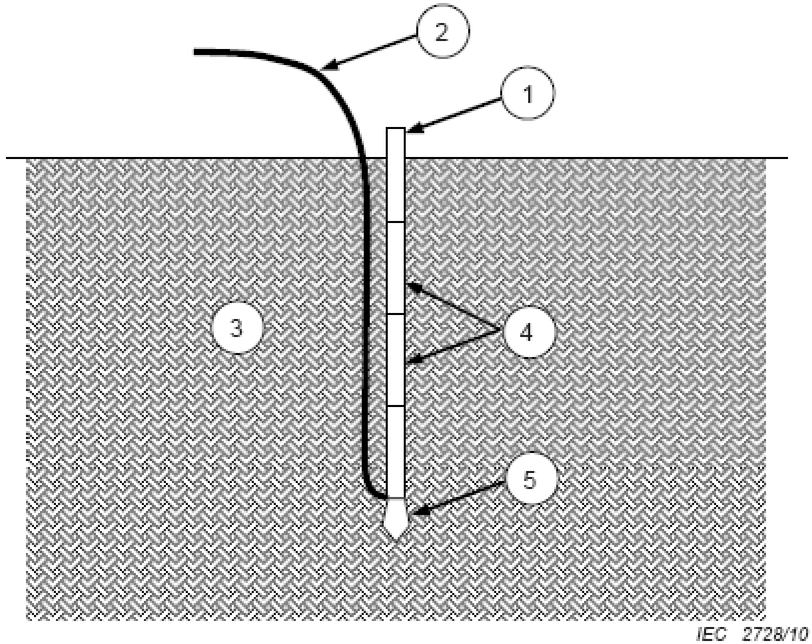
b) a system of at least 10 down-conductors is employed;

c) the contact resistance of the surface layer of the soil, within 3 m of the down-conductor, is not less than 100 kΩ.

If none of these conditions is fulfilled, protection measures shall be adopted against injury to living beings due to step voltages as follows:

- equipotentialization by means of a meshed earth-termination system;

- physical restrictions and/or warning notices to minimize the probability of access to the dangerous area, within 3 m of the down-conductor.



Key

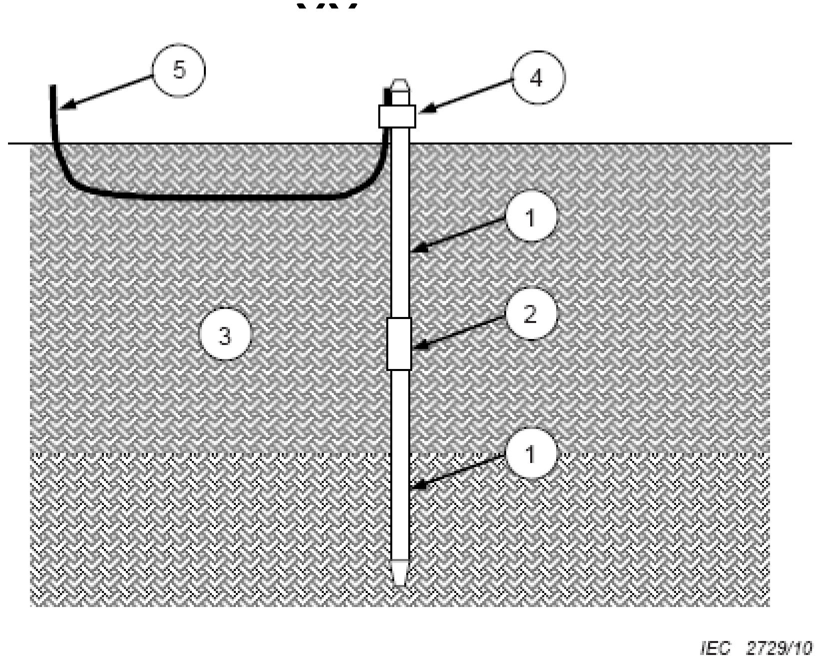
1	short upper-most driving rod
2	earthing conductor
3	soil
4	short driving rods
5	driving steel dart

NOTE 1 A continuous wire conductor is driven into the soil by means of short driving rods. The electrical continuity of the earth electrode conductor is of great advantage; using this technique, no joints are introduced into the earth electrode conductor. Short driving rod segments are also easy to handle.

NOTE 2 The short upper-most driving rod may be removed.

NOTE 3 The uppermost part of the earthing conductor may have an insulating jacket.

Figure E.41a – Example of a type A earthing arrangement with a vertical conductor type electrode

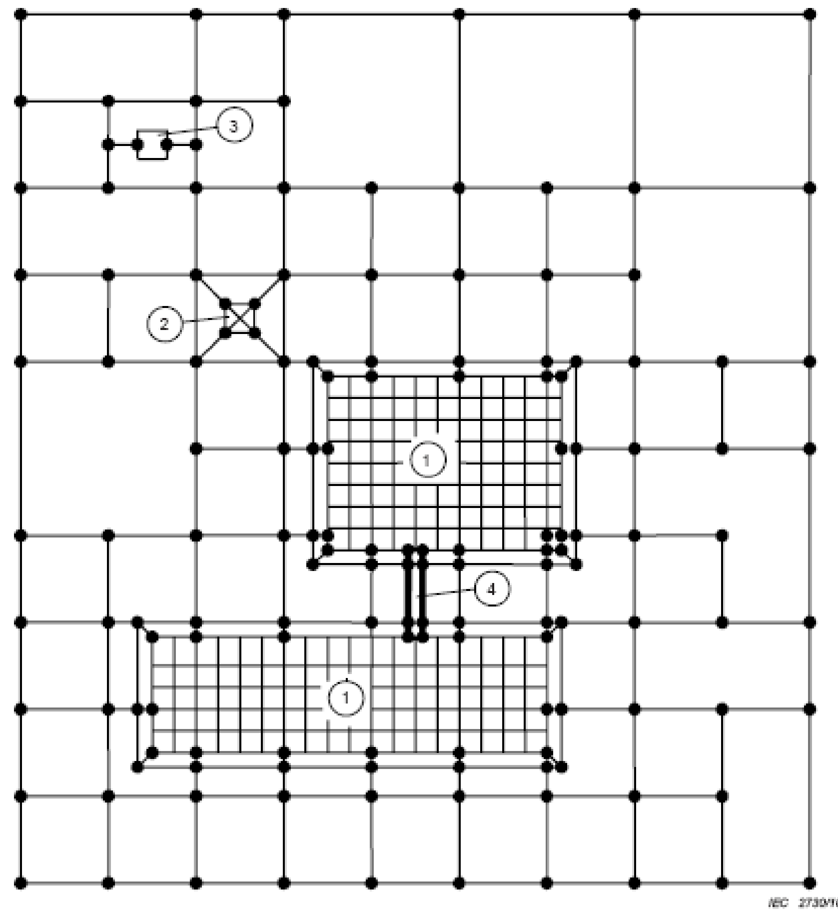


Key

1 extensible earth rod
2 rod coupling
3 soil
4 conductor to rod clamp
5 earthing conductor

Figure E.41b – Example of a type A earthing arrangement with a vertical rod type electrode

Figure E.41 – Two examples of vertical electrodes in type A earthing arrangement

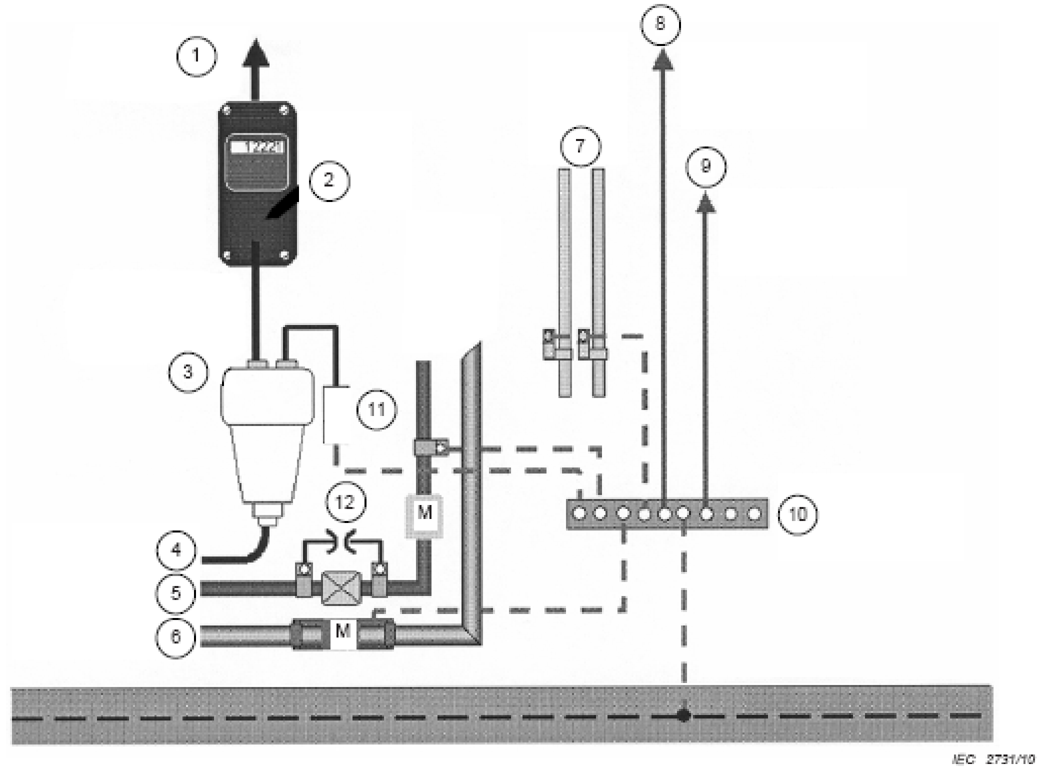


Key

1 building with meshed network of the reinforcement
2 tower inside the plant
3 stand-alone equipment
4 cable trenches

NOTE This system gives a low impedance between buildings and has significant EMC advantages. The size of the meshes next to buildings and other objects may be in the order of 20 m × 20 m. Beyond a 30 m distance they may be enlarged to the order of 40 m × 40 m.

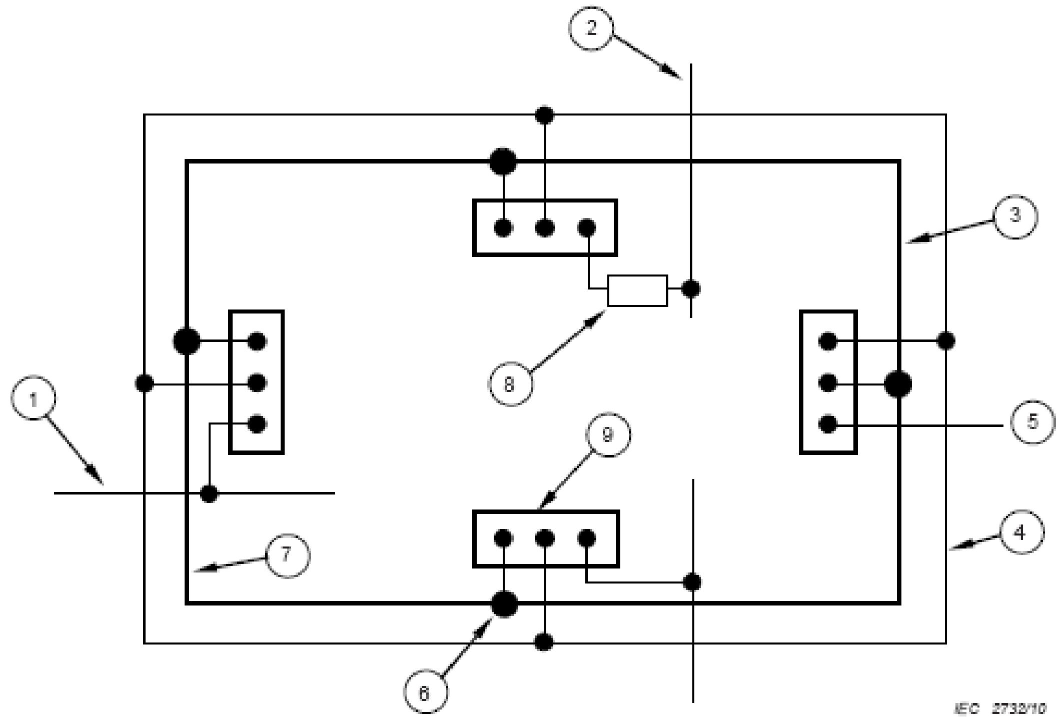
Figure E.42 – Meshed earth-termination system of a plant



Key

1	power to user
2	power meter
3	house connection box
4	power from utility
5	gas
6	water
7	central heating system
8	electronic appliances
9	screen of antenna cable
10	equipotential bonding bar
11	SPD
12	ISG
M	meter

Figure E.43 – Example of an equipotential bonding arrangement

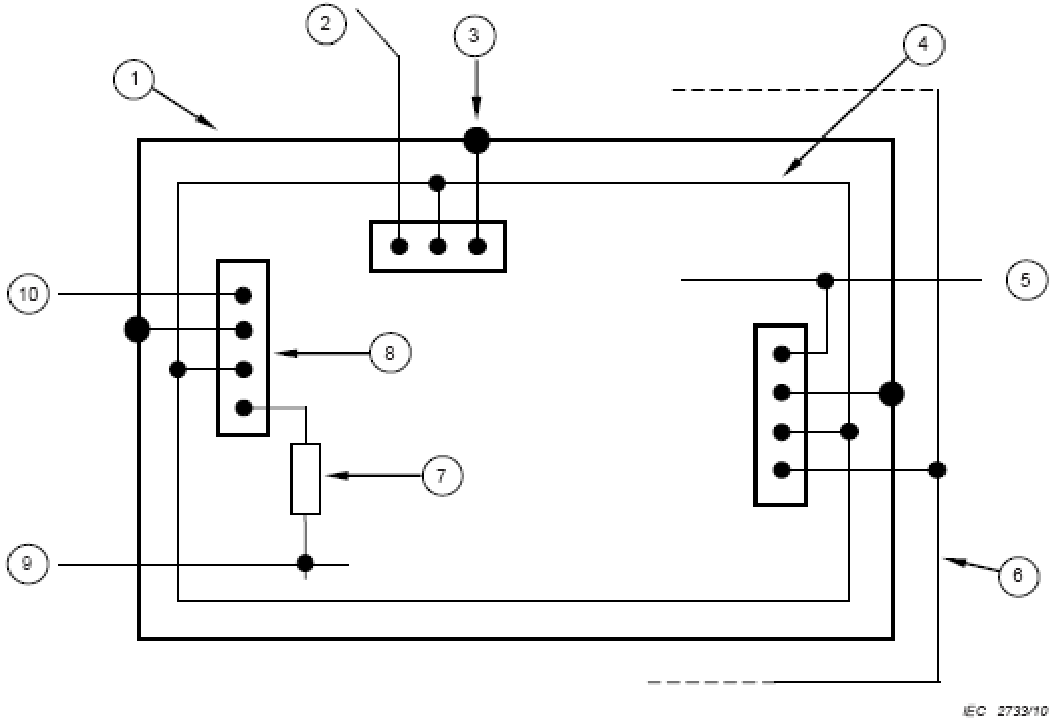


Key

1 external conductive part, e.g. metallic water pipe
2 electric power or communication line
3 steel reinforcement of the outer concrete wall and the foundation
4 ring earthing electrode
5 to an additional earthing electrode
6 special bonding joint
7 steel-reinforced concrete wall, see Key, 3
8 SPD
9 bonding bar

NOTE The steel reinforcement in the foundation is used as a natural earth electrode.

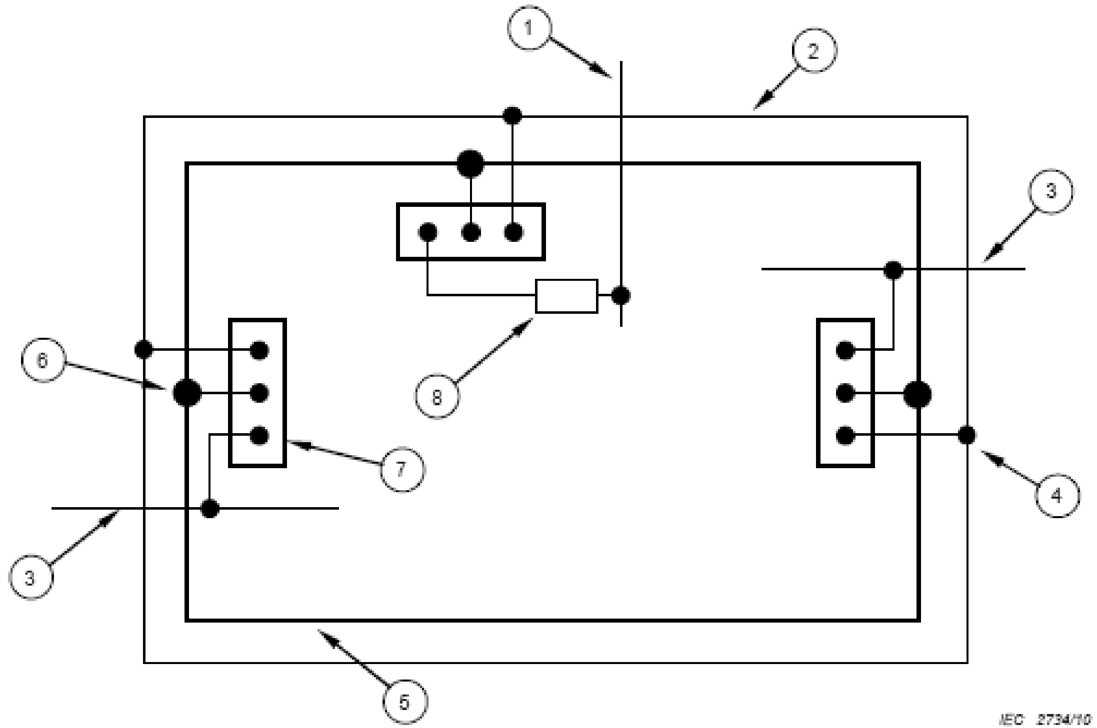
Figure E.44 – Example of bonding arrangement in a structure with multiple point entries of external conductive parts using a ring electrode for interconnection of bonding bars



Key

1 steel reinforcement of the outer concrete wall and foundation
2 other earthing electrode
3 bonding joint
4 internal ring conductor
5 to external conductive part, e.g. water pipe
6 ring earthing electrode, type B earthing arrangement
7 SPD
8 bonding bar
9 electric power or communication line
10 to additional earthing electrode, type A earthing arrangement

Figure E.45 – Example of bonding in the case of multiple point entries of external conductive parts and an electric power or communication line using an internal ring conductor for interconnection of the bonding bars



Key

1 electric power or communication line
2 external horizontal ring conductor (above ground)
3 external conductive part
4 down-conductor joint
5 steel reinforcement in the wall
6 bonding joint to construction steel
7 bonding bar
8 SPD

Figure E.46 – Example of bonding arrangement in a structure with multiple point entries of external conductive parts entering the structure above ground level

4.7 Earthing System Measurements

Earthing System Measurements

- *Electrode ground resistance and Measurement of electrode ground resistance (FOP)*
- *Ground resistance meters* and *Field work*
- *Earth resistivity and Measurement of earth resistivity*

Objectives of the ground resistance measurements

- **Verify** the **adequacy** of new grounding system
- **Detect changes** in an existing grounding system
- **Determine** the **hazardous step and touch voltages**
- **Design protection** for personnel

Fall-Off Potential Method

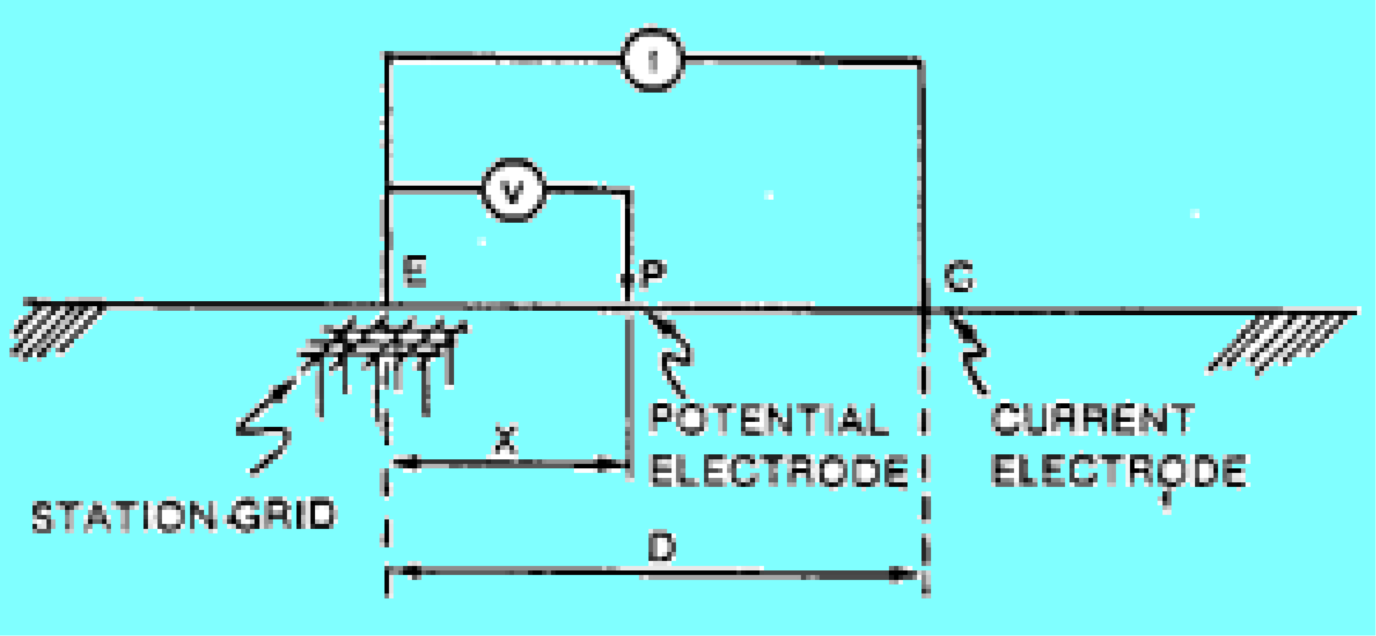
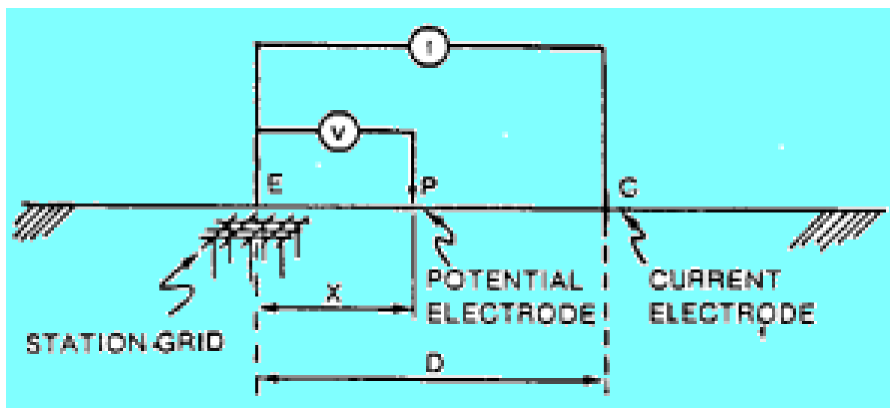


Figure 1: Ground resistance measurement using FOPM

Fall-Off Potential Method

- Using first principle, if the grid in the following diagram is replaced by a hemispherical electrode, derive the ground resistance of the hemispherical electrode, R_E.



- Prove that $R_{measured} = R_{true}$ if and only if $X = 0.618D$

Fall-Off Potential Method

To minimize errors,

- ✓ D must be at least 10 times (or so) the dimension of the grid/electrode
- ✓ Repeat measurements in at least another perpendicular direction
- ✓ One can repeat measurements with a bit smaller and larger X than computed to ensure more or less within 2% changes in resistance value to ensure correct X and D.

Development in Ground Resistance Measurement

- **Polarization in the Soil (if using DC)**

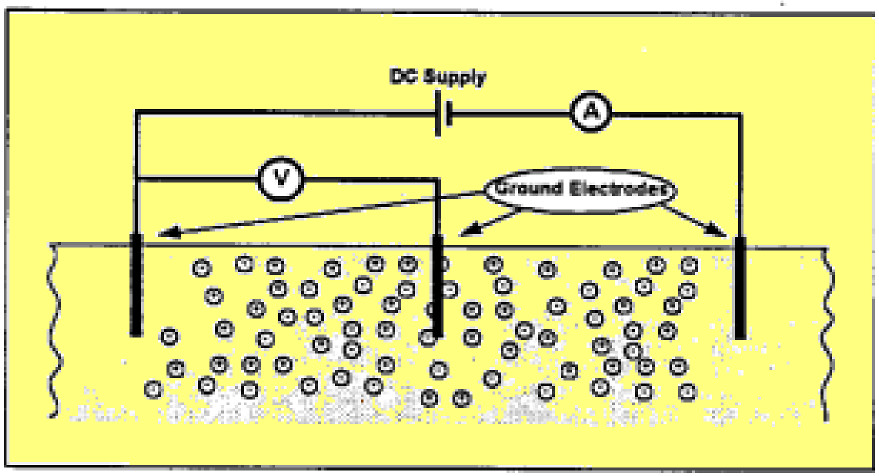


Figure 2: Ions in the soil before polarization occurs

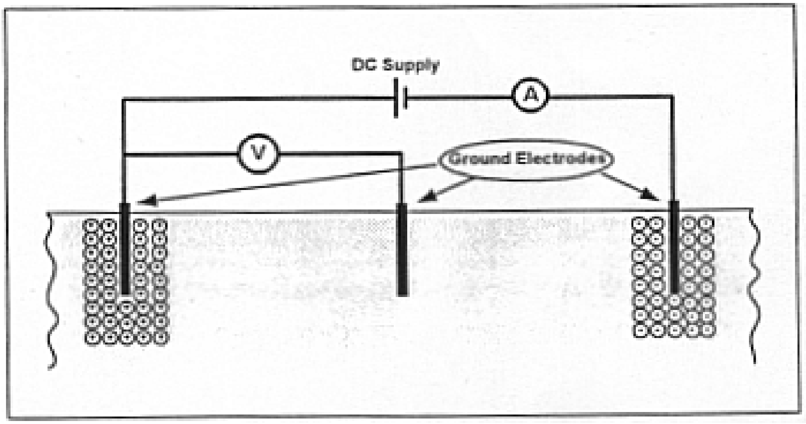


Figure 3: Ions in the soil after polarization

A simple equivalent of grounding system circuit of a grounding system under controllable frequency voltage

- If the frequency of the injected current of a value as such X_C = XL i.e. X = 0, the circuit is in resonant.
- The impedance of the circuit equals the ohmic resistance R, and the current is at maximum.
- At resonant frequency, ω_o the imaginary part of the complex number is zero.

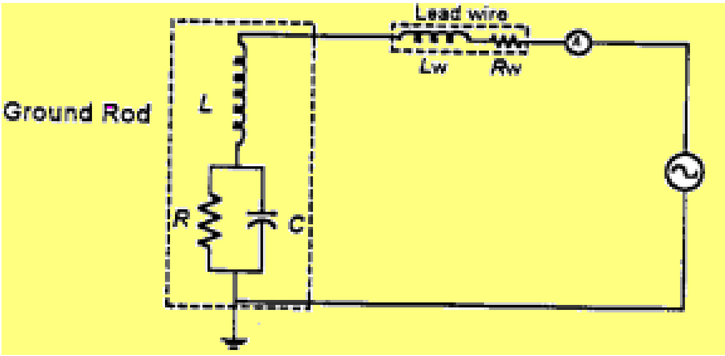


Figure 4: Grounding System Equivalent Circuit

Typical Grounding Resistance Measuring Instrument

Homework

- Search various types of grounding resistance measurement meters available in the market.
- Compare and contrast between the meters.

Ground Resistance Meters

- Any instrument for measuring the resistance of a grounding point and the resistivity of soil mainly comprises an ac source of an adjustable frequency and a measuring circuit
- DC currents would not be suitable for such tests because of the entailed electrolysis and polarization, introducing serious errors
- The frequency to be sued should differ from that of any neighboring network, otherwise, any pickup would cause errors in the measurements

Soil Resistivity Measurement

1. Pole to Dipole

- The following measuring electrode arrangement can be used for resistivity measurement. *m* is at a far away distance.

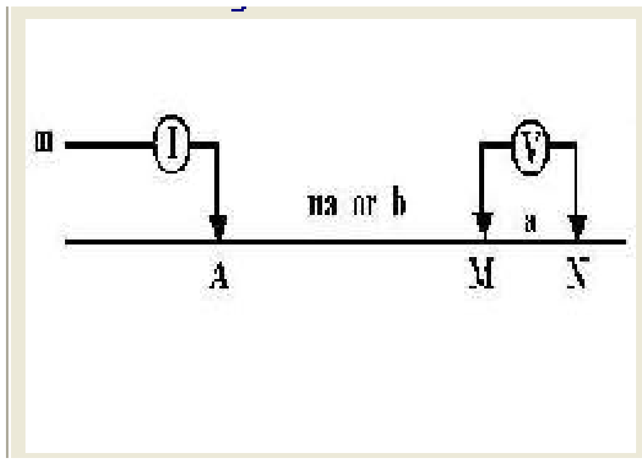


Figure 5: Pole to Dipole Arrangement

Derive the expression for resistivity for the pole-dipole arrangement above.
If b is replaced with *na*, rewrite the expression for the resistivity, ρ.

- If only one of the current electrodes is placed at infinity, the apparent resistivity is then given as

$$\rho_A = 2\pi \frac{b(a+b)}{a} \frac{V}{I}$$

- This arrangement is used frequently in resistivity surveying and the *b* spacing are usually described and taken in integer multiples of the voltage electrode spacing *a*.
- The standard nomenclature is to call the potential electrode spacing *a* so the configuration apparent resistivity become

$$\rho_A = 2\pi a n(n+1) \frac{V}{I}$$

- Pole-dipole sounding data is plotted as apparent resistivity versus *a*.

2. Schlumberger electrodes arrangement

- One of the first used in the 1920’s and still popular
- It is a variant of the pole-dipole, with the second current electrode placed symmetrically opposite the first.
- Derive the expression for resistivity.

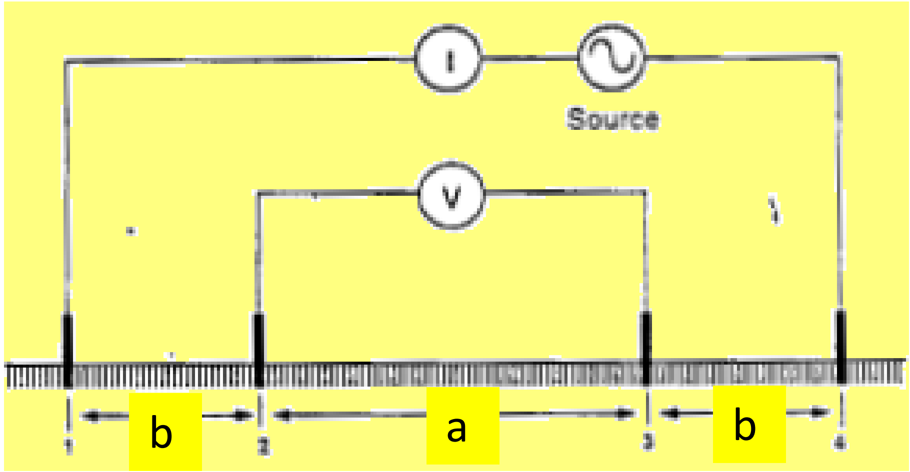


Figure 6: Schlumberger electrodes arrangement

- It can be shown that the voltage difference is consequently doubled and so the apparent resistivity is the same as that for the general pole-dipole with a factor of ½ in the geometric factor.

- In a Schlumberger sounding the voltage electrodes are usually kept small and fixed while only the *b* spacing is changed.

$$\rho_A = \frac{V}{I}\pi\frac{b(a+b)}{a}$$

$$\approx \frac{V}{I}\pi\frac{b^2}{a} \qquad \text{if } a << b$$

- Data from a Schlumberger sounding is plotted vs. spacing (*b*).

3. Wenner Method

- A special case of Schlumberger method.

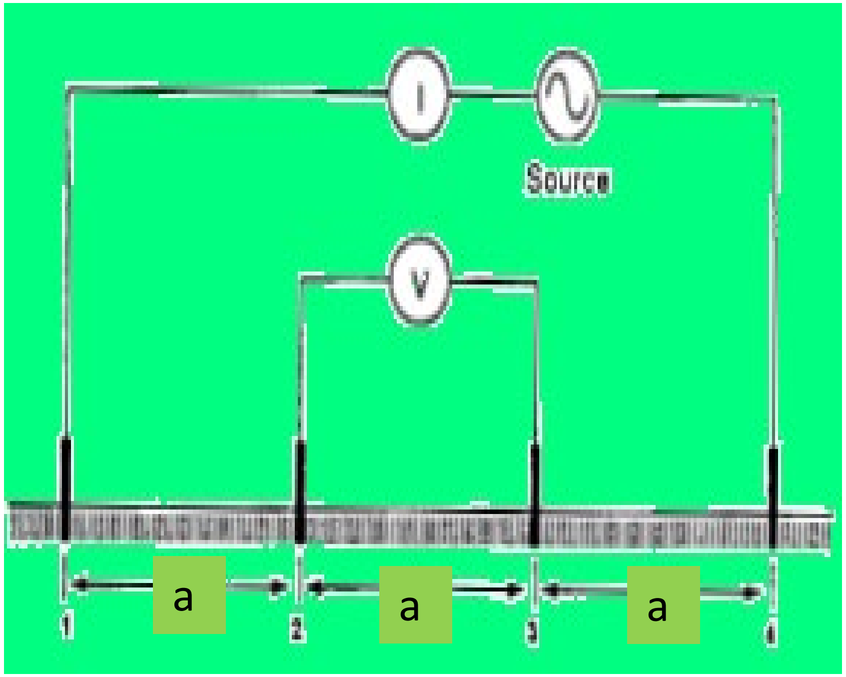


Figure 7: Wenner electrodes arrangement

Wenner Method

- Wenner array will be used for both resistivity profiling and depth sounding.
- It has the advantage that it is very widely used and therefore has a vast amount of interpretational material.
- However, in this array, all **four electrodes** are moved making it **less time efficient** for profiling, but since the distances between the electrodes are small, mistakes are less likely.
- In the Wenner array **near-surface condition differs** at all four electrodes for each reading, giving a **rather high noise level**.
- A very much smoother curve can be used using **offsetting techniques**.
- Offsetting is achieved by setting out five equi-spaced electrodes, two reading are then taken at each expansion and averaging of the two produces a curve in which local effects are suppressed, while differencing provides estimates of the significance of those effects.

- The Wenner arrangement is seen as a simple variant of the Schlumberger method.

- Wenner arrangement is now also seen to be a simple variant of the **pole-dipole** (in which the distant pole at infinity is brought in and all the electrodes are given the same spacing, a).

- The soil resistivity measurements based on using **Wenner** method

$$\rho = 2\pi a R$$

where

R is the apparent resistant (Ω)

ρ is soil resistivity (Ω.m)

a is spacing between electrodes (m)

4. Pole to Pole

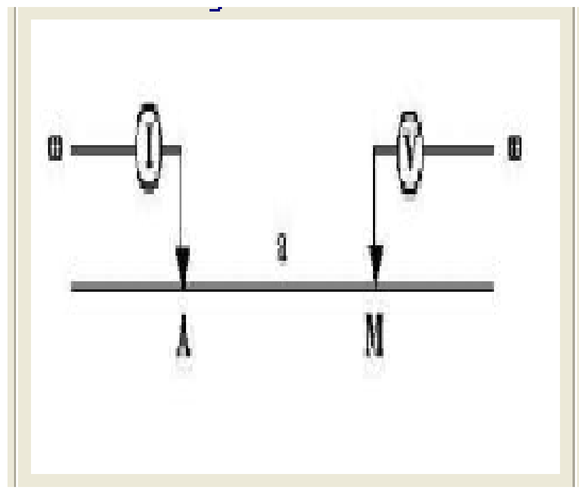


Figure 8: Pole to Pole Arrangement

Pole to Pole

- The simplest array is one in which one of the current electrodes and one of the potential electrodes are placed so far away that they can be considered at infinity.
- This configuration with its formula for apparent resistivity is shown below:

$$\rho_A = \frac{V}{I} 2\pi a$$

- This array can actually be achieved for surveys of small overall dimension when it is possible to put the distance electrodes some practically distance away.
- For a survey in area of a few square meters "infinity" can be one the order of a hundred meters.
- Pole-pole sounding data is plotted as apparent resistivity vs *a*.

5. Dipole to Dipole

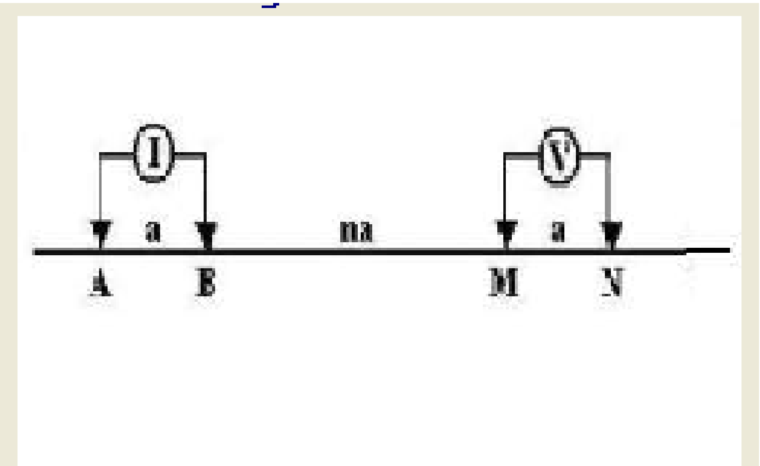


Figure 9: Dipole to Dipole arrangement

- The dipole-dipole array is logistically the most convenient in the field, especially for the large spacing.
- All the other arrays require significant lengths of wire to connect the power supply and voltmeter to their respective electrodes and these wires must be moved for every change in spacing as the array is either expanded for a sounding of moved along a line.
- The convention for the dipole-dipole array shown that current and voltage spacing is the same, *a*, and the spacing between them is an integer multiple of a.

- The apparent resistivity is given by

$$\rho_A = \frac{V}{I}\pi an(n+1)(n+2)$$

6. Driven-Rod

- Based on fall-off potential method
- If the expression for the resistance of a rod with length L and radius d is given (refer to table), determine the resistivity ρ.

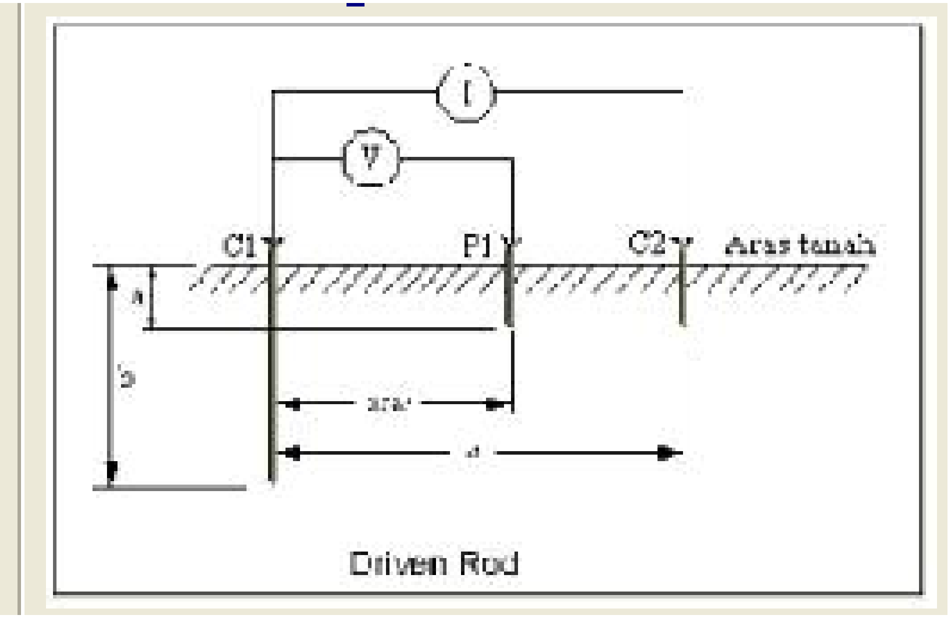


Figure 10: Driven-Rod Arrangement

Conclusions

Earthing designs are required for:

- Basic operation of an LPS
- Guaranteed safety of personnels in relation to an LPS as well as in facilities where possible short circuit currents may give rise to dangerous potential on the ground (transferred, touch and step)