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EARTHING COURSE

For South African Conditions

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6) About the CDAA

The Copper Development Association Africa (CDAA) has represented the local copper industry in southern Africa since 1962 and now promotes copper usage throughout Africa. The CDAA's head office is based in Johannesburg and on behalf of its members the organisation is committed to advancing and expanding the use of copper and copper alloys throughout Africa. The CDAA, through continuous projects and trials, facilitates the adoption of downstream products, and the uses and benefits of copper across a plethora of industries.

The content in this booklet forms part of a collection of training material developed for the electrical sector in South Africa where the content relates directly to prevailing standards used in South Africa at the time of print.
Standards that have been referenced are both IEC & SANS standards as is used & practiced

7) How to use this guide

a) Familiarize yourself with the principles
   i) Read the introduction
   ii) Take a look at the practical applications of earthing
b) Gain an understanding of corrosion implications related to earthing systems
c) Decide on a means of testing soil resistivity
d) With due consideration of the above, decide on the correct earthing system for your specific application
   i) Horizontal
   ii) Vertical
   iii) Foundation
   iv) Armored
   v) Meshed
e) As a final step, choose the correct calculations for the specific application
f) Apply the results by applying the fault current to determine the amount of earthing required.
g) This document also contains some additional formulas for your interest

8) Introduction

Earthing means to connect an electrically conductive part to an earthing system, which in turn, is connected to earth. An earthing system that has been adequately designed should provide a low impedance return path to the ground in order for fault current to be detected, isolated and, or dissipated.
In certain countries “earthing” is also called “grounding”.
Earthing of equipment improves the correct operation of electrical networks and provides a barrier of safety to keep operators, end users and equipment safe.

With the rapid growth of electrical networks that include a growing number of non-linear loads and embedded renewable energy generators, a clear understanding of earthing principles is becoming increasingly important.

a) Earthing and bonding

- Provides safety for human and animal life by limiting touch and step voltages to safe values, (protective earthing, earthing of work),
- Ensures good power quality through the correct operation of the electricity supply network (power system earthing)
- Limits electromagnetic disturbances and improves electromagnetic compatibility (EMC) levels.
- Protects buildings and electrical installations/networks against lightning and surges.

b) Creating a path to earth

Designing and installing a grounding/earthing system that is in contact with the earth creates a path to earth. Electrodes, rods, earth mesh, metallic re-enforcing bars or copper spikes are used as a means of achieving an effective path.
The effectiveness of a ground electrode system is measured by the lowest possible resistance between the ground electrode system and the earth mass.
A number of factors determine the effectiveness of this design, such as soil resistivity and type of electrodes used.

Metallic parts of an earth electrode have direct contact with soil and for this reason are affected by natural elements potentially limiting the life of the earthing system. The earth electrode conductors should therefore conform to minimum criteria in order to withstand:

1. Mechanical stress during installation and operation,
2. Fault or lightning currents,
3. Corrosive attack by acidic conditions in soil.

These three parameters are interdependent when choosing the electrode material and its cross section. For the majority of commercial & domestic power installations, the lifetime of an earthing system can exceed 25 years and for power lines, 35 – 50 years. An earthing system should be included in repair and maintenance cycles with an annual testing regime to ensure continued performance.

9) Earthing and its application in electrical systems

a) General Earthing / Bonding requirements

Correct earthing system design is intended to achieve a required earth resistance (impedance) value as well as ensuring satisfactory surface potential distribution by selecting equipment that is both reliable and suitable and will ensure equipment and operator safety during varying operating conditions.

The intention is for the earthing conductor arrangement to provide a connection to earth. Equipment and conductors being used for this purpose should therefore be:

i) Reliable
ii) Suitable to carry earth fault currents without
    (1) Thermal
    (2) Thermo mechanical
    (3) Chemical and;
    (4) Electromechanical stresses arising from normal operational as well as fault currents.

The construction and effectiveness of an earth electrode is dependent on factors such as:

- The value of the expected fault current,
- Ground conditions on site where the earth electrode is planned.

In practice one can distinguish the following typical earth electrode constructions:

- Horizontal earth electrodes,
- Vertical electrodes,
- Meshed electrodes,
- Foundation earth electrodes
- Cable with exposed metal sheath

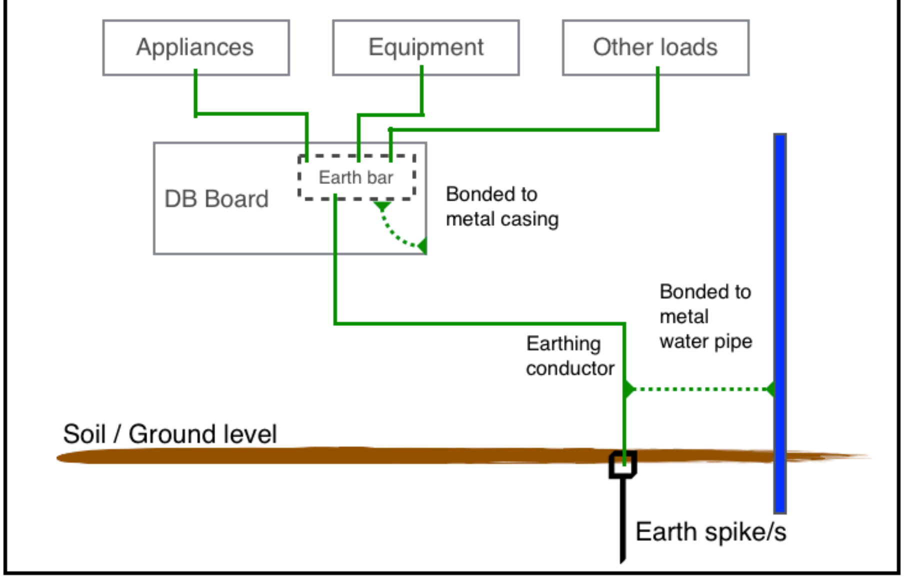


Diagram showing a typical earthing and bonding arrangement of an electrical system not connected to the utility grid. Diagram is illustrative only and should not be used as a guide to assist in earthing system design.

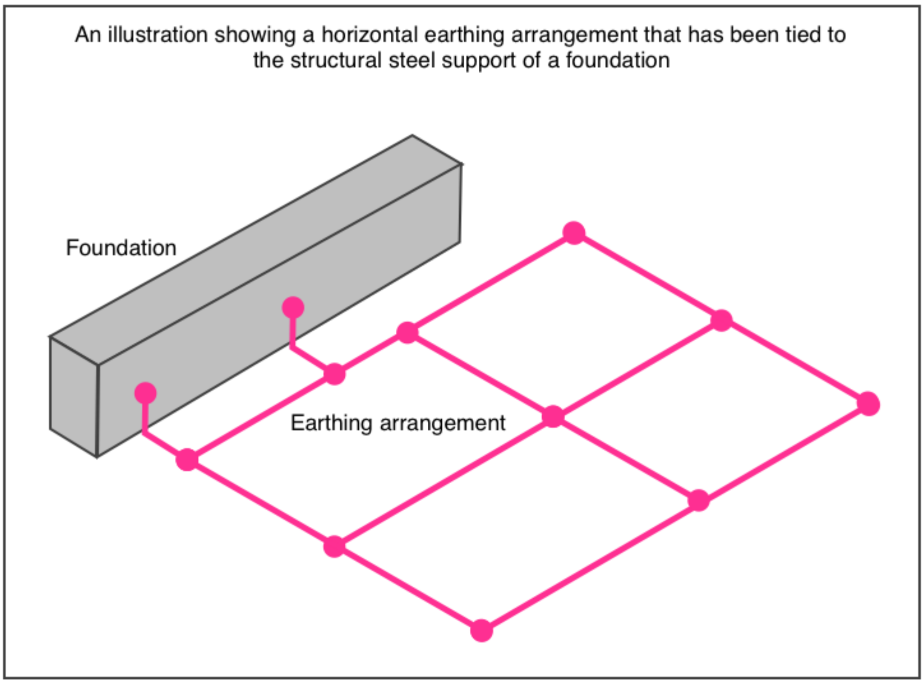
b) Different types of electrodes

i) Horizontal Earthing Rods[1]

Simple horizontal earth electrodes are metal rods, strips or pipes placed horizontally under the ground surface at a given depth t, which is usually in the range from 0.6m up to 1 m deep. In

[1] ref Leonardo Energy . . . . "Typical earth electrode construction"

regions where the ground freezes these electrodes may be placed deeper than 1 m as horizontal electrodes should be mounted beneath the freezing line.



ii) Vertical Earthing Electrodes

Simple vertical earth electrodes are metal rods or pipes placed vertically in the ground. The typical length of rods is in the range from 3 m up to 30 m and could; in extreme cases be even longer/deeper. They are usually mounted as a set of rods with the length of about 1.5 m, placed successively one over other and driven into soil with a mechanical hammer. Vertical earth electrodes have considerable advantages as the rod passes through various layers of soil when it is embedded into the ground. Water or moisture content generally increases with depth of soil. A stable temperature can also be expected at increased depths below ground level. Thus, the resistance to earth of a vertical rod electrode is more stable than when compared to horizontal electrodes. This is due to sensitivities as a result of weather and ground conditions.
Another advantage is that a smaller surface area is required to install the vertical rod electrode. Vertical rods are recommended in dense building areas, or where the surface is covered with asphalt or concrete. Vertical earth electrodes are often also used in addition to horizontal rods in order to supplement and improve the resistance of existing horizontal electrodes. A disadvantage of vertical rod electrodes; is un-favourable surface potential distribution.

iii) Foundation earth electrodes

Foundation earth electrodes are recommended as a very practical solution to building earthing and are constructed from conductive metal parts embedded in the concrete of the building foundation. Concrete buried directly in the ground has natural moisture content and can be considered as conductive matter with conductivity similar to that of earth. Because of the large area of this type of electrode, low resistance can be achieved. Furthermore, concrete protects metal parts against corrosion; and steel electrode elements
embedded in the concrete do not need any additional corrosive protection.
In practice there are two basic foundation earth electrode constructions:

- A foundation without concrete reinforcement (Figure 12),
- A foundation with concrete reinforcement (Figure 13).

In both cases the earth electrode is made from:

- Steel strip, usually with rectangular cross section not less than 30 mm x 3,5 mm, or
- Steel bar, usually with round cross section not less than 10 mm diameter.

The steel elements can be galvanized (i.e. with a zinc coating), but this is not necessary if the layer of concrete covering the electrode is greater than 50 mm, because the concrete ensures sufficient protection against corrosion, as shown in Figure 12.
In a foundation without concrete reinforcement (Figure 12) the electrode usually follows the contour of building foundation, i.e. it is placed under the main walls. In buildings with extensive foundations, the electrode is usually installed in the form of multiple loops covering the parts of foundation outlines, and connected to each other.

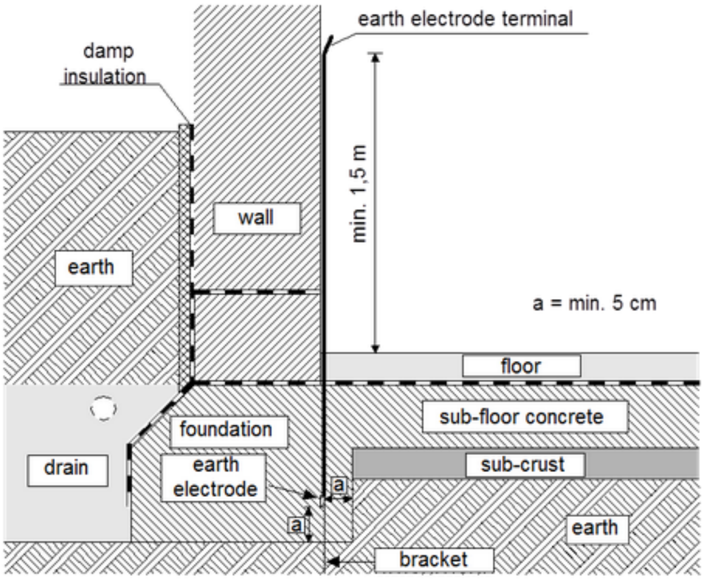


Figure 12. Illustration of the placement of the foundation earth electrode in foundation without concrete reinforcement.

In a foundation using concrete reinforcement the earth electrode is placed over the lowest layer of wire-mesh reinforcement (Figure 13) thus ensuring adequate corrosion protection for the electrode. The electrode should be fastened to the reinforcement mesh with wire strands at intervals of not more than 2 m over the electrode length. It is not necessary to make a sound electrical connection at each point because the main electrical connection is via the concrete. If the foundation is constructed as separate panels connected to each other with expansion joints, the earth electrodes of each panel should be galvanically connected each other. These connections must be flexible and must be located so that they remain accessible for measurement and maintenance purposes.

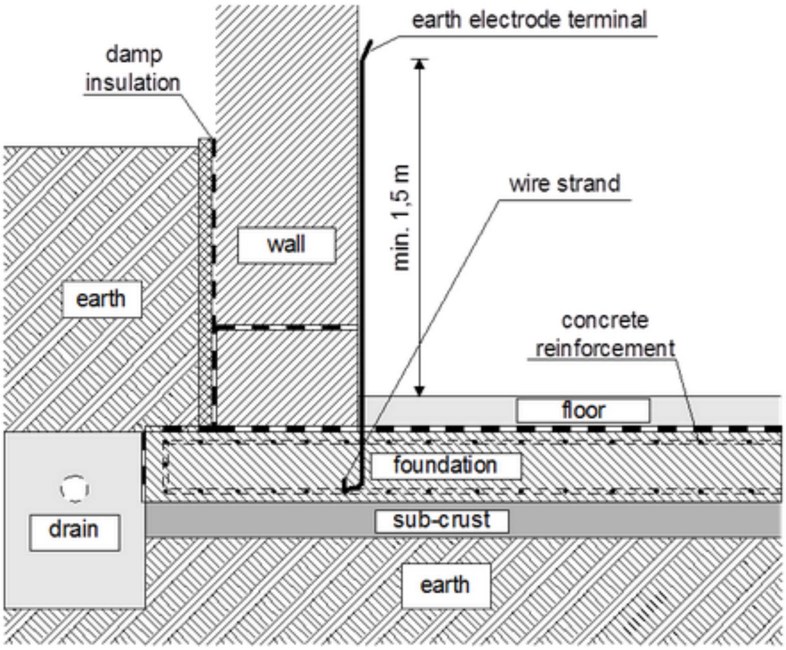


Figure 13. Illustration of the placement of the foundation earth electrode in foundation with concrete reinforcement.

iv) Using armored cable as earth

An armored cable's metal shield can be used as a means of providing leakage to earth with efficiency similar to that of a strip earth electrode.

These types of installations are mainly used as earth electrodes in power electrical substations supplied with cable lines as well as other infrastructure networks. Additionally, it can be connected with the foundation earth electrode of the substation building. In other cases an additional earth electrode system may need to be installed in order to satisfy the fault current values. The impedance to earth of a single cable line depends on the cable length and the electric resistivity of soil.

v) Meshed electrodes

Meshed electrodes are:

- Designed as a grid of strip or rods placed horizontally in the ground. Strip is normally the preferred material as it has a larger surface for a given cross section and is considered to have superior performance at higher frequencies due to a slightly higher capacitance when installed in soil.
- Mainly used in earthing arrangements where multiple devices in a specific area are installed within close proximity of one another. In power systems a typical example is the power substation.

Meshed electrodes are usually rectangular in shape and is constructed in such a way that the size of the rectangle corresponds to the size of the object area. In this way the earthing arrangement ensures a favorable and approximately uniform, surface earth potential distribution throughout the object area.

A significant advantage of the meshed electrodes is a favorable potential distribution in the earth's surface. During an earth fault meshed electrodes increase the surface area that experiences a voltage rise as the result of current flow to the earth electrode. Although an equipotential exists over the area of the mesh, there is a potential gradient at the periphery of the electrode. Due to the mesh extending beyond any metal structure by more than one meter it is unlikely that there would be any touch potential during fault conditions, however, dangerous step voltages could occur. 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.

A disadvantage of the meshed earth electrodes is that, due to the large area, which is covered by the grid system, it is not practical to bury the earthing system very deep, hence this type of system is 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.
The resistance to earth of meshed electrodes is approximated to be proportional to the resistance of a plate electrode buried into the soil.

vi) Natural Earth electrodes

Metallic pipes (e.g. water pipes) embedded in the ground as well as foundation earth electrodes, are sometimes also called “natural” earth electrode systems.

10) Corrosion

Corrosion is the most common problem when considering the service life of metallic elements buried in soil. The following types of corrosion could affect earth electrodes caused by chemical compounds and moisture in the soil,

1. Electrolytic corrosion
2. Galvanic Corrosion
3. Stray current corrosion caused by stray (DC) currents flowing in the soil.

Corrosion is caused by a chemical reaction between the different electrode metals and the chemical compounds found in soil. Corrosive properties of soil are characterized by its pH value, which indicates if soil is acidic, neutral or alkaline. The pH number of neutral soil is 7, smaller values show greater acidity, while higher values greater alkalinity.

The following metals are recommended for use as earth electrodes:

- Steel (un-coated steel or reinforcement steel is used in foundation earth electrodes, where the concrete protects the steel material against corrosive attack),
- Hot galvanized steel,
- Steel coated with copper,
- Zinc,
- Copper,
- Copper coated with tin or zinc,
- Copper with lead sheath.

On the other hand, consideration should be given to other metals in the vicinity of copper and; or other metals that may be connected to copper, or could be affected by the connection through electrochemical corrosion.
This problem can be found in buildings with foundation earth electrodes, where the main water supply pipes are made from galvanised steel. They are connected together in the main earthing terminal of the building, but the galvanised steel has the lowest galvanic potential with respect to the steel in concrete. For that reason the water pipes can be affected by the electrochemical corrosion.

a) Galvanic Corrosion

Galvanic corrosion[2] refers to corrosion damage that occurs when two different metals are in electrical contact in an electrolyte, where the more noble metal is protected and the more active metal tends to corrode.

b) Stray current corrosion

What causes Stray current corrosion? Stray current corrosion is different from natural corrosion because it is caused by an externally induced electrical current and is basically independent of such environmental factors as oxygen concentration or pH. Environmental factors may enhance other corrosion mechanisms involved in the total corrosion process, but the stray current corrosion portion of the mechanism is unaffected.

Stray current may originate from the following sources:

- (1) Electric railways

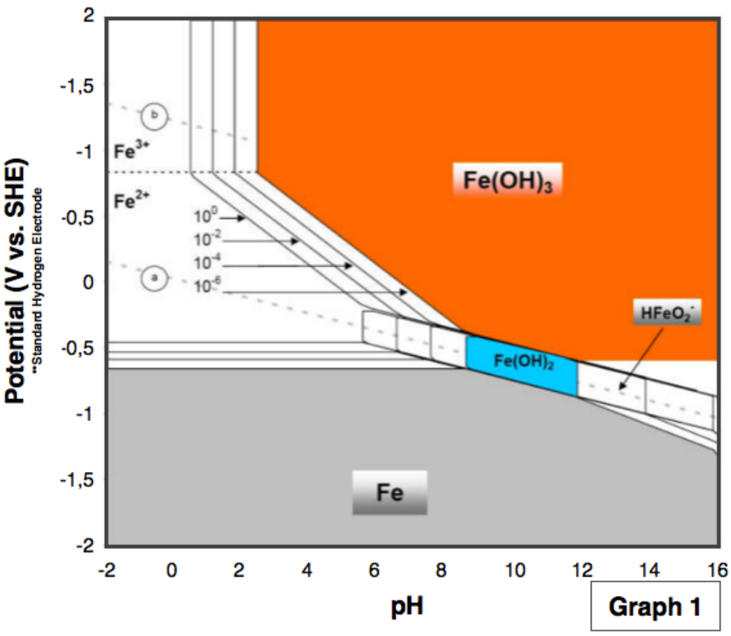
[2] https://www.corrosionpedia.com/definition/568/galvanic-corrosion

- (2) Cathodic protection systems
- (3) Electrical welding machines
- (4) Grounded DC electric sources

c) Electrolytic corrosion

Electrolytic corrosion is often confused with galvanic corrosion. While galvanic corrosion is driven by the difference in corrosion potential between two metals, the electrolytic corrosion is driven by the external sources of EMF. In the case of large motor bearings and generator bearings, induced EMF of the shaft results in current flow in the bearing, resulting in bearing corrosion in the shape of pinhole-type pits formed on the bearing surface.

Soil contains a certain amount of water, which can act as an electrolyte when dissimilar metals are connected with one another. This type of connection in electrical networks is quite common where; as an example galvanized water pipes are bonded to copper pipes, or where aluminium lightning protection equipment is bonded to the copper earthing system and all of the various metals are buried in ground. The galvanic potential of a range of metals can be seen in the table below. The relationship between the potential of dissimilar metals are complex and can be influences by a number of factors, which would include the soil pH, soil temperature and moisture content.



Graph 1

Estimated voltages of certain metals under specific conditions. Values indicated can fluctuate based on on-site conditions and is only indicated as an example.	
Metal	**Galvanic Potential (estimate)**
Aluminium	-1,71
Zinc	-0,9 to -1,1
Galvanized Steel	-0,7 to -1,1
Steel	-0,5 to -0,8
Steel embedded in concrete	-0,1 to -0,3
Tin	-0,14
Lead	-0,13
Copper	0,0 to -0,1

Table 1

d) How corrosion takes place

Due to the different types of corrosion being closely related; a section has been included to explain how corrosion in earthing systems work, in order to enable the reader to better identify solutions and reduce possible issues linked to corrosion.

Traditional batteries rely on an electrolyte in order to ensure the transfer of electrical potential. The moisture that is present in soil could resemble the electrolyte in a similar chemical reaction as is found in batteries. Metallic parts embedded in electrolyte have a galvanic potential. Galvanic potential for different metals under specific conditions are indicated in Table 1 above. The galvanic current source created with the combination of metals and an electrolyte is similar to that of a battery. When two metallic parts are connected with a wire, the difference of galvanic potential of both metals, form a type of battery circuit. The galvanic battery now supplies the circuit with the voltage that is equal to the potential difference of the two metals. For example electrodes made from steel and copper have the galvanic potential of about 0.5V, where the copper electrode has the positive polarity with respect to steel. In the external part of the circuit (let say in the wire connecting both electrodes) the current direction is from the positive to the negative electrode.

However, inside the electrolyte, within the moisture of the soil, the direction of current is from the electrode with higher negative potential to that of the positive. Thus, for the current in soil, the negative electrode becomes an “anode”, while a “cathode” is formed by the positive, i.e. in an opposite manner like for the circuit outside of the electrolyte. This principle is explained when looking at the difference between electrolytic and galvanic cells.

The current flowing inside the electrolyte from the more negative to the more positive electrode transports ions, which leave the negative electrode. In this way the electrode loses material mass, i.e. it is affected by electrochemical corrosion. The metallic parts with more negative potential will diminish, while that with positive potential will remain without losses.

The described process is more intensive in soil with greater levels of moisture compared to soil with lower levels of moisture, i.e. the phenomenon depends on the resistivity of the soil. The soil with good resistivity, lower than 25 Ωm is treated as “aggressive” to electrochemical corrosion, while grounds with resistivity over 100 Ωm are treated as nearly “neutral” for it. Thus, good soil resistivity could affect the life of earth spikes due to corrosion.

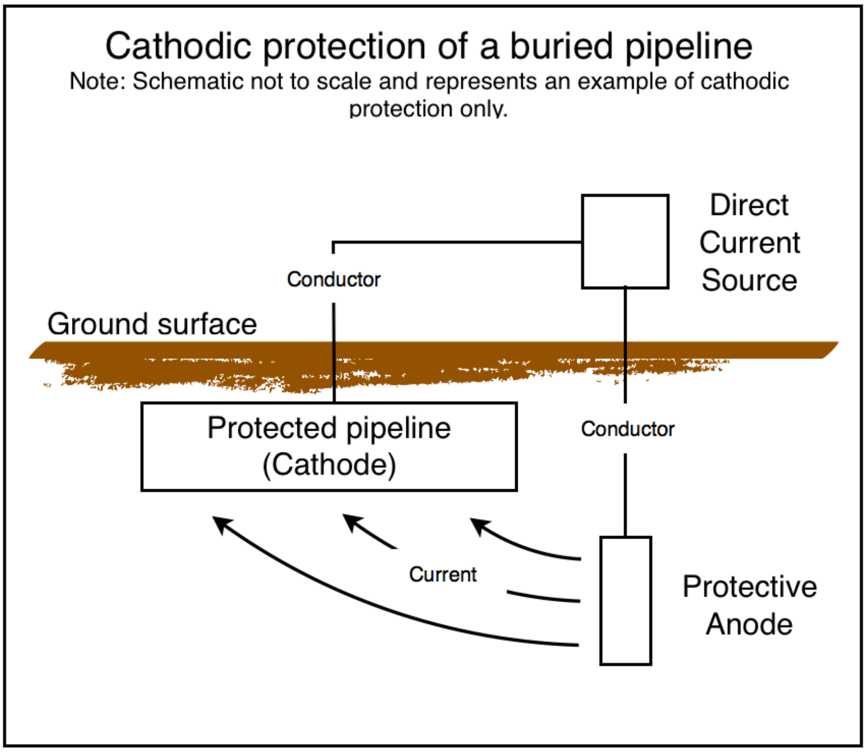
e) Solutions to prevent corrosion

Standards provide requirements, guidelines and best practice with regards to the minimum cross section of electrode materials to be used in different types of soil profiles or earthing installations. These minimum cross section recommendations should also ensure adequate mechanical strength and resistance against chemical corrosion.

Protection against corrosion is maximized when choosing the correct material when specifying an earthing electrode for a specific application. Usually materials consisting of a more noble metal will result in a longer service life of the electrode. A larger cross section of the electrode metal will also improve durability and extend the life of electrodes in acidic conditions.

Corrosion can be controlled in different ways.

1. Use copper as the preferred material for earth electrodes. Copper has a higher potential when compared with steel, zinc and other common used metals, and can be seen as a metal that is resistant against galvanic corrosion.
2. Use steel embedded in concrete, as is seen in foundation earth electrodes, which again has a higher potential than steel, or that of galvanized steel buried directly in soil.
3. Protection against galvanic corrosion of earth electrodes could be promoted with the use and connection of a combination of different metals that could act as a sacrificial anode. The sacrificial electrode is designed in such a way to corrode, and thereby protect the pipe. In this case any losses incurred by the “protected” metal would be negligible. Sacrificial anodes are additional electrodes with a potential that is lower than both of the other materials used in the earthing system; i.e, that of pipe and that of steel in concrete. Sacrificial anodes could be Magnesium or Zinc. This method is similar to that of cathodic protection. However, the need and maintenance regime of this type of solution must be considered with caution.



11) Soil Resistivity

One of the main factors affecting the performance capability of an earthing system is the resistivity of soil. When designing an earthing system an accurate resistivity model of the soil is required and will show the extent to which soil will resist the flow of current.
As earthing systems are installed near the surface of the earth, the topsoil layers are subjected to higher current densities; are therefore more significant than deeper levels and require more accurate modeling. In SABS 0199-1985, soil resistivity is defined as the resistance between the opposite faces of a cube of soil having sides of length 1m. Soil resistivity is expressed in Ohm-meter(Ωm).

a. Soil resistivity principles

Throughout Africa, operating conditions vary significantly according to region and season and the following summarized factors have an impact on the resistivity of soil.

- Type of earth/soil (eg, clay, loam, sandstone, granite).
- Stratification of soil; layers of different types of soil (eg, loam backfill on a clay base).
- Moisture content; resistivity may fall rapidly as the moisture content is increased, however, in areas where the moisture content exceed 20%; the rate of decrease in resistivity is less.
- Temperature; above freezing point, the effect of changes in temperature on earth resistivity is practically negligible and can be considered for academic purposes/modeling.
- Salt content.
- Presence of metal and concrete pipes, tanks, large slabs, cable ducts, rail tracks, metal pipes
- Topography; rugged topography has a similar effect on resistivity measurement as local surface resistivity variation caused by weathering and moisture.

Type of Soil	Typical resistivity in Ωm (Ohm meter)
Loams, Garden soils	5 to 50
Clays	8 to 50
Clay, sand & gravel mixtures	40 to 250
Sand & Gravel	60 to 100
Slates, shale, sandstone	10 to 500
Crystalline rocks	200 to 10000

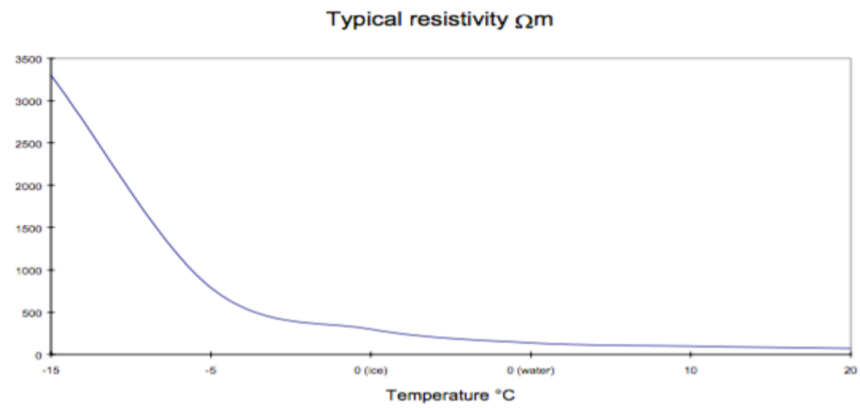


Figure 1-1 Variations in resistivity with temperature for a mixture of sand and clay with a moisture content of about 15% by weight

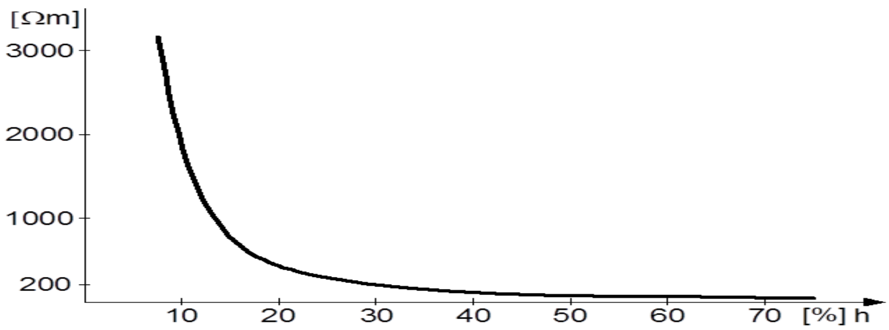


Figure 3. - Exemplary soil resistivity ρ of clay against soil humidity h

a. Testing type guidelines

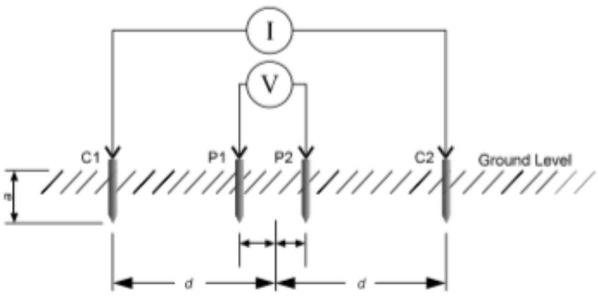
The purpose of resistivity testing is to obtain a set of measurements; which may be interpreted to yield a model that can be applied to represent the electrical performance of the earth, as seen by the particular earthing system. However, the results may be incorrect or misleading if an inadequate testing regime is undertaken, or when measurements are not accurately recorded. To overcome these risks, the following guidelines are suggested.

- Conduct high-level site research, of which the result should provide adequate background, regarding the type of test to be used, and against which the results may be interpreted.
  - The following additional data may also be useful in the analysis. Data related to:
    - Nearby metallic structures, as well as
    - The geological and geographical nature of the area. Geological data regarding soil types and layers will give an indication of the water retention properties of the upper layers and also the variation in resistivity to be expected due to fluctuating seasonal water content. By comparing recent rainfall data, against the seasonal average, it may be ascertained whether the testing results are realistic or not, as seasonal patterns would affect the resistivity of soil.

- When selecting the test type the following factors should be considered
  - Maximum probe depths,
  - Lengths of cables required,
  - Efficiency of the measuring technique,
  - Cost (determined by the time and the size of the survey crew) and
  - Ease of interpretation of the data

Three common test types are shown in Figure 1-2.

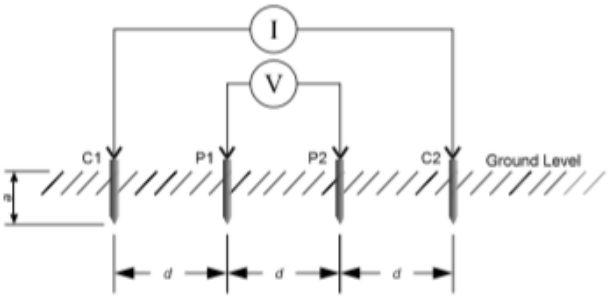
a. The Schlumberger array



Schlumberger Array

With this type of test array the potential electrodes remain stationary while the current electrodes are moved for a series of measurements. In each method the depth penetration of the electrodes is less than 5% of the separation to ensure that the approximation of point sources, required by the simplified formulae, remains valid. Economy of manpower is gained with the Schlumberger array since the outer electrodes are moved four or five times for each move of the inner electrodes. The reduction in the number of electrode moves also reduces the effect of lateral variation on test results. Considerable time saving can be achieved by using the reciprocity theorem with the Schlumberger array when contact resistance is a problem. Since contact resistance normally affects the current electrodes more than the potential electrodes, the inner fixed pair may be used as the current electrodes in a configuration called the 'Inverse Schlumberger Array'. Use of the inverse Schlumberger array increases personal safety when a large current is injected. Heavier current cables may be needed if the current is of large magnitude. The inverse Schlumberger reduces the heavier cable lengths and time spent moving electrodes. The minimum spacing accessible is in the order of 10 m (for a 0.5m inner spacing), thereby, necessitating the use of the Wenner configuration for smaller spacings. Lower voltage readings are obtained when using Schlumberger arrays. This may be a critical problem where the depth, required to be tested; is beyond the capability of the test equipment or the voltage readings are too small to be considered. The Schlumberger test is considered more accurate and cost effective than comparative tests.

b. The Wenner,

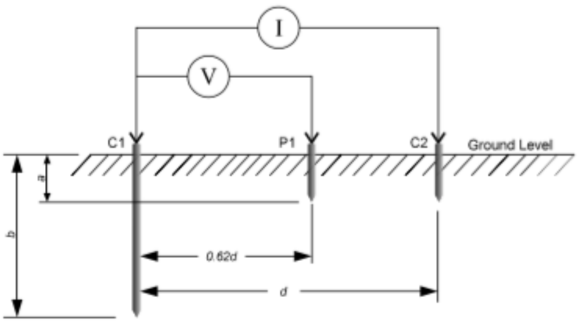


Wenner 4 Pin Method

All four electrodes are moved for each test with the spacing between each adjacent pair remaining the same. Although the Wenner array is the most efficient in terms of the ratio of received voltage per unit of transmitted current it is the least efficient from an operational perspective. It requires the longest cable layout, largest electrode spreads and large spacings; one person per electrode is necessary to complete the survey in a reasonable time.

Also, because all four electrodes are moved after each reading, it is most susceptible to lateral variation effects and where un-favourable conditions such as very dry or frozen soil exist, considerable time may be spent trying to improve the contact resistance between the electrode and the soil.

c. Driven Rod methods



Driven Rod (3 Pin) Method

Figure 1-2 Resistivity Test Probe Configurations

Provided a current source of sufficient power is used, the driven rod method (or Three Pin or Fall-of-Potential Method) is normally suitable for use in circumstances such as transmission line structure earths, or areas of difficult terrain, because of the shallow penetration that can be achieved in practical situations, the very localised measurement area, and the inaccuracies encountered in two layer soil conditions.

a) Traverse Locations.

Soil resistivity can vary significantly both with depth, and from one point to another at a site, and as such, a single soil resistivity measurement is usually not sufficient. To obtain a better picture of soil resistivity variations, it is advisable to conduct a detailed survey which would include testing at different depths. Testing at different depths, means varying the spacing between probes as well as the depth to which the probes are driven into the ground for testing purposes. A rule of thumb is that the penetration depth of the potential probes should be no more than 10% of the pin spacing, whereas the current probes must not be driven more than 30% of the pin spacing.

The Line Traverse technique is a commonly used method for performing soil resistivity surveys. In this method, a series of imaginary parallel lines are drawn across the area to be surveyed, and a number of soil resistivity measurements, at various stake separations, are performed along each of these lines (see Figure 1-3). Larger earthing systems require a greater number of traverses.

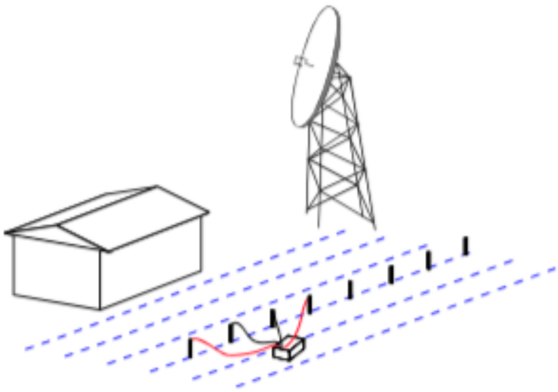


Figure 1-3 Performing a Line Traverse Survey

Taking a number of measurements along each 'line', using different stake separations, will provide an indication of how the soil resistivity varies with depth, whilst taking measurements along different lines will indicate how the resistivity changes across the site.
In this way, a picture can be built up of the resistivity variation at the site and the areas of lowest resistivity can be identified. By measuring the resistivity at different depths, it is possible to build up information about the underlying soil and whether or not any advantage can be gained by installing the earthing system to a greater depth.
A Line Traverse survey is a cheap and simple way of mapping variations in soil resistivity at a site and could well provide significant cost savings, in terms of material and labour, when attempting to achieve the required resistance figure.
It is also useful to include a 'check' traverse near to, yet beyond the influence of the grid. Measurements are re-made on this traverse when undertaking an injection test on the installed grid, to correlate the test results with the initial measured conditions at the time of design.

(d) Spacing Range.
The range of spacings recommended includes accurate close probe spacings (>1m), which are required to determine the upper layer resistivity, used in calculating the step and touch voltages, to spacings larger than the radius or diagonal dimension of the proposed earth grid. The larger spacings are used in the calculation of remote voltage gradients and grid impedance.
Measurements at very large spacings often present considerable problems (eg inductive coupling, insufficient resolution on test set, physical barriers) they are important if
Practical Testing Recommendations.
It has been found that special care is required when testing to:

- Eliminate mutual coupling or interference due to leads parallel to power lines. Cable reels with parallel axes for current injection and voltage measurements, and small cable separation for large spacings (>100m) can result in errors;
- Ensure the instrumentation and set up is adequate (ie equipment selection criteria, power levels, interference and filtering);
- Undertake operational checks for accuracy (ie, a field calibration check);
- Reduce contact resistance (use salt water, stakes and/or the reverse Schlumberger);
- Instruct staff to use finer test spacings in areas showing sharp changes (ie to identify the effect of
  local inhomogeneities and give increased data for interpretation). Plot test results immediately during testing to identify such problem areas.

12) Calculations

a) Horizontal

The results of example calculations, using formulas (14 -17), for the horizontal earth electrode made from a strip with the length l = 10 m, are presented in Figure 9 . The analysis of these curves let to conclude some general remarks:

- By increasing the buried depth of the horizontal earth electrode, a change in the curve can be observed $V^*=f(x)$. The change in the curve is as a result of the touch and step voltages decreasing as the buried depth of the horizontal earth electrodes are increased.
- Increasing the buried depth also causes a slight decrease of the resistance to earth. However, in this example increasing t from 0.6 m up to 1.4 m (more than two times) only resulted in an improvement of R_E of about 10%.
- The resistance to earth R_E decreased as the electrode diameter d increased. Increasing d from 0.02 m up to 0.1 m (five times) resulted in a decreasing R_E of about 18%. It is not recommended to increase earth rod diameter in order to decrease resistance, however, increasing the diameter is sometimes necessary in order to fulfill the mechanical and corrosion requirements.

$$R_E = \frac{\rho}{2\pi l} \ln \frac{l^2}{td} \qquad (14)$$

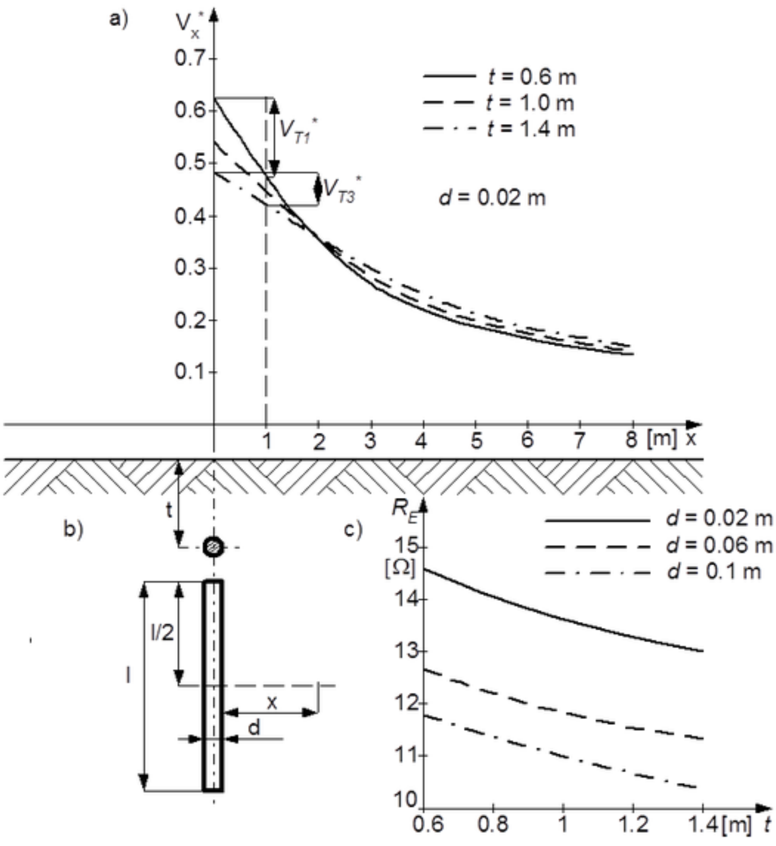


Figure 9

In order to do an example calculation, a number of factors need to be considered.
In practice the simple horizontally placed earth electrodes can have different shapes, besides those presented in Table 2. The resistance of the various shapes can be calculated using the following formula:

$$R = \frac{\rho}{2\pi l_{\Sigma}} \ln \frac{Bl^2}{td_e} \qquad (17)$$

where :
the values of *B* are given in Table 2 for each configuration of earth electrodes.
l_{Σ} - sum of all arms of the electrode

Values of the factor B for various geometrical forms of horizontal electrodes can be seen in Table 2 above.

Due to the interaction of the radial conductors doubling the number will not half the resistance. The increase in resistance is approximated by: [3]
For two wires at right angles, energised at the joint, the resistance is:

$$= R + \frac{3R}{100}$$

For a 3 point star	4 point star	5 point star	6 point star
$= R + \frac{6R}{100}$	$= R + \frac{12R}{100}$	$= R + \frac{42R}{100}$	$= R + \frac{65R}{100}$

where: R Resistance of a straight wire of same total length energised at one end

As discussed in the section titled "The Significance of Impedance", due to the shorter effective length of radials compared to a single run, the radial will be a much more effective earth under transient conditions. It is better to run multiple radials, rather than a single long (or deep) conductor.

[3] Earthing fundamentals, Lightning and Surge Technologies

The calculation for buried radials is given by:

$$R_g = \frac{\rho}{n\pi L}\left[\ln\left(\frac{4L}{(dh)^{\frac{1}{2}}}\right) - 1 + N(n)\right]$$

$$N(n) = \sum_{m=1}^{m=n-1} \ln \frac{1+\sin \pi m/n}{\sin \pi m/n}$$

or

for n=	2	3	4	6	8	12
N(n)=	0.7	1.53	2.45	4.42	6.5	11

where: ρ *Soil Resistivity in Ω-m*
L *Length of each radial in m*
d *Diameter of each radial in m*
h *Buried depth of the radials in m*
n *Number of radials*

Horizontal earth electrodes are often made from a strip with a rectangular cross-section, usually 30-40 mm wide (*b*) and 4-5 mm thick (*c*). In this case the effective equivalent diameter *d* can be calculated by [6]:

$$d_e = \frac{2b}{\pi} \qquad (16)$$

and substituted $d = d_e$ in formula (14). In some literature [6], it is suggested that $d_e = b/2$.

The surface potential distribution of horizontal earth electrode (Figure 9) (15) during an earth current I_E , in direction *x* perpendicular to the length *l* (Figure 9) , is described by following formula [7] :

$$V_x = \frac{\rho I_E}{2\pi l} \ln \frac{\sqrt{l^2 + 4t^2 + 4x^2} + l}{\sqrt{l^2 + 4t^2 + 4x^2} - l} \qquad (15)$$

Usually the length of the electrode elements, *l*, is much larger than *t.*
Given this assumption, the resistance to earth can be calculated with following formula [6, 7]:

Illustration of the relative potential distribution *V** versus distance *x* from the horizontal electrode (a), for different buried depths *t*;
b) explanation of the earth electrode dimensions, where the length *l* = 10 m;

c) R_E versus t for three electrode diameters d; V_{T1}*, V_{T3}* - exemplary relative values of touch voltages for t = 0.6 m and t = 1.4 m respectively; all calculations were made for an uniform soil with resistivity ρ = 100 Ωm.

b) Vertical earth electrodes

A high surface potential distribution during fault conditions is a disadvantage for this method of earthing system. Surface potential distribution can be calculated with the following formula for a given earth current I_E :

$$V_x = \frac{\rho I_E}{4\pi l} \ln \frac{\sqrt{x^2 + l^2} + l}{\sqrt{x^2 + l^2} - l} \qquad (18)$$

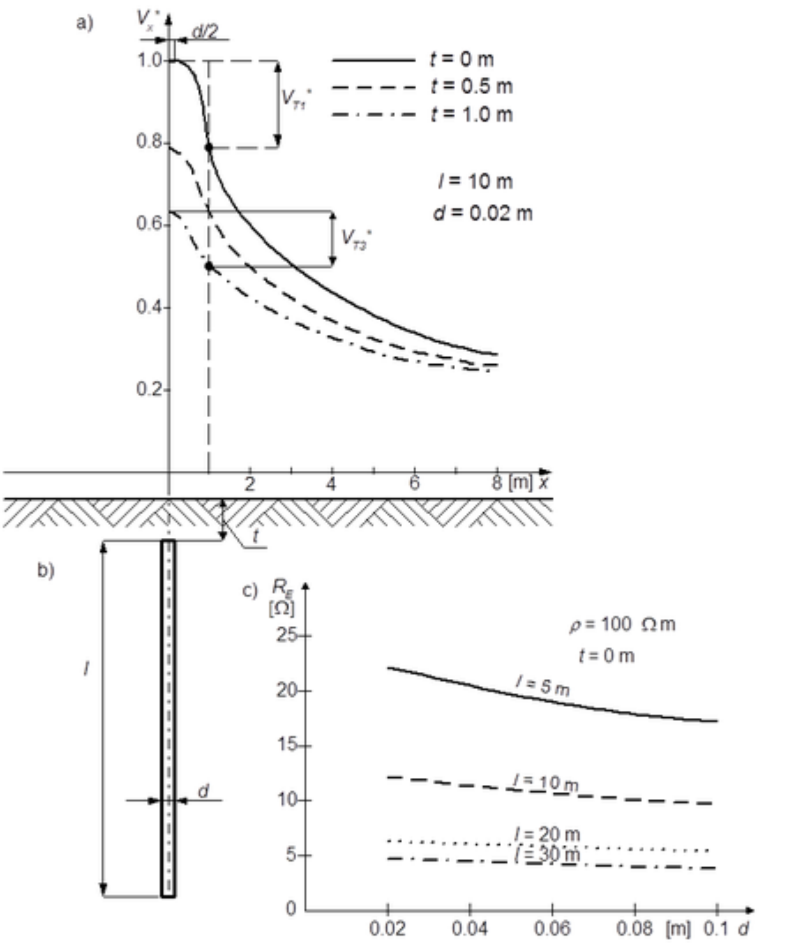


Figure 10. Illustration of the relative potential distribution V* versus distance x from the rod electrode (a), for different buried depths t; b) explanation of the earth electrode

Figure 10. Illustration of the relative potential distribution V^* versus distance x from the rod electrode (a), for different buried depths t; b) explanation of the earth electrode dimensions; c) R_E versus electrode diameter d for different electrode length l ; V_{T1} *, V_{T3} * - exemplary relative values of touch voltages for t = 0 m and t = 1 m respectively; in parts a) and c) of the Figure are given respective values of parameters l, d, ρ and t for which the curves were calculated.

An example of the relative surface potential distribution $V_x^* = f(x)$ (18), for certain electrode dimensions is presented in Figure 10. Comparison of characteristics in Figures 9 and 10 shows that the potential gradients on the earth surface are considerably higher for a rod electrode and the

touch voltages (*VT1*, VT3**, Figure 9 and 10) are unfavourable in comparison with horizontal electrodes.
The unfavourable potential distribution of the rod electrodes can be improved by changing the burial depth (*t* , Figure 10 b) of the electrode. In practice there are used two solutions:

- the top of the electrode is buried in a given deepness under the ground surface, like it is illustrated in Figure 10 b, or
- the upper part of the rod is insulated from the soil.

Both solutions result in smaller gradients of the potential to earth, especially in the direct vicinity of the electrode. It is illustrated in Figure 10 a, where the curves $V^* = f(x)$ for three different buried depths *t* are shown.
In curves shown in Figure 10 there was assumed the uniform soil structure with resistivity ρ = 100 W m.
The earth resistance of simple earth electrodes are presented if form of diagram like in Figure 11 for rod electrode. The resistance of a simple rod can be calculated using a simplified equation:

$$R = \frac{\rho}{2\pi l} \ln \frac{4l}{d} \qquad (19)$$

The important factor, which can change the resistance to earth, is the resistivity of the soil. In curves shown in Figure 10 there was assumed the uniform soil structure with resistivity ρ = 100 W m. Figure 11 illustrates changes of the earth resistance versus electrode length *l* , for different values of the soil resistivity ρ. Such diagrams are used in the literature for the prompt estimation of the resistance to earth [2, 6].

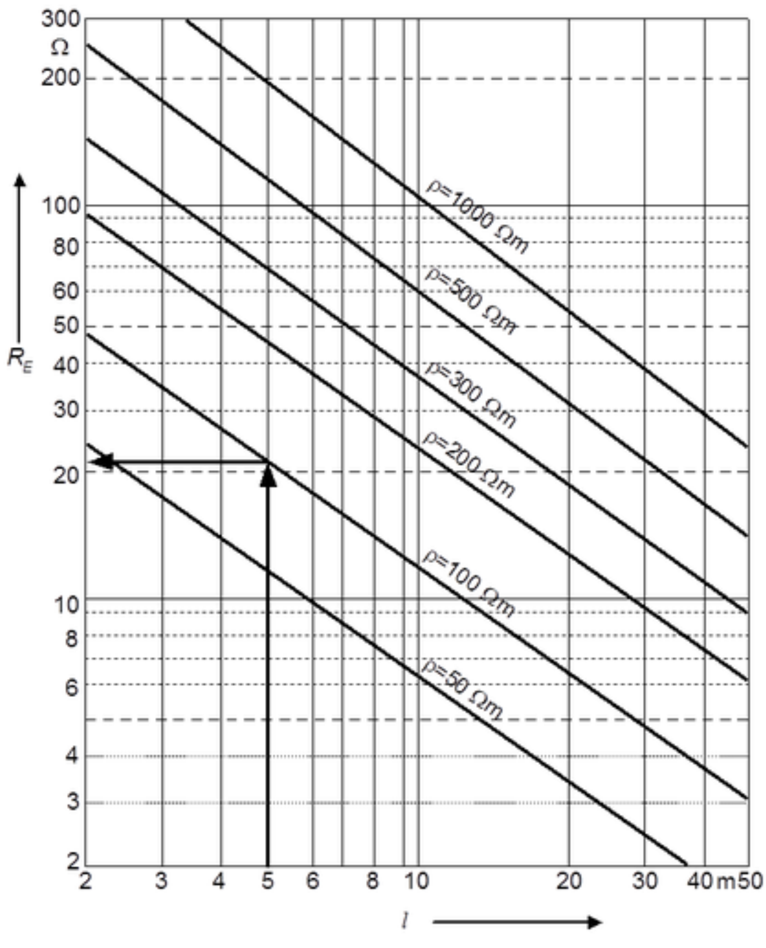


Figure 11 - Earth resistance of a rod electrode with the length *l* and diameter 0,02 m, in a homogenous ground with resistivity *r* [6]. Arrows presented manner of reading resistance R_E for a given length *l*

c) Foundation earth electrodes

The foundation earth resistance can be calculate using the following simplified equation:

$$R_E = 0{,}2\frac{\rho}{\sqrt[3]{V}} \qquad (20)$$

where: R is in Ω, V is volume of the foundation in m^3.

The terminal of the foundation earth electrode should have a minimum length of 150 cm above the floor level (Figures 12 and 13). It should be placed as close as possible to the main earthing terminal of the building installation. The terminals of the foundation earth electrode, which are connected to the lightning protective installation, should be placed outside the building.

d) Using armored cable as earth

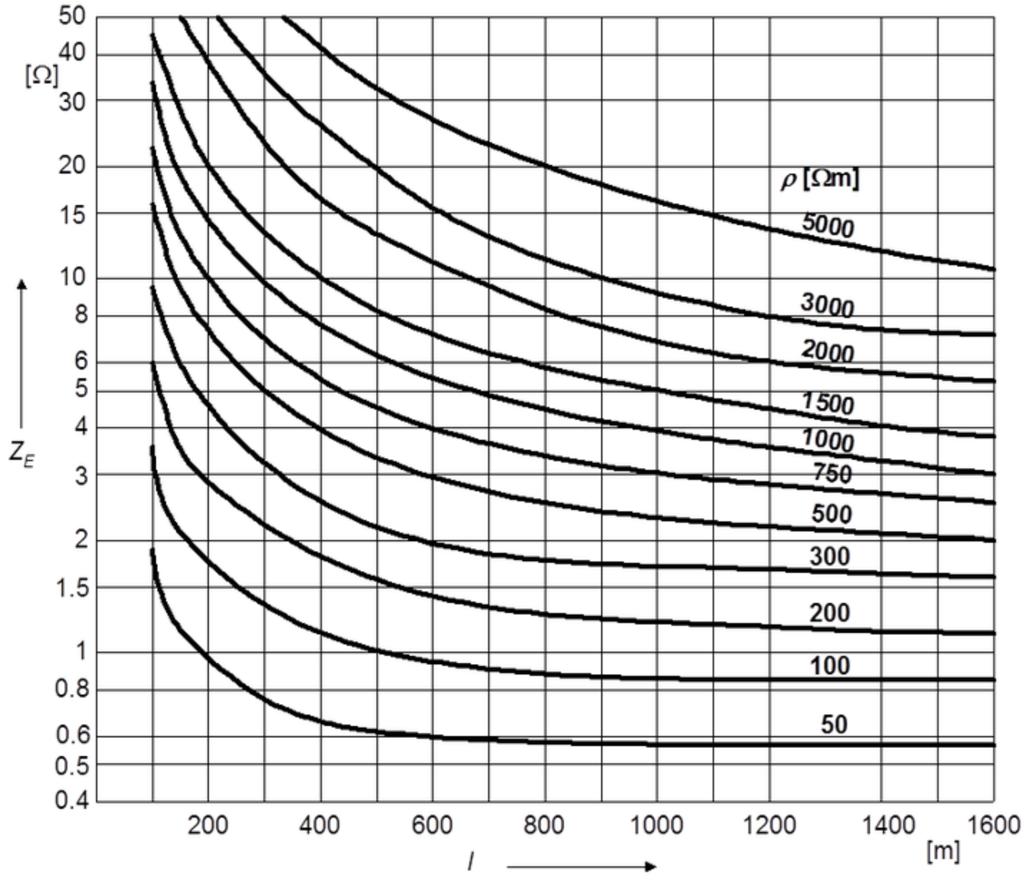


Figure 14. - Impedance to earth of cables with earthing effect versus cable length, for different resistivity of soil [2].

e) Meshed electrodes

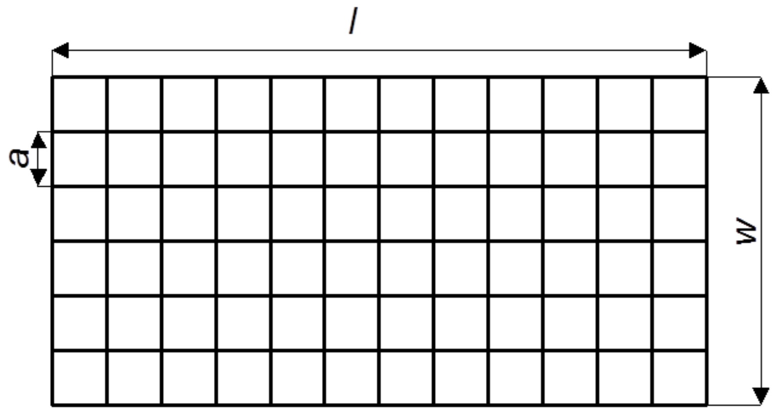


Figure 15. The typical diagram of the meshed earth electrode.

The general formula for calculation of the resistance to earth of the meshed electrode from Figure 15, is as follow [2]:

$$R_E = \frac{\rho}{4r_e}k_m = \frac{\rho}{4\sqrt{\frac{lw}{\pi}}}k_m \qquad (21)$$

where: r_e is the equivalent radius of a ring, with the same area like the meshed electrodes (Figure 16),

k_m – is the factor dependent on the single mesh dimensions:

$$k_m = 1.3 \text{ for } a \leq 0.1l \text{ and } k_m = 1.2 \text{ for } a \leq 0.05l$$

For meshed electrodes, in which the meshes are not squares, or if electrodes are composed from few rectangles (Figure 16) one can use the following simplified equation [5]:

$$R_E = \frac{\rho}{4r_e} + \frac{\rho}{l_\Sigma} \qquad (22)$$

where:
re - is the equivalent radius of a ring, with the same area like the meshed electrodes (Figure 13),
l_Σ - sum all sides of electrode,

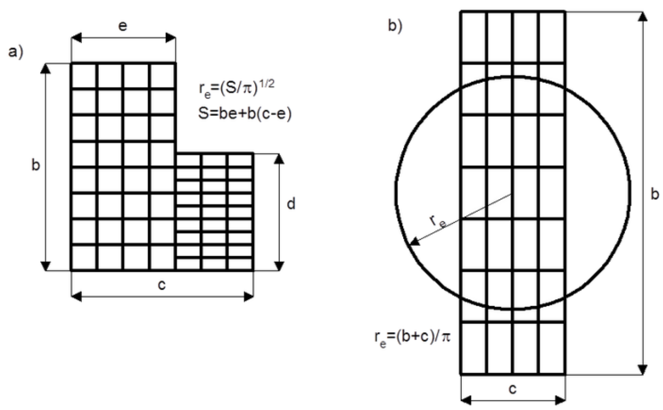


Figure 16. Examples of meshed earth electrodes with not regular forms, explaining manner of calculation of the equivalent radius re in equation (10.28), for two forms of the earth electrode: nearly similar to a square (a) and of a long rectangle, but with not square meshes (b).

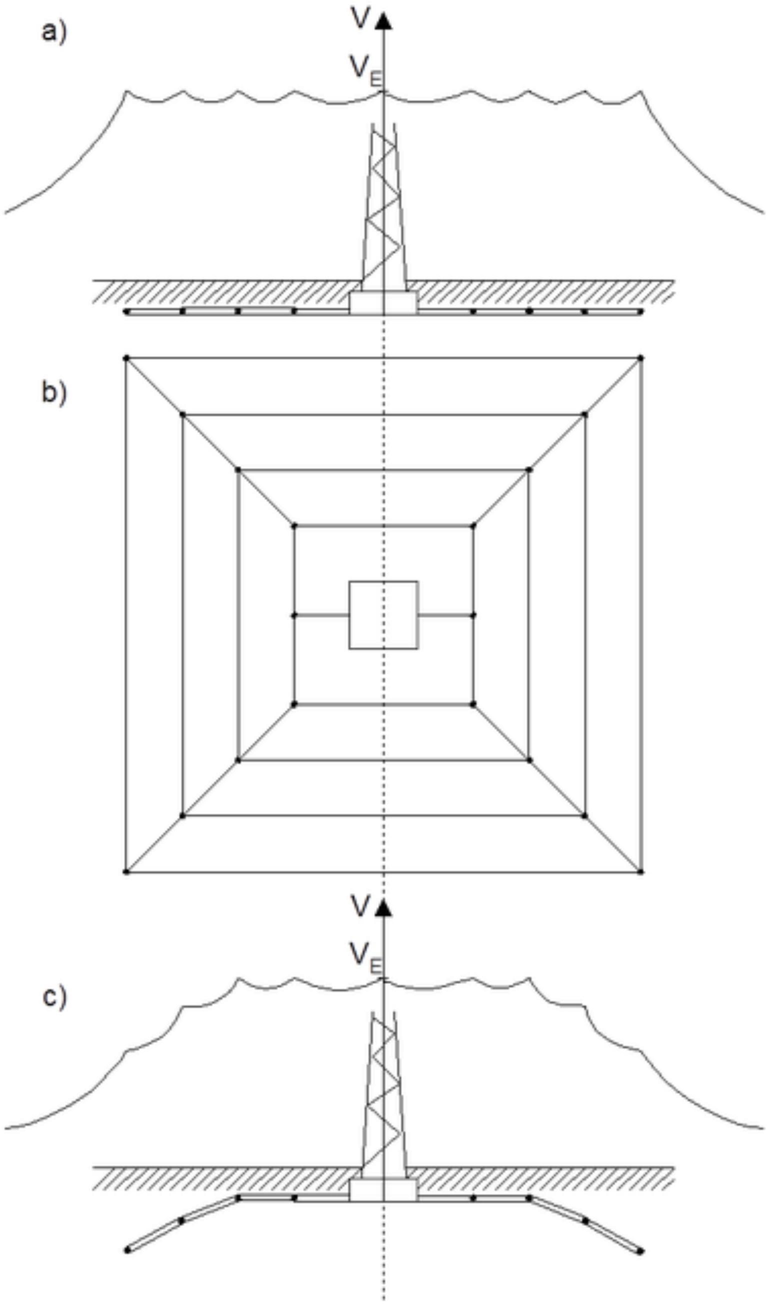


Figure 17. Illustration of the phenomenon of potential carryover and the earth surface potential distribution for two meshed earth electrodes; a) meshed plane electrode with almost full potential outside of the last envelope, b) plan of electrode; c) electrode with two last elements placed deeper.

8) Power quality & surges

This section covers how the earthing system could protect the electrical network against certain effects such as surges, spikes, static and power quality.

a) Lightning

The characteristics of earthing systems have been discussed assuming moderate current flow under steady-state conditions at the network frequency. In areas with lightning, the earthing arrangement will have to be able to withstand lightning currents or fault currents conducted by the distribution network or utility. During a lightning strike; pulsed, or high frequency currents flowing through the earth electrode could be expected. Lightning currents differ from the currents at network frequency, and may differ from short-circuit currents in the following way:

- Very high current values; the mean value of peak current is estimated to be about 30 kA, and could reach values as high as 200 kA
- Very fast current rise times with values estimated to be in the region of 20 kA/μs to 200 kA/μs.
- Very high Voltage values

Lightning current causes two subsequent effects in the earth electrode and in the soil, schematically illustrated in Figure 18.

The first phenomenon is that extremely high current density in soil increases the electric field strength to values which could cause electrical discharges in small gaseous voids (lower picture in Figure 18). This phenomenon occurs mainly near the earth electrode, where the current density is highest, and the influence is most significant. The intensity of it is especially high when the soil is dry or of high resistivity. This phenomenon causes decreased levels of soil resistivity and consequently the earthing resistance.

The second phenomenon caused with the effect of lightning current is damping of the current wave due to reactance of the metallic earth electrode parts (upper picture in Figure 18). The inductance of earth electrode components can be estimated as equal 1 μH/m. It is usually neglected when considering earth impedance at the network frequency (RL in Figure 5). However, inductance becomes an important parameter when the current increase rate is high, in the range of hundred of kA/μs or more. During lightning strikes the inductive voltage drop ($L \times di / dt$) reaches very high values. As a result, remote parts of the earth electrode play a reduced role in conducting current to earth, while the main part of the lightning current is conducted through the parts placed in vicinity of the earthing conductor.

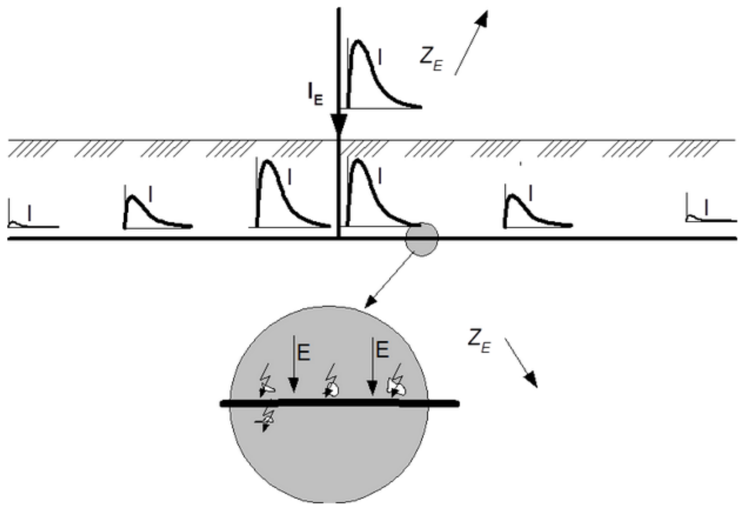


Figure 18. Schematic diagram illustrating two different effects of earthing current flow in the earth electrode and the soil; Z_E with arrow directed down or up, indicates growing or diminishing of the impedance to earth.

During a lightning strike both the phenomena described above have an effect, but operate in opposite directions. The first one diminishes the earth resistance, while the second one increases the impedance to earth. For those reasons, it is difficult to say if the effective impedance to earth during lightning will increase or decrease. Usually, in practical considerations, the second factor is treated as dominant, and it is assumed, that earth impedance for pulse currents increases in comparison with its impedance for static conditions.

Increasing the length of earth electrodes over the, so-called, critical length (Figure 13) does not cause any reduction of the earth impedance to transients. One of solutions in designing of meshed electrodes, considering lightning currents, is the much dense grid of meshes in vicinity of terminal, where the earthing conductor is connected to the earth electrode.
An advantage in the use of meshed electrodes when considering lightning current, is the much dense grid of meshes in vicinity of terminal, where the earthing conductor is connected to the earth electrode.

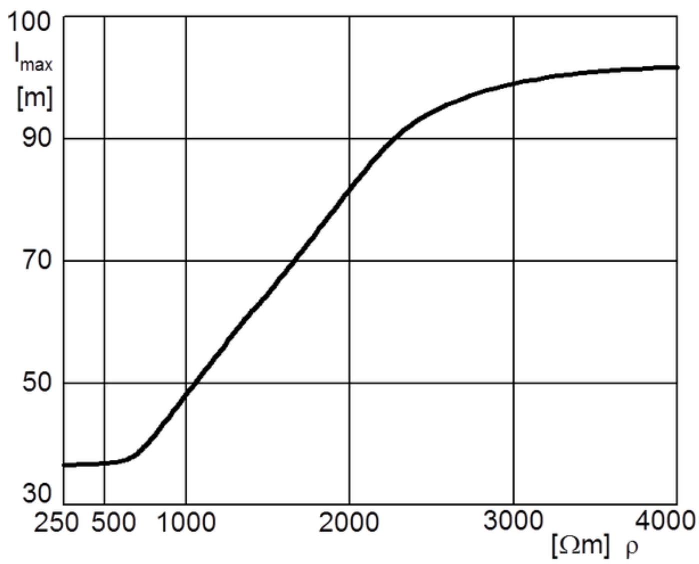


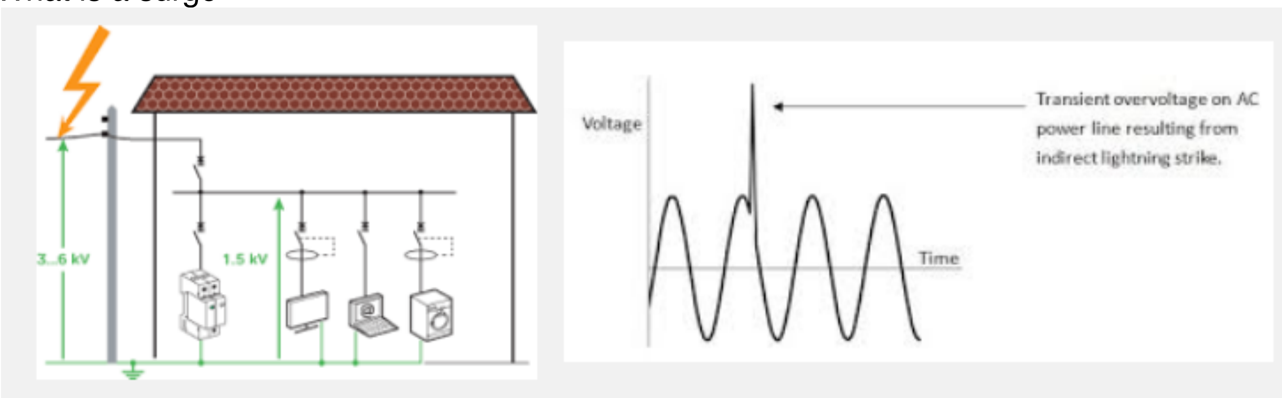
Figure 19. Maximal length l_{max} of earth electrodes in lightning earthing electrodes in dependence on the earth resistivity r.

b) Switching Equipment

(1) Ground leads should be adequately sized
    (a) Temperature capability of conductors should be checked
(2) Conductor I2t rating should match the circuit protective devices
    (a) t is determined by the fuse/cb or switching equipment and the speed at which the equipment will be able to handle the fault current.
    (b) If we have a 10kA fault current over 1 second then $I^2t = 10^2t$
    (c) The relay or fuse should be able to withstand the fault current and break the fault faster than the fault will last.
(3) Other wise the system equipment could become a fire or explosion hazard

c) Surges

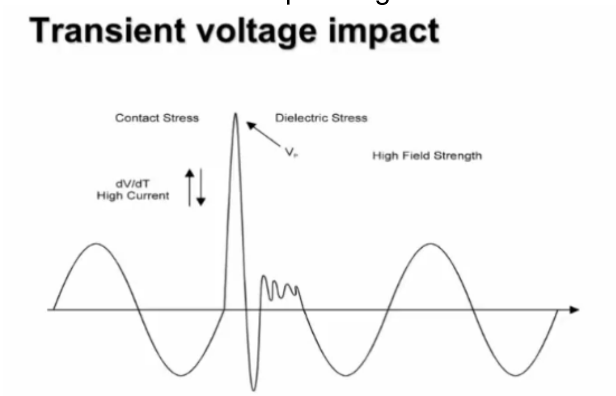
What is a surge



Types of surges

- Lightning, fault currents, Induced Voltages
- Surge protection earthing / grounding
- Electro Magnetic Interference

Transient vs lightning vs spike
Could be caused by network conditions (i.e. switching on and off of large loads during maintenance conditions or normal operating conditions.



d) Static Electricity
Why is static electricity produced and how does it affect an earthing or electrical system.

Everyday occurrence of static
When energy is applied to a substance the result could be the separation of electrons from parent atoms. When two bodies of dissimilar materials are in close contact with one another the electrons may migrate from the one body to the other. If one or both of the substances have properties associated with insulating materials, electrons get trapped on the surface of the material to which they have migrated. The surfaces of both materials now exhibit electrical charge.

If two people were standing next to one another both of whom are charged with static electricity the separation distance between the two bodies would prevent them from discharging static to each other; in this case the air is acting as an insulating material.
The higher the static charge, the bigger the distance that electricity would be able to bridge the gap between the two bodies.

In an electrical network, static charges could compromise the safety of the installation, as the static charge would now add another level of voltage over and above the normal operating voltage of the system by reducing the fault clearance distances
Bonding and earthing interventions will reduce the voltages by creating a path to earth that will allow the electrical network to operate safely and efficiently.

In motors we also see the pitting of bearings due to static charges and or floating voltages on motor systems.

Static charge build-up depends on the following factors:
- Type of materials involved
- Size of contact area
- Rate of separation
- Motion between substances
- Atmospheric conditions

Voltage buildup for different applications:
- Belted drives 60kV – 100kV
- Fabric handling 15kV – 50kV
- Paper Machines 5kW – 100kV
- Tanker trucks <25kV
- Belt conveyors <45kV

Energy of a spark (see formulas)

e) Controlling static discharge
By connecting charged surfaces together and then to ground with a conductive medium in order to provide a leakage path in an effort to control the accumulation of static electricity is also referred to as bonding.

9) Maintenance of an earthing system.

General maintenance recommendations

- Periodical ground electrode resistance testing is recommended.
- Do a comparison and analysis of readings
- Check connections
- Check integrity
- Check moisture content/soil acidity where required.

10) Standards for typical elements of an earthing system

This section covers the various elements of an earthing system as well as the local standards available covering requirements related to each part of an earthing system in detail.
These standards are available to purchase from the SABS.

- Earth leakage circuit breakers VC8035
- Earth leakage circuit breakers SANS60947-2 + SANS556-1:2012 7.2.7
- Earth leakage switches VC 8035
- Earth Leakage switches SANS556-2-2 + SANS556-1:2012 7.2.7
- Earth electrodes SANS 10199
- Earth Rods – SANS1063 Performance standard
- Earth Wire Safety standard SANS1411-1
- Earth Installations guidelines SANS10142-1

a) Earthing SANS 10142-1 (Guidelines)

Please see the SABS website for standards that have been updated or amended.

- Section 4.2.6.1 The electrical installation shall be earthed in accordance with SANS 10142-1 and SANS 10142-3 (as applicable). The earthing requirements for different embedded generation configurations in conjunction with the customer network are described in annex B for the most common earthing systems.NOTE SANS 10142-1 applies to EG feeding a UPS and no connection to the utility supply (see table B5).

- Section 4.2.6.2 Installations with utility-interconnected inverters without simple separation shall make use of earth leakage protection which are able to respond to d.c. fault currents including smooth d.c. fault currents (i.e. without zero crossings) according to IEC 62109-2 unless the inverter can exclude the occurrence of d.c. earth fault currents on any phase, neutral or earth connection through its circuit design[4]. This function may be internal or external to the inverter. NOTE IEC 62109-2, Edition 2011, section 4.8.3.5 gives selection criteria for RCD sensitivities.

- Section 4.2.6.3 Where an electrical installation includes a PV power supply system without at least simple separation between the AC side and the DC side, an integrated RCD function shall be present to provide fault protection by automatic disconnection of supply shall be type B according to

- IEC/TR 60755 amendment 2. Where the PV inverter by construction is not able to feed DC fault currents into the electrical installation, an RCD of type B according to IEC/TR 60755 amendment 2 is not required. NOTE 1 Consideration must also be given to ensure that any d.c. currents do not impair the effectiveness of any other RCD'S installed throughout the a.c. system. NOTE 2 The earth leakage unit may also fulfil the requirement of the all-pole disconnection device as stated in 4.2.6. NOTE 3 The function of this RCD is not to provide

[4]) The appropriate earth leakage unit should be selected to accommodate the higher leakage current of inverters without transformers to avoid nuisance tripping.

protection against circulating d.c. current in the inverter and a.c. supply, i.e. does not override 4.1.8.

Earthing systems

NOTE Please see the latest versions of the SANS 10142-1, which may be obtained directly from the SABS.

Section B.1 Application of SANS 10142-1

- Section B.1.1 General SANS 10142-1 applies to low-voltage wiring, earthing, bonding and safety. The requirements in B.1.2 to B.1.5 relating to earthing and to neutral and earth path connections apply.

- Section B.1.2 Neutral conductor The neutral conductor shall not be connected direct to earth or to the earth continuity conductor on the load side of the point of control (see 6.1.6 in SANS 10142-1:2012).

- Section B.1.3 Customer's earth terminal Each installation shall have a consumer's earth terminal (see 3.18 of SANS 10142-1:2012) at or near the point where the supply cables enter the building or structure. All conductive parts that are to be earthed (see 6.12.3 in SANS 10142-1:2012) shall be connected to the main earthing terminal (see 3.29.4 in SANS 10142-1:2012), which shall be connected to the consumer's earth terminal. The consumer's earth terminal shall be earthed by connecting it to the supply earth terminal (see 3.78 in SANS 10142-1:2012) or the protective conductor (see 3.15.8 in SANS 10142-1:2012) and, if installed, the earth electrode. The effectiveness of the supply protective conductor shall be determined in accordance with 8.7.5 in SANS 10142-1:2012 (see 6.11.1 as amended by amendment No. 6 in SANS 10142-1:2012).

- Section B.1.4 Earthing of combined sources When an installation that has a common neutral is supplied from a combination of transformers and generators located near one another, the neutral terminal of these shall be connected to a single neutral bar. This neutral bar shall be the only point at which the neutral of the installation is earthed except in the case in 7.12.3.1.3 in SANS 10142-1:2012 (see 6.12.4 as amended by amendment No. 6 in SANS 10142-1:2012).

- Section B.1.5 Neutral bar earthing B.1.5.1 Protection in accordance with the requirements in 6.7 in SANS 10142-1:2012 shall be provided for the electrical installation in such a manner as to ensure correct operation of the protection devices, irrespective of the supply or combination of sources of supply. Operation of the protection devices shall not rely upon the connection to the earthing point of the main supply.

- Section B.1.5.2 Where there is no existing earth electrode in the electrical installation, a suitable earth electrode may be installed in accordance with SANS 10199. When installed, the electrode shall be bonded to the consumer's earth terminal and to the earthing point of the generating set with a conductor of at least half the cross-section of that of the phase conductor, but not less than 6 mm copper, or equivalent. This also applies to a single-phase supply. NOTE 1 In the case of the TN system of electricity supply, an earth electrode is normally not required in an electrical installation (see 7.12.3.1.1 as amended by amendment No. 6 in SANS 10142-1:2012). NOTE 2 IEC 60364-1 distinguishes three families of earthing arrangement, using the two-letter codes TN, TT, and IT. The first letter indicates the connection between earth and the power-supply equipment (generator or transformer). The second letter indicates the connection between earth and the electrical device being supplied. In the case of TN systems, T indicates a direct connection of a point with earth (Latin: terra) and N indicates direct connection to neutral at the origin of the installation, which is connected to the earth.

- Section B.1.5.3 When an installation is supplied from a combination of transformers and generators located near one another, including alternative supplies, the neutral terminal of these shall be connected to a single earthed neutral bar. This neutral bar shall be the only point at which the neutral of the installation is earthed. Any earth leakage unit shall be positioned to avoid incorrect operation due to the existence of the parallel neutral or earth path (see 7.12.3.1.2 as amended by amendment No. 6 in SANS 10142-1:2012).

- Section B.1.5.4 Where alternative supplies are installed remotely from the installation and it is not possible to make use of a single neutral bar, which is earthed, the neutral of each unit shall be earthed at the unit and these points shall be bonded to the consumer's earth terminal (see 6.12.4 of SANS 10142-1:2012). The supply that supplies the installation or part of the installation shall be switched by means of a switch that breaks all live conductors operating substantially together (see annex S of SANS 10142-1:2012), to disconnect the earthed neutral point from the installation neutral when the alternative supply is not connected (see also 6.1.6 of SANS 10142-1:2012 and 7.12.3.1.3 (as amended by amendment No. 6 in SANS 10142-1:2012)).

- Section B.1.5.5 Where only part of an installation is switched to the alternative supply in the same distribution board, the neutral bar shall be split (see figure S.2 in annex S of SANS 10142-1:2012) and 7.12.3.1.3 (as amended by amendment No. 6 in SANS 10142-1: 2009).

b) Embedded generator and UPS configurations

- Section B.2.1 Various configurations of embedded generator and UPS systems were examined, and cross-referenced with the main electrical supply earthing configurations (i.e. TN-S, TN-C-S). Permutations can be found in Table B1 of the SANS 10142-1. NOTE The TT configuration is generally not used in South Africa, but could sometimes be found in certain rural electrification network spurs.

11) Additional Formulas

Static electricity calculations
(ref idc online – static)

Voltage buildup due to static

Voltage build-up due to static charge

- The voltage of a charged body can be calculated using the formula

  V = Q/C

  where
  - V is the voltage (in Volts)
  - Q is the charge (in Coulombs)
  - C is the capacitance of the body (in Farads) with reference to the surface of measurement

Spark energy formula

$$E = 0.5 * \left(C \cdot V^2 \cdot 10^{-9}\right)$$

Where
- C is the capacitance of the body, which stores the charge (in pF)
- V is the voltage (in Volts)
- E is the energy (in milli Joules)

Typical capacitance values

• Human body	100 to 400 pF
• Tank truck	1000 pF
• Tank with rubber lining	100000 pF

Soil resistance

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

Where

R = Soil resistance (in Ohms)
A = Area of the sample (in m^2)
L = Length of the sample (in meters)
ρ = Soil resistivity (in Ohm-meters)

Measurement of soil resistivity

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

Where

- R = Resistance measured in Ohms by the tester
- S = Distance between the pins in meters as shown in figure
- ρ = Soil resistivity in Ohm meters

Resistance of single rod electrode

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

where

R = Resistance of the electrode (in Ohms)
ρ = Soil resistivity (in Ohm meters)
L = Length of the buried part of the electrode (in meters)
D = Outer diameter of the rod (in meters)

Standard electrode: simplified formula

$$R = \frac{\rho}{3.35}$$

The electrode resistance of a standard electrode of 5/8 inch (15mm) diameter (D = 15) which is driven 10 ft (3m) into the ground (L = 3)

where

R = Resistance of the electrode (in Ohms)
ρ = Soil resistivity (in Ohm meters)

Current carrying capacity of an earth spike.

Current carrying capacity

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

where

- I = Maximum permissible current (in amperes)
- d = Outer diameter of rod (in meters)
- L = Length of the buried part of the electrode (in meters)
- ρ = Soil resistivity (in Ohm meters)
- t = Time period of the fault current flowing (in seconds)

Resistance of multiple ground rods

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

- R_N = Combined ground electrode system resistance
- N = Number of electrodes
- R = Earth resistance of a single electrode
- F = The factor shown here

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

12) References

f) Iron's relationship to electrolyte under varying pH conditions.
   i) http://www.corrosion-doctors.org/Corrosion-Thermodynamics/Potential-pH-diagram-iron.htm
g) Copper/Copper sulphate reference electrode
   i) http://www.corrosion-doctors.org/Corrosion-Thermodynamics/Reference-Half-Cells-Copper.htm
h) Anodes for use in Earthing applications
   i) http://www.pipecorr.com.au/files/D94112052.pdf
i) Leonardo energy : Earthing and bonding: Angelo Baggini
j) Additional methods for resistivity testing – International Electrical Testing Association
   i) http://www.netaworld.org/sites/default/files/public/neta-journals/ResistTest-102-105.f.pdf
k) High Frequency earth impedance testing
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13) Tests

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