Bachelor of Science
(Electrical Engineering)

BEE310: Electrical Safety, Earthing and Lightning Protection

Tutorial

Earth Electrode and Substation Earthing Design

Step and Touch Voltage due to Earth Fault (Earth Potential Rise)

Aim to design earthing system to keep EPR's at acceptable limits

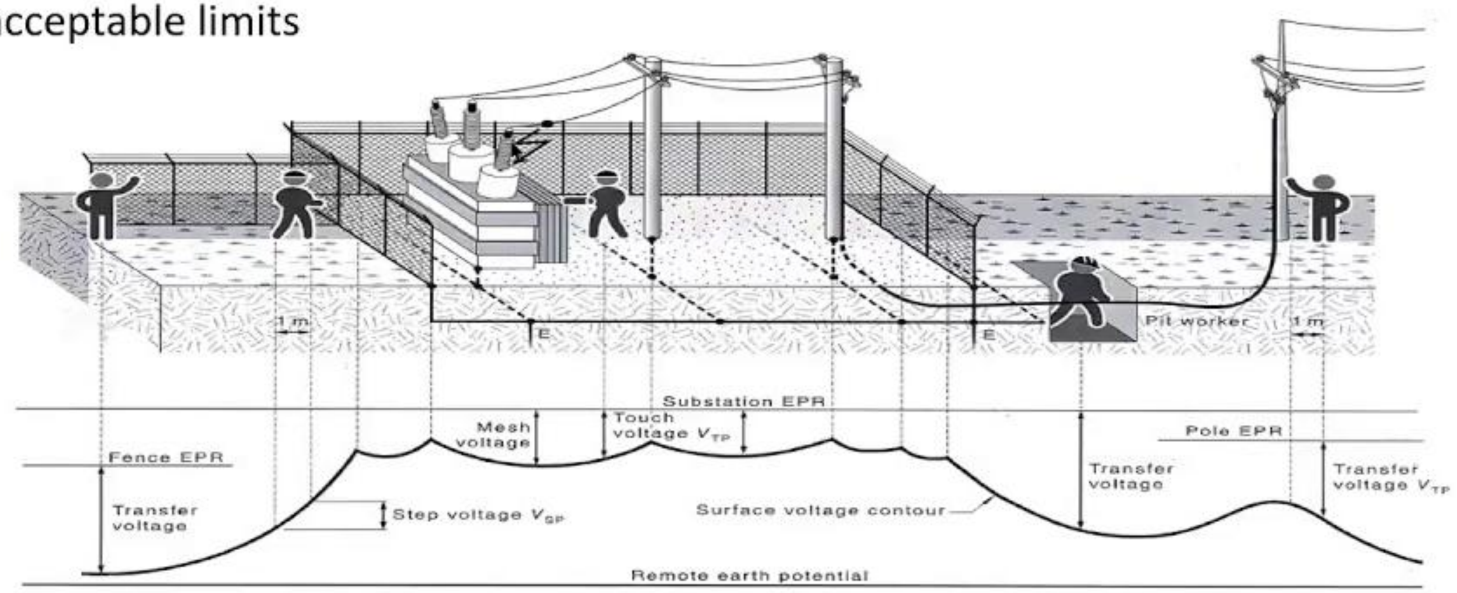


FIGURE 8.2 HAZARDOUS LOCATIONS RELATED TO AN EARTH FAULT (EPR)

True or False?

True/False

The highest mesh voltage in a substation ground grid occurs at the central area of the substation.

a) True

b) False

True/False

The highest mesh voltage in a substation ground grid occurs at the central area of the substation.

a) True

b) False

True/False

La magnitud de la corriente que fluye a través del cuerpo humano está directamente relacionada con la resistencia eléctrica del cuerpo humano

Verdadero

Falso

True/False

The magnitude of current that flows through the human body is directly related to the electrical resistance of the human body

a) **True**

b) False

Definitions and Meanings

Define

Soil resistivity

Define

Soil resistivity.

Answer:

A measure of how much a volume of soil will resist an electric current and is usually expressed in Ohm Meter

Define

Ground electrode.

Define

Ground electrode.

Answer:

A conductor embedded in the earth and used for collecting ground current from or dissipating ground current into the earth

Knowledge-based Questions and Quiz Questions

Question 1

What are the components that constitute the earth electrode resistance? Explain the effect of moisture and temperature on soil resistivity?

Answer 1

What are the components that constitute the earth electrode resistance? Explain the effect of moisture and temperature on soil resistivity?

Answer:

The resistance of a ground electrode is made up of the following components:

- The resistance of electrode material
- Contact resistance of the electrode with soil
- Resistance of the soil itself

Soil resistivity for a given type of soil will decrease with an increase in moisture content and temperature and vice versa.

Question 2

What is soil resistivity? State the governing equation. Mention the factors which vary the Soil resistivity for a given type of soil.

Answer 2

What is soil resistivity? State the governing equation. Mention the factors which vary the Soil resistivity for a given type of soil.

Answer:

Soil resistivity is the electrical property of soil which decides its resistance to the flow of electric current. Soil resistivity is equal to the resistance between two opposite faces of a cube of soil of 1 metre side. The governing equation is:

$$R = \rho \left(\frac{L}{A}\right) \Omega$$

where R is the resistance in ohms between the opposite faces of the cube; A is the area in m^2 of these opposite faces of the cube; L is the distance in metres between between the faces of the sample and ρ is the soil resistivity in Ohm-metre.

Answer 2

What is soil resistivity? State the governing equation. Mention the factors which vary the Soil resistivity for a given type of soil.

Answer

Soil resistivity for a given type of soil may vary widely depending on:

- The presence of conducting salts
- Nature of soil material
- Moisture content
- Temperature
- Level of compaction

Quiz 1

Protective equipotential bonding is achieved by:

a) Preventing current from passing through the body

b) Ensuring adequate continuity between extraneous conductive parts

c) Automatic disconnection of supply in the event of a fault

d) Separation of equipment from the supply using a safety isolating transformer

Quiz 1

Protective equipotential bonding is achieved by:

a) Preventing current from passing through the body

b) Ensuring adequate continuity between extraneous conductive parts

c) Automatic disconnection of supply in the event of a fault

d) Separation of equipment from the supply using a safety isolating transformer

Quiz 2

The equipment grounding system impedance is dependent on a number of physical characteristics including:

a) Tightness of equipment grounding conductor terminations

b) Length of the equipment grounding conductor path

c) Number of bends in the equipment grounding conductor path

d) Radius of each bend in the equipment grounding conductor path

e) All of the above

Quiz 2

The equipment grounding system impedance is dependent on a number of physical characteristics including:

a) Tightness of equipment grounding conductor terminations

b) Length of the equipment grounding conductor path

c) Number of bends in the equipment grounding conductor path

d) Radius of each bend in the equipment grounding conductor path

e) **All of the above**

Quiz 3

A conductor that originates at the neutral or equipment ground buses in the main services entrances panel board or separately derived system and grounding electrode is called what?

a) Grounding electrode conductor
b) Grounding electrode
c) Circuit protection device
d) Surge protection device

Quiz 3

A conductor that originates at the neutral or equipment ground buses in the main services entrances panel board or separately derived system and grounding electrode is called what?

a) **Grounding electrode conductor**

b) Grounding electrode

c) Circuit protection device

d) Surge protection device

Quiz 4

A conducting item (e.g. a continuous underground metallic water pipe, building metal frame, concrete encased electrode, bare copper conductor, rod, pipe, or plate) that is in contact with the earth is called what?

a) Grounding electrode conductor
b) Grounding electrode
c) Circuit protection device
d) Surge protection device

Quiz 4

A conducting item (e.g. a continuous underground metallic water pipe, building metal frame, concrete encased electrode, bare copper conductor, rod, pipe, or plate) that is in contact with the earth is called what?

a) Grounding electrode conductor

b) Grounding electrode

c) Circuit protection device

d) Surge protection device

Work Examples

Ground Electrode Resistance

Problem 1:

An earthing system comprises of 20 numbers of identical electrodes connected in parallel. What would be the percentage of the net ground resistance of these electrodes when compared that of a single electrode's resistance?

a) Electrodes spaced several electrode lengths apart

b) Electrodes spaced one electrode length apart

Ground Electrode Resistance

Solution 1:

The net ground resistance of multiple electrode is given by:

$$R_N = \frac{R * F}{N}$$

Where

R_N is the combined ground electrode system resistance for N no. of electrodes
R is the earth resistance of a single electrode and
F is the factor shown in Figure 6.8 for N no. of electrodes

The table in Figure 6.8 shows the value of the factor F used above.

No. of Rods	F
2	1.16
3	1.29
4	1.36
8	1.68
12	1.80
16	1.92
20	2.00
24	2.16

Ground Electrode Resistance

Solution 1

For twenty electrodes, the value of $F = 2$

a) Combined ground electrode resistance (spaced several electrode lengths apart)

$$R_N = \frac{R}{N} = \frac{R}{20} = 5\%\ of\ R$$

b) Combined ground electrode resistance (spaced one electrode length apart)

$$R_N = \frac{R}{N} = \frac{R \times 2}{20} = 10\%\ of\ R$$

Problem 2:

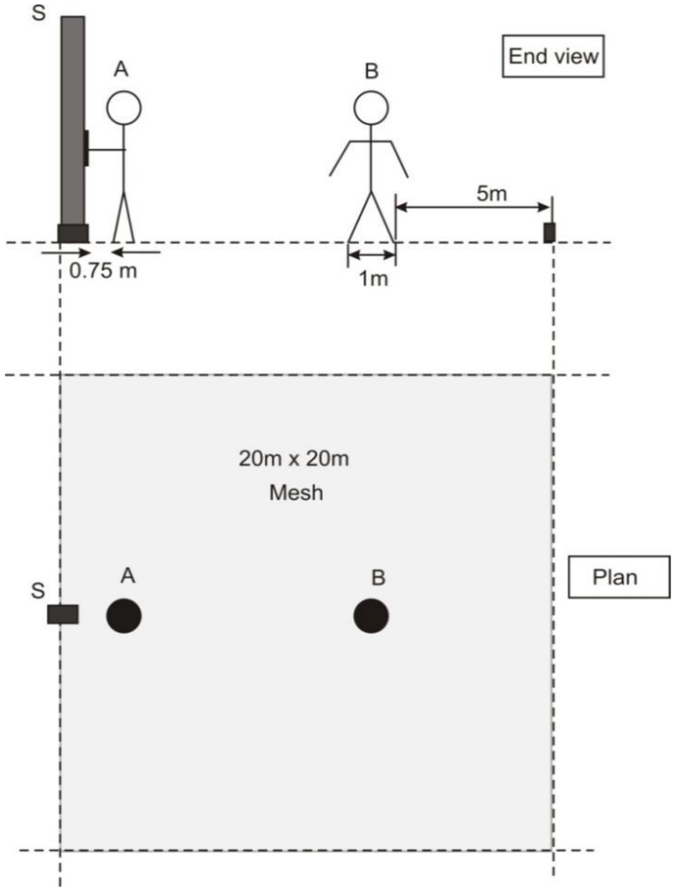
Calculate the touch voltage and step voltage.Centre of mesh has voltage of 5 kV with reference to mesh and the voltage gradient between centre point and mesh is assumed to be uniform (linear)

What will be the touch and step voltage that will be impressed on persons A and B respectively?

A is touching structure S which is connected to mesh and B stands on the ground within the mesh as shown

All external impedances can be neglected.

Problem 2



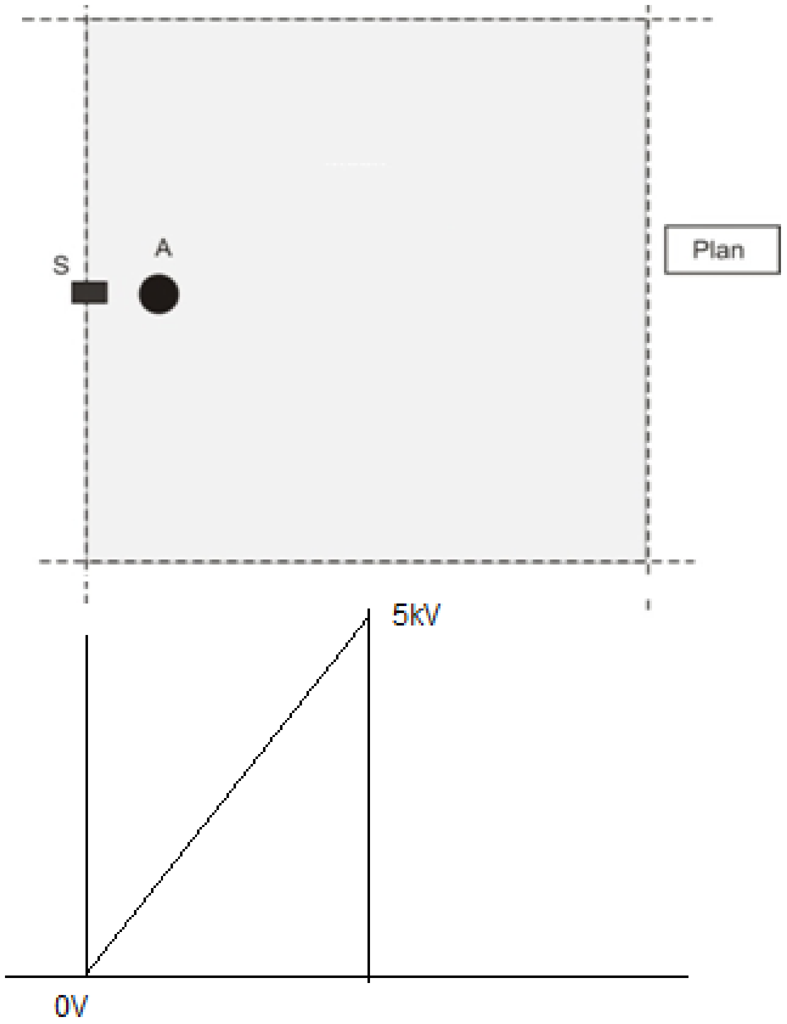
Touch Voltage, Step Voltage

Solution 2:

The center of the mesh has a voltage of 5 kV.

The voltage drops to zero at the border of the mesh.

Assume linear distribution of voltage from center to the side of the mesh.



Touch Voltage, Step Voltage

Engineering Institute of Technology.

Solution 2

i.e. For $10\ \mathrm{m}$, the drop in voltage $= 5\ \mathrm{kV}$

i.e. For a distance of $0.75\ \mathrm{m}$ the voltage

$$= 5000 \times 0.75/10$$

Touch voltage $= 375\ \mathrm{volts}$

For $10\ \mathrm{m}$, the drop in voltage $= 5\ \mathrm{kV}$

i.e. For a distance of $1\ \mathrm{m}$, voltage $= 5000 \times 1/10$

$$= 500\ \mathrm{volts}$$

Earth Potential Rise (EPR)

Problem 3:

For the high voltage switchyard mesh earthing system shown in question 2, the earth resistance of the grid was measured to be 0.9 ohms.

When a fault current of 12 kA flows into the ground through the grid what will be the earth potential rise (EPR) of the substation earth grid with respect to true ground?

What will the voltage difference be?

Earth Potential Rise (EPR)

Solution 3:

- Earth potential rise (EPR) of the earth grid is the product of fault current and the grid's earth resistance.
- Thus EPR $= 12000 \times 0.9$

  $= 10800$ volts (with reference to true earth)
- The voltage at the centre of the mesh is 5 kV with reference to earth.
- The voltage difference between the grid and the centre point of the mesh (in the soil) is the difference between EPR and the voltage at the centre of the mesh.
- Voltage difference $= 10800 - 5000$

  $= 5800$ volts

Wenner’s 4 pin

Problem 4:

A soil resistivity measurement by Wenner’s 4 pin method gives the following readings. Calculate the resistivity values and interpret the results to express the nature of soil layers.

Spacing in metres	Resistance reading Ohms
5	3
10	1
15	0.75
20	0.6
25	0.5
30	6
35	5
40	1

Frank Wenner's Four Pin Method

Solution:

All the pins should be located in a straight line with equal separating distance between them.

The pins should not be driven 10% more deep than the distance above.

Connection between pins should be done with insulated wires

Resistance of soil between the potential electrodes can be determined by Ohms law:

$$R = V/I$$

Resistivity is calculated by:

$$\rho = 2\pi S R$$

Where:

- ρ is the soil resistivity in Ohm meters
- S is the distance between the pins in meters as shown in fig.
- R is the resistance measured in Ohms

Frank Wenner’s Four Pin Method

Table 4.4

Soil resistivity of typical soil types

Soil type	Average resistivity Ohm M	Resistance of rod dia. 5/8” length 10' in Ohms
Well graded gravel	600 to 1000	180 to 300
Poorly graded gravel	1000 to 2500	300 to 750
Clayey gravel	200 to 400	60 to 120
Silty sand	100 to 800	30 to 150
Clayey sands	50 to 200	15 to 60
Silty or clayey sand with slight plasticity	30 to 80	9 to 24
Fine sandy soil	80 to 300	24 to 90
Gravelly clays	20 to 60	17 to 18
Inorganic clays of high plasticity	10 to 55	3 to 16

Frank Wenner's Four Pin Method

Solution 4

Spacing in metres	Resistance reading Ohms	Soil resistivity ohm m	Nature of soil layers
5	3	94.25	Fine sandy soil
10	1	62.83	Clayey sands
15	0.75	70.70	Silty or clayey sand with slight plasticity
20	0.6	75.40	Silty or clayey sand with slight plasticity
25	0.5	39.30	Inorganic clays of high plasticity
30	6	1131	Poorly graded gravel
35	5	1099.50	Poorly graded gravel
40	1	251	Clayey gravel

ρ = soil resistivity in Ω-cm A = Distance between test rods (in feet) R = Resistance obtained from tester (in ohms)

Problem 5:

A driven rod electrode of made of 40 mm diameter GI pipe is buried to a depth of 3m in soil of resistivity 50 ohm-m.

Find the resistance of ground rod

To improve resistance, 12 rods are used in rectangular array and bonded together.

Calculate overall ground resistance of the array

Ground Electrode Resistance

Solution:

For a rod driven vertically into ground, electrode resistance is given by:

$$R = \frac{\rho}{2\pi L} \cdot \left\{ \ln\left(8 \cdot L / D\right) - 1 \right\}$$

Where:

- R - Resistance of the Electrode in Ohms
- ρ - Soil resistivity in Ohm.m
- L - Length of the buried part of electrode in metre
- D - Outer diameter of rod in metre

Ground Electrode Resistance

Solution

Step 1: Arrive at Resistance of Single Electrode

Given:

- Soil resistivity (ρ) is 50 Ohm-metre
- Electrode dia (d) is 40 mm (0.04 m)
- Length L is 3 m

Ground Electrode Resistance

Solution

$$R = \frac{\rho}{2\pi L} \cdot \left\{ \ln\left(8 \cdot L / D\right) - 1 \right\}$$

Where:

R - Resistance of electrode in ohms

ρ - Soil resistivity in Ohm-metre

L - Length of buried part of electrode in metres

D - Outer diameter of rod in metre

R can be calculated as 14.31 Ohms.

Ground Electrode Resistance

Solution

Resistance of Multiple Ground Rods

$$R_N = (R.F/N)$$

Where:

R_N is combined ground electrode system resistance for 'N' number of electrodes spaced one rod length apart.

R is Earth resistance of single electrode

No. of Rods	F
2	1.16
3	1.29
4	1.36
8	1.68
12	1.8
16	1.92
20	2
24	2.16

Ground Electrode Resistance

Solution

<u>Step 2:</u> Resistance of Parallel Combination

There are 12 electrodes connected together

- Resistance of parallel combination is:

  $$R \times F/N$$

  where $N = 12$ and F can be arrived at from the table given earlier.

For $N = 12, F\ is\ 1.8$

- Substituting
  - Resistance of combination is $14.31 \times 1.8/12$
  - Result Resistance $= 2.147\ Ohms$

Electrode Current Carrying Capacity

Problem 6:

Calculate for the above example the ground fault current that can be safely dissipated into the ground for the following fault clearance times.

a) 0.1 sec.

b) 0.5 sec.

c) 1.0 sec.

d) 5.0 sec

Electrode Current Carrying Capacity

Solution:

To calculate the current carrying capacity for individual electrodes use the formula:

$$I = \frac{38400 \cdot d \cdot L}{\sqrt{\rho \cdot t}}$$

Where

I is the maximum permissible current in amperes

d is the outer diameter of the rod in metre

L is the length of the buried part of the electrode in metres

r is the soil resistivity in Ohm.metre

t is the time of the fault current flow in seconds

Electrode Current Carrying Capacity

Solution:

Given:

Soil resistivity (r) is 50 Ohm.m

Electrode dia (d) is 40 mm (0.04 m)

Length L is 3 m

Time ‘t’ has different values 0.1. Sec, 0.5 sec, 1 sec and 5 sec.

- Substituting in the formula, safe current for a single electrode is:

$$I = \frac{38400 \cdot 0.04 \cdot 3}{\sqrt{50 \cdot t}}$$

Electrode Current Carrying Capacity

Solution

Total safe current for 12 electrodes can be taken as $12 \times I$

The values can be calculated as:

$I\ for\ 0.1\ Sec = 22410\ amps$

$I\ for\ 0.5\ Sec = 10022\ Amps$

$I\ for\ 1\ Sec = 7086\ Amps$

$I\ for\ 5\ Sec = 3169\ Amps$

Resistivity Example No1

Problem:

Calculate the total DC resistance of a 100 metre roll of $2.5mm^2$ copper wire if the resistivity of copper at 20^oC is $1.72 \times 10^{-8}\Omega$ metre.

Resistivity Example No1

Solution:

Given:

resistivity of copper at $20^{o}C$ is $1.72 \times 10^{-8}\Omega$ metre

coil length $L = 100\ \text{m}$

cross-sectional area of the conductor is $2.5\ \text{mm}^2$ giving an area of:

$$A = 2.5 \times 10^{-6}\text{m}^2$$

Resistivity Example No1

Solution

$$R = \rho \frac{L}{A} \Omega$$

$$R = \frac{(1.72 \times 10^{-8}) \times 100}{2.5 \times 10^{-6}} = 688 \text{ m}\Omega$$

That is, 688 milli-ohms or 0.688 ohms.

Resistance of Driven Rods

The Ground Resistance (R) of a single rod, of diameter (d) and driven length (i) driven vertically into the soil of resistivity (ρ), can be calculated as follows:

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

Where: ρ Soil resistivity in Ω-m

l Buried length of the electrode in m

d Diameter of the electrode in m

The rod is assumed as carrying current uniformly along its rod.

Examples

$20\ \mathrm{mm}$ rod of $3\ \mathrm{m}$ length and soil resistivity $50\ \Omega - \mathrm{m}$. What is R?

Examples

$20\ \mathrm{mm}$ rod of $3\ \mathrm{m}$ length and soil resistivity $50\ \Omega - \mathrm{m}$. What is R?

Answer:

$$R = 16.1\ \Omega$$

Examples

$25\ \mathrm{mm}$ rod of $2\ \mathrm{m}$ length and soil resistivity $30\ \Omega - \mathrm{m}$. What is R?

Examples

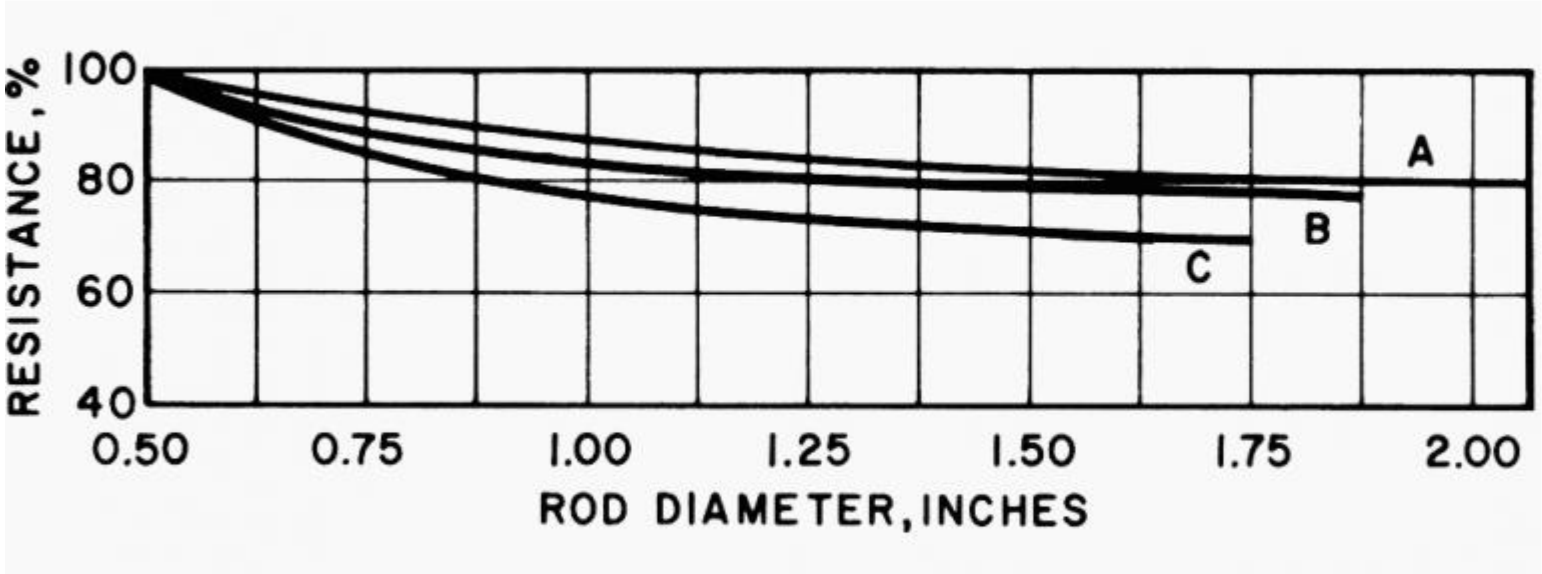
$25\ \mathrm{mm}$ rod of $2\ \mathrm{m}$ length and soil resistivity $30\ \Omega - \mathrm{m}$. What is R?

Answer:

$$R = 13.0\ \Omega$$

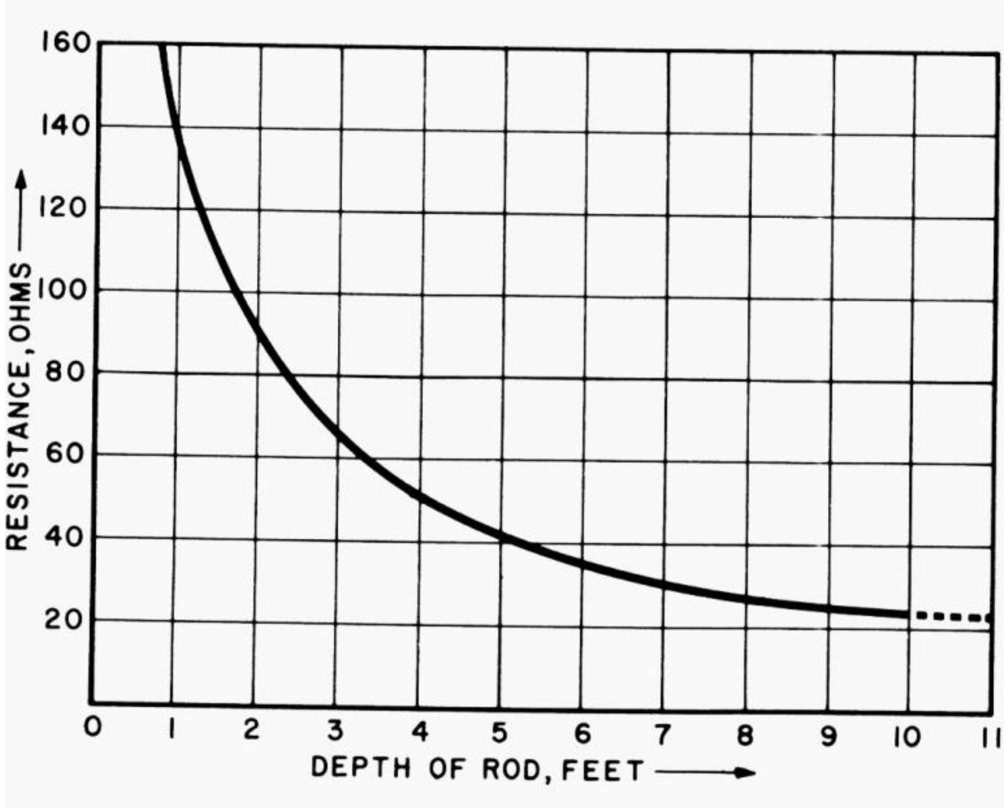
Increasing Rod Diameter

- Increasing the electrode diameter lowers the rod resistance **only very slightly.**
- The only reason for increasing the diameter would be to increase its physical strength to drive it deeper into the soil, or if the soil is very hard.



Driving Rod Deeper

The same rod driven 4 ft down has a resistance of about $50\ \Omega$. Using the 40 percent reduction rule, $88 \times 0.4 = 35\ \Omega$ reduction.



Use of Multiple Rods

- Two well-spaced rods driven into the earth provide parallel paths. They are, in effect, two resistances in parallel.
- The rule for two resistances in parallel does not apply exactly.
- That is, the resultant resistance is not one-half the individual rod resistances (assuming they are of the same size and depth).

Use of Multiple Rods

- It is often necessary to use more than one rod, in which case the spacing between them should exceed the depth to which they are driven, by a factor of 2 to 3
- The total resistance (in homogeneous soil) is then equal to the resistance of one rod, divided by the number of rods in question

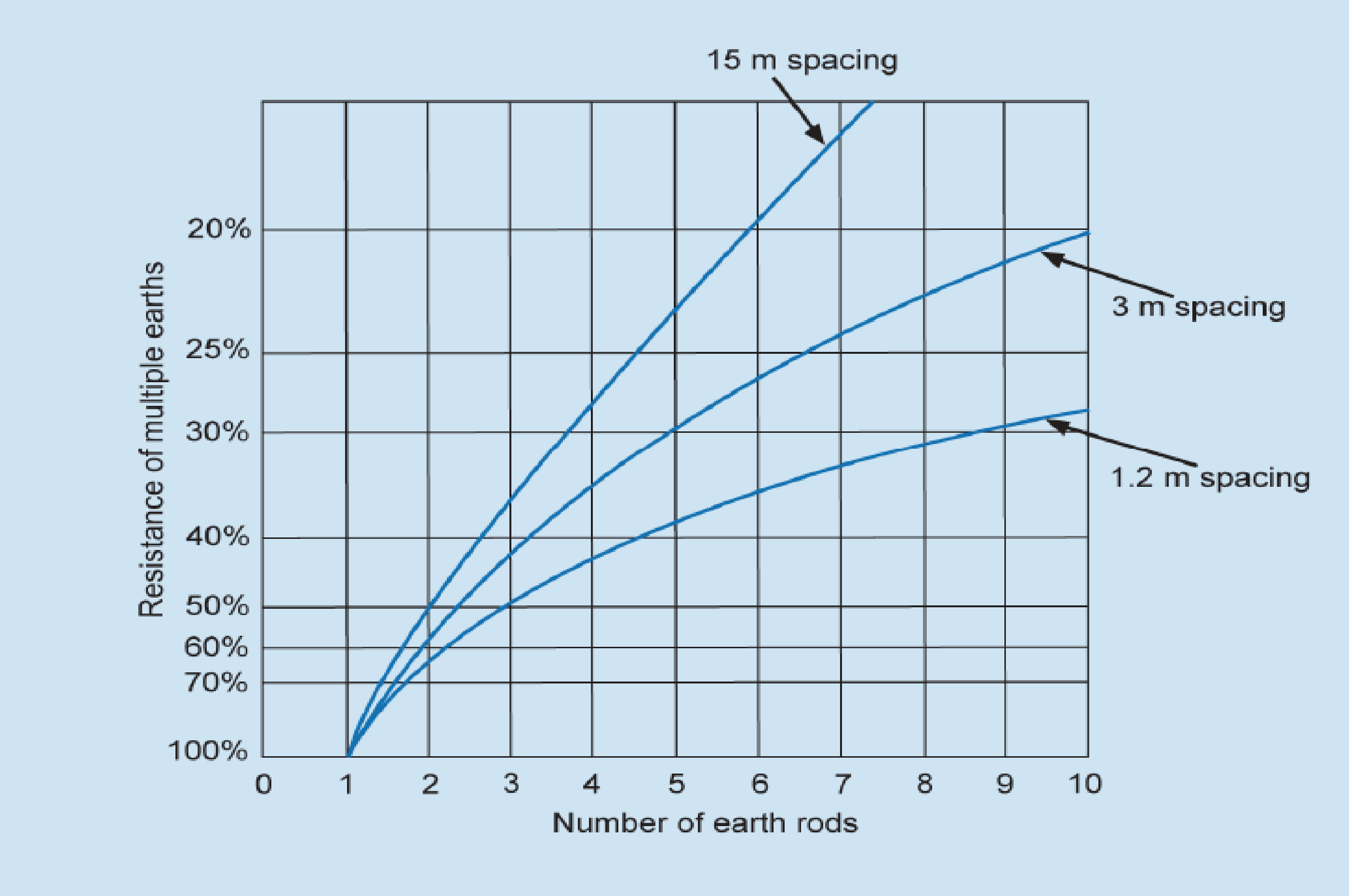
Use of Multiple Rods

- The approximate resistance R obtained if the distance separating the rods > 4L is:

$$R = \frac{1}{n}\frac{\rho}{L}$$

- Where:
  - L = the length of the rod in metres
  - ρ = resistivity of the soil in ohm-metres
  - n = the number of rods

Use of Multiple Rods



When you use multiple rods, **they must be spaced apart further than the length of their immersion**. There are theoretical reasons for this, but you need only refer to curves.

Rod in Parallel to Reduce R

- If the desired ground resistance cannot be achieved with one ground electrode, the overall resistance can be reduced by connecting a number of electrodes in parallel.
- These are called **arrays of rod electrodes.**
- The combined resistance is a function of the number and configuration of electrodes, the separation between them, their dimensions and soil resistivity.
- Rods in parallel should be spaced at least twice their length to utilize the full benefit of the additional rods.

Rod in Parallel to Reduce R

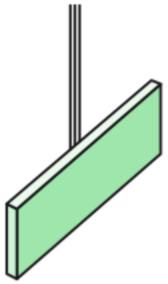
- If the separation of the electrodes is much larger than their lengths and only a few electrodes are in parallel, then the resultant ground resistance can be calculated using the ordinary equation for resistances in parallel.
- In practice, the effective ground resistance will usually be higher than this.
- Typically, a 4 spike array may provide an improvement of about 2.5 to 3 times.
- An 8 spike array will typically give an improvement of may be 5 to 6 times.

Vertical Plates

- For a vertical plate electrode:

$$R = \frac{0.8\rho}{L}$$

- Where
  - $L =$ the perimeter of the plate in metres
  - $\rho =$ resistivity of the soil in ohm-metres



Vertical Plates

- Rectangular plates, each side of which must be ≥ 0.5 metres, are commonly used as earth electrodes, being buried in a vertical plane such that the centre of the plate is at least 1 metre below the surface of the soil.

The plates may be:

- Copper of 2 mm thickness
- Galvanised steel of 3 mm thickness

Summary - IEC Defined Voltage Levels

Extra High Voltage (EHV):

- Shall mean a voltage exceeding 275 kV

High Voltage(HV):

- Shall mean a voltage exceeding 36-kV but not exceeding 275 kV

Medium Voltage (MV):

- Shall mean a voltage exceeding 1001 volts but not exceeding 36 kV

Low Voltage (LV):

- Shall mean a voltage of 1000 volts or lower

Electrical Hazards

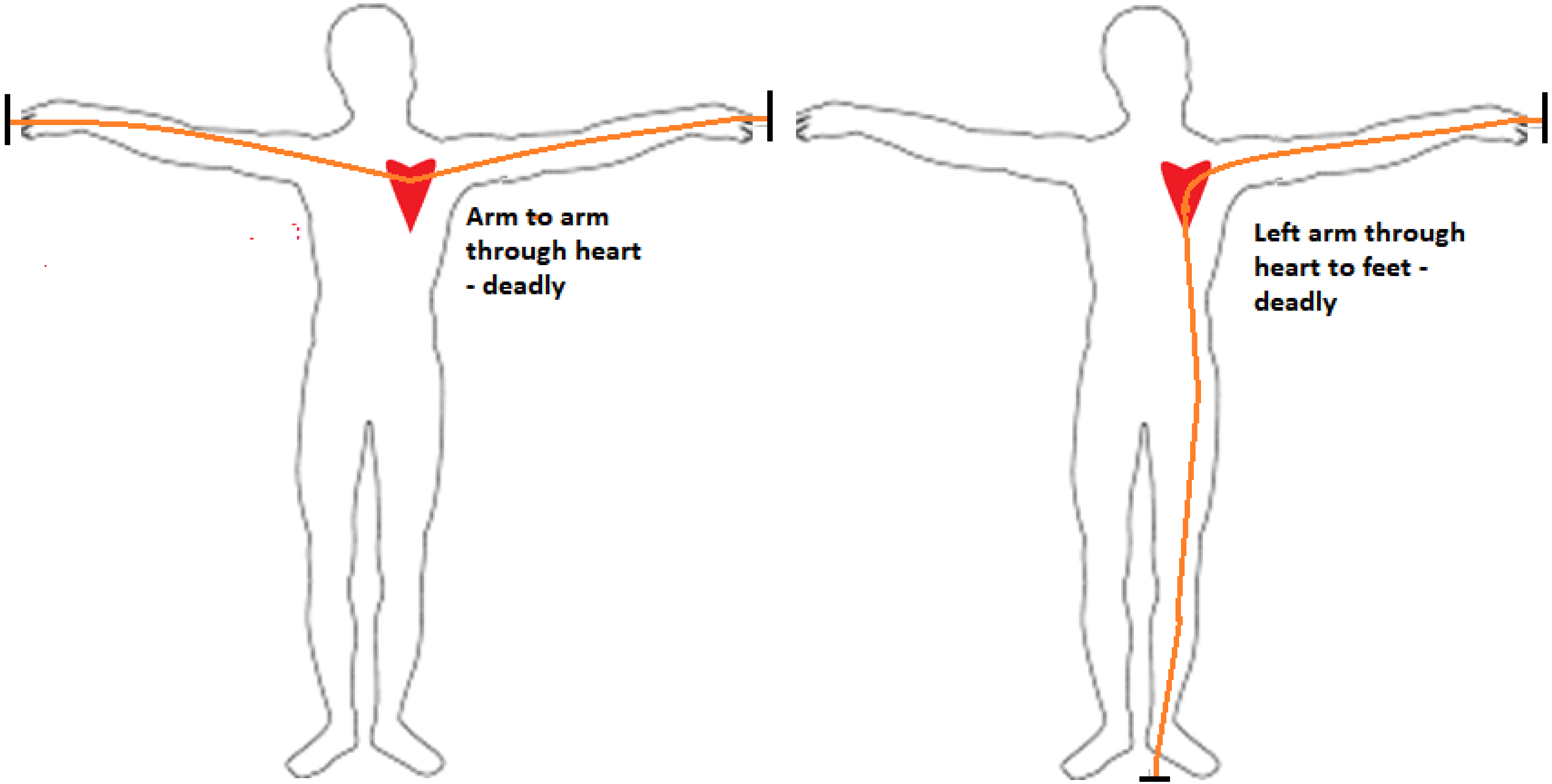
The hazards due to electricity may be summed up in three words, namely:

- Shock
- Arc flash
- Blast

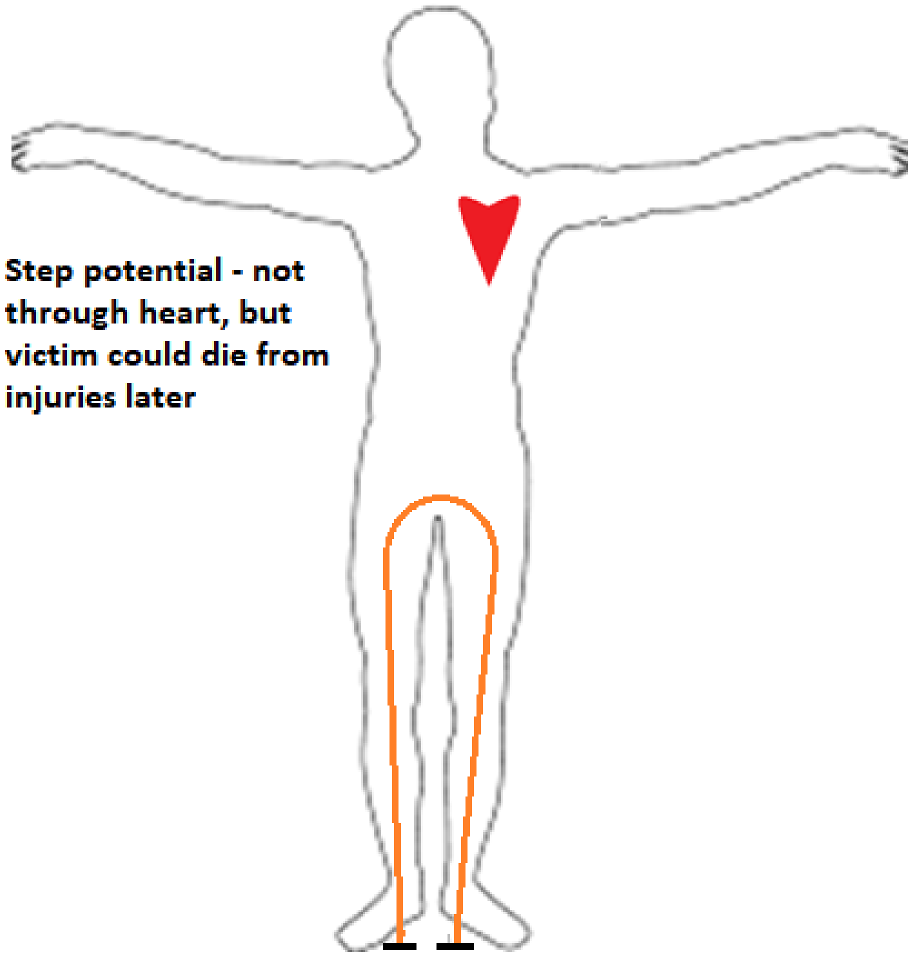
The consequences to humans of these three effects, especially the first one is determined by:

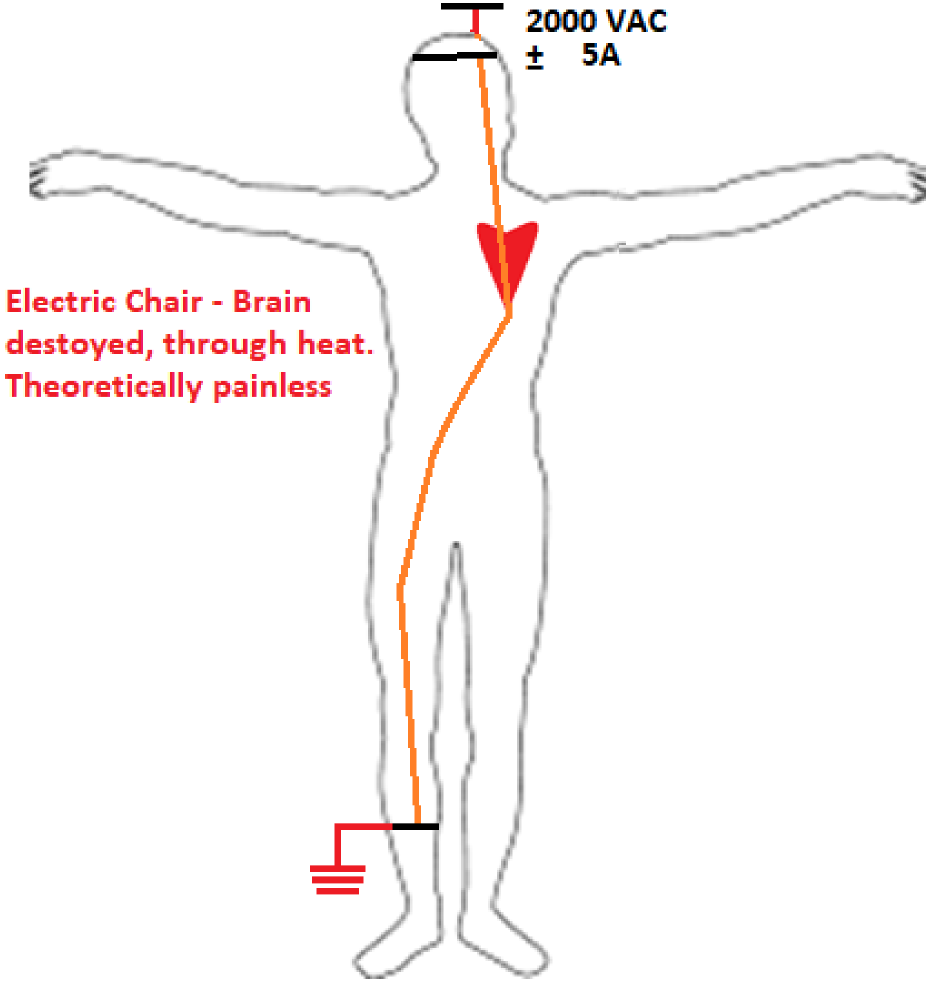
- Voltage level
- Amount of current
- Current path through the body
- Length of time current flows

Current Paths



Current Paths





Soil Resistivity

- Soil resistivity plays important role in effectiveness of earthing. Major factors contributing to soil resistivity are:
  - Soil type
  - Size of grains
  - Density of soil and pressure
  - Moisture content
  - Temperature
  - Salt content
- Where soil resistivity values are low, longer earth electrodes, improvement of soil resistivity by soil treatment would be required.

End of Tutorial 4

Any questions or comments?