Power Quality Application Guide

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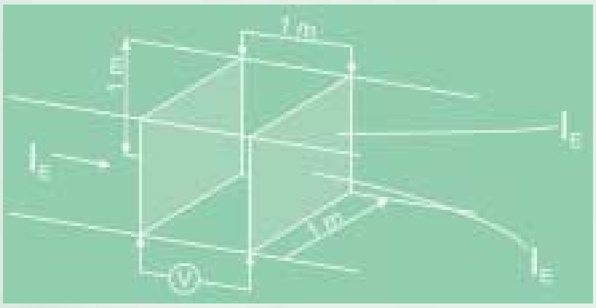
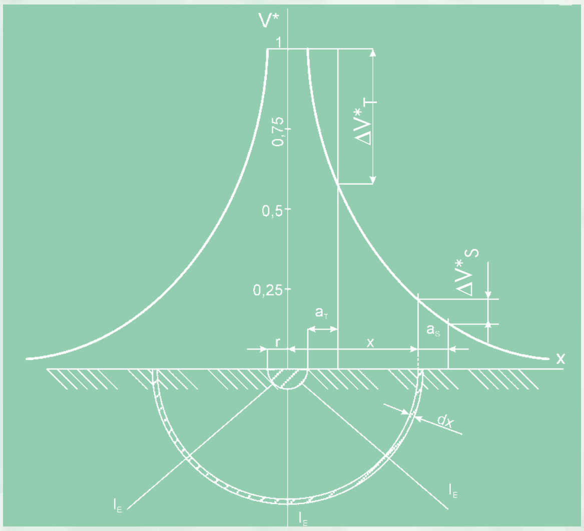
Earthing Systems - Fundamentals of Calculation and Design

6.3.1





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Earthing Systems - Fundamentals of Calculation and Design

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Earthing Systems – Fundamentals of Calculation and Design

Introduction

Section 6.1 of this Guide gives an overview of the requirements of the earthing system and discusses the need for a systematic approach to its design, concentrating on building installation aspects. This application note deals with the design of the ground electrode system while Section 6.5.1 gives practical guidance on the design and calculation of ground electrodes.

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:

- protection of buildings and installations against lightning
- safety of human and animal life by limiting touch and step voltages to safe values
- electromagnetic compatibility (EMC) i.e. limitation of electromagnetic disturbances
- 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.

Basic definitions [1,2]

Earthing or earthing system is the total of all means and measures by which part of an electrical circuit, accessible conductive parts of electrical equipment (exposed conductive parts) or conductive parts in the vicinity of an electrical installation (extraneous conductive parts) are connected to earth.

Earth electrode is a metal conductor, or a system of interconnected metal conductors, or other metal parts acting in the same manner, embedded in the ground and electrically connected to it, or embedded in the concrete, which is in contact with the earth over a large area (e.g. foundation of a building).

Earthing conductor is a conductor which connects a part of an electrical installation, exposed conductive parts or extraneous conductive parts to an earth electrode or which interconnects earth electrodes. The earthing conductor is laid above the soil or, if it is buried in the soil, is insulated from it.

Reference earth is that part of the ground, particularly on the earth surface, located outside the sphere of influence of the considered earth electrode, i.e. between two random points at which there is no perceptible voltages resulting from the earthing current flow through this electrode. The potential of reference earth is always assumed to be zero.

Earthing voltage (earthing potential) V_E is the voltage occurring between the earthing system and reference earth at a given value of the earth current flowing through this earthing system.

Earth resistivity ρ **(specific earth resistance)** is the resistance, measured between two opposite faces, of a one-metre cube of earth (Figure 1). The earth resistivity is expressed in Ωm.

Earth surface potential V_x is the voltage between a point x on the earth's surface and reference earth.

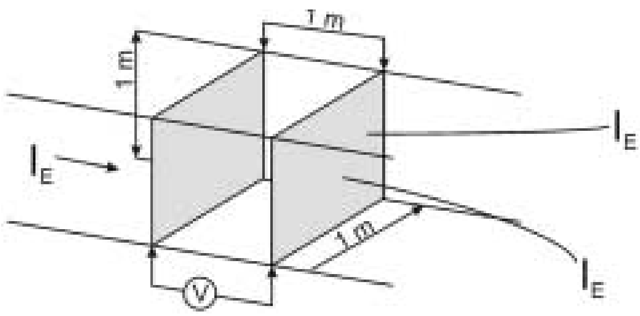

Figure 1 - Diagram illustrating the physical sense of earth resistivity ρ

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:

- the ground does not have a homogenous structure, but is formed of layers of different materials
- 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.

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

Table 1 - Ground resistivity ρ for various kinds of the soil and concrete [2, 3].

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.

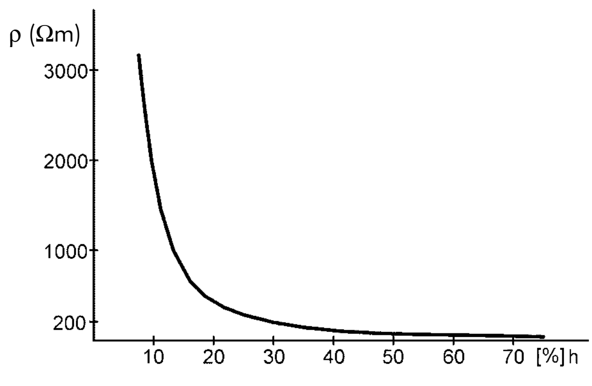

Figure 2 - Earth resistivity ρ of clay as function of soil humidity h

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. The amplitude in February is approximately 30% larger than average, while in August it is about 30% smaller than the average [4].

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.

Electrical properties of the earthing system

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. These questions are discussed briefly below.

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.

Any earth connection made available by the supplier appears in parallel with the locally provided earth and may well be expected to have a lower impedance at fundamental and harmonic frequencies. However, the availability and characteristics of this path are beyond the designer's control and hence should not be considered in the design of the earthing system which should be adequate for the required purpose in its own right.

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 relationship between the earth voltage, earth potential distribution and the earth current. For extended and meshed earth electrodes, approximations of earth resistance are used.

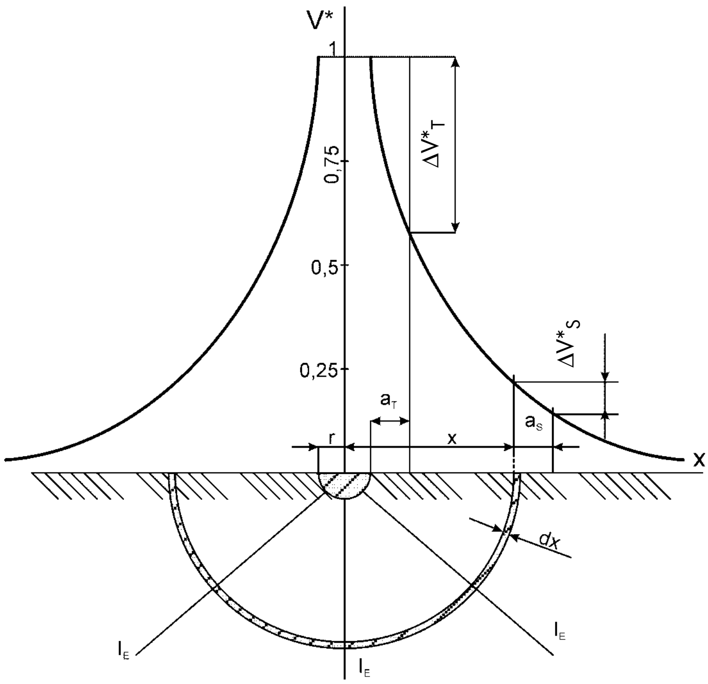

Figure 3 - Illustration of a notional hemispherical earth electrode, showing parameters required to calculate the earthing resistance and potential distribution on the ground surface (with ρ = const)

r	Electrode radius
x	Destination from the centre of the electrode
a_T, a_S	Touch and step distances respectively
V^*	Relative value of the potential distribution
ΔV^*_T, ΔV^*_S	Touch and step voltages respectively

A basic model of the earth electrode configuration, used for illustrating the fundamental electrical properties, is a hemisphere embedded in the ground surface (Figure 3). The earth current flowing to such an electrode is assumed to flow radially to the earth. The surface of the hemisphere, as well as all hemispherical cross-sections d_x of the ground, are assumed to be equipotential, and the current lines are therefore perpendicular to these surfaces. Under these conditions the resistance of the hemispherical element of thickness d_x and the radius x is expressed as follows (with ρ assumed constant):

$$dR = \frac{\rho}{2\pi \cdot x^2} dx \qquad (2)$$

The resistance of the hemisphere-earth electrode is given by:

$$R = \frac{\rho}{2\pi} \int_r^\infty \frac{dx}{x^2} = \frac{\rho}{2\pi r} \qquad (3)$$

The earth resistance depends significantly on how deep the electrode is sunk in the ground. This is because the moisture content is higher and more stable for deeper ground layers than for shallow layers. Layers near the surface are influenced more by seasonal and short-term weather variations and are subject to freezing. This problem is illustrated in Figure 4, for a rod earth electrode, where one can see the considerable reduction of earthing resistance as the depth of a rod electrode increases. However, it is not always possible to place electrodes at the preferred depth for geological reasons, for example, where there are rocks or obstructions close to the surface or where the electrode system covers a large area.

One can distinguish several types of earth electrodes including:

- *simple surface earth electrodes* in the form of horizontally placed strip or wire, either as a single ended strip or a ring
- *meshed electrodes*, constructed as a grid placed horizontally at shallow depth
- *cable with exposed metal sheath* or armour which behaves similarly to a strip-type earth electrode
- *foundation earth electrodes* formed from conductive structural parts embedded in concrete foundation providing a large area contact with the earth.
- *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.

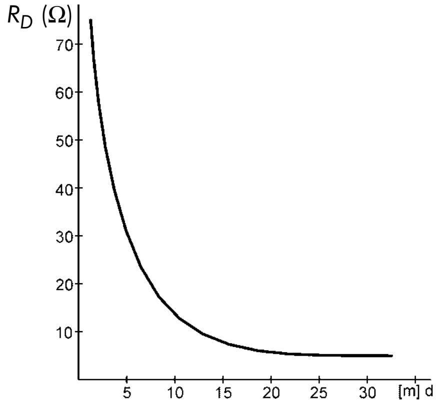

Figure 4 - Example of dissipation resistance of a progressively longer rod earth electrode R_D as a function of the depth d

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. Surface potential distribution is the subject of the next section.

More detailed descriptions and basic equations concerning earth resistance of typical earth electrodes mentioned are given in Section 6.5.1.

Earthing voltage and earth surface potential distribution

Earthing voltage, as well as distribution of the earth surface potential during the current flow in the earthing system, are important parameters for protection against electric shock. The basic relations will be shown on the earth model presented in Figure 3.

The potential of any point located at distance x from the middle of earth electrode, in which earth current I_E flows, can be formulated with the following equation:

$$V_x = \frac{\rho I_E}{2\pi x} \qquad (4)$$

and its relative value:

$$V_x^* = \frac{V_x}{V_E} \qquad (4a)$$

where V_E is the earthing voltage, which is equal to the earthing potential (assuming that the potential of the reference earth is equal zero). The earthing potential can be described as follows:

$$V_E = I_E R_E = \frac{\rho I_E}{2\pi r} \qquad (5)$$

The potential difference between two points on the earth surface: one at distance x and other at distance $x+ a_S$, where a_S is assumed to be equal to 1 metre, illustrates the step potential ΔV_S, i.e. earth surface potential existing between two feet, when a person stands at that position on the earth surface:

$$V_S = \frac{\rho I_E}{2\pi}\left(\frac{1}{x} - \frac{1}{x + a_S}\right) \qquad (6)$$

and its relative value: $$V_S^* = \frac{V_S}{V_E} \qquad (6a)$$

where x ≥ r.

A similar relationship can be described for any other distances x and a. Particularly for $x = r$ and $a = a_T$ = 1m the formula (6) enables the calculation of the touch voltage, i.e. the voltage between a palm and a foot of a person who is just touching the earth electrode or metal parts connected to it:

$$V_T = \frac{\rho I_E}{2\pi}\left(\frac{1}{r} - \frac{1}{r + a_T}\right) \qquad (7)$$

and its relative value: $$V_T^* = \frac{V_T}{V_E} \qquad (7a)$$

A practical illustration of touch and step voltages is shown in Figure 5. Persons A and B are subject to the touch potential while person C is subject to the step potential. The touch voltage V_T is sometimes differentiated from the shocking touch voltage V_{TS} , (and step voltage V_S from the shocking step voltage V_{SS}.) Voltages V_T and V_S are the pure values resulting from the potential distribution, whereas V_{TS} and V_{SS} consider the small changes in potential distribution caused by flowing of shocking current – i.e. including the distorting effect of the current flow through the person. In practice the difference between V_S and V_{SS} or V_T and V_{TS} is usually small, so that the same values for the respective potentials are assumed: $V_S \approx V_{SS}$ and $V_T \approx V_{TS}$.

The left-hand side of 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 (as is common practice in Belgium and Germany, for example) 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 –

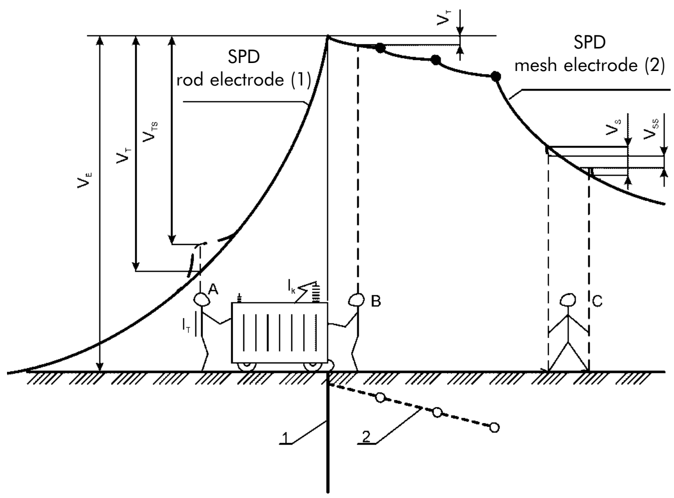

Figure 5 - Comparison of earth surface potential distribution (SPD) during the current flow in the earthing system, for two earth electrode constructions

1	Rod electrode
2	Meshed electrode
V_E	Earthing voltage
V_T, V_{TS}	Touch voltage and shocking touch voltage respectively
V_S, V_{SS}	Step voltage and shocking step voltage respectively
I_T	Shocking touch current
I_K	Short circuit current equal the current flowing to the earthing system
A, B, C	Persons at various earth surface potentials

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 6c).

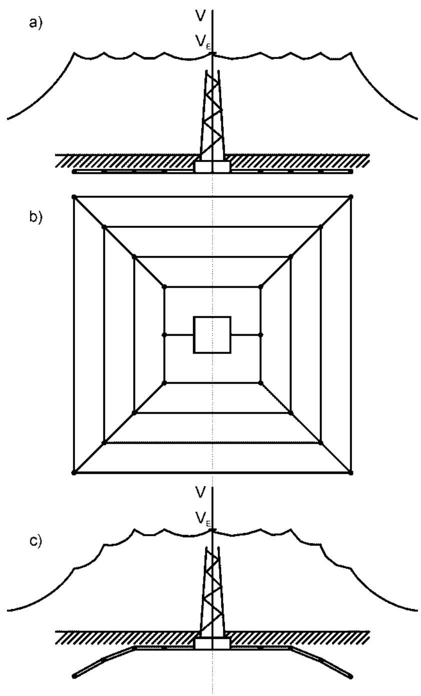

Figure 6 - The phenomenon of potential carryover. Earth surface potential distribution for two meshed earth electrodes

a) Meshed plane electrode
b) Plan of electrode
c) Electrode with two last elements placed deeper.

Properties of earthing at high impulse currents

So far, the characteristics of earthing systems have been discussed assuming moderate current flow under steady-state conditions at the network frequency. Differences between steady-state and pulsed properties of an earthing system are caused mainly by:

- flow of currents with very high values, up to a few hundreds of kA
- very fast current rise times - typical lightning strikes reach a few hundred kA/µs.

Extremely high current density in the soil increases the electric field strength up to values which cause electrical discharges in small gaseous voids, decreasing the ground resistivity and earthing resistance. This phenomenon occurs mainly near the earth electrode, where the current density is highest, and the influence is most significant. The intensity of this phenomenon is especially high when the soil is dry or of high resistivity.

The inductance of metal parts of earth electrodes, which can be estimated as equal 1 µH/m, is usually neglected when considering earth impedance at the network frequency. However, inductance becomes an important parameter when the current slew rate is high, in the region of hundred of kA/µs or more. During lightning strikes the inductive voltage drop (L×di/dt) reaches very high values. As a result, remote parts of the earth electrode play a reduced role in conducting current to earth.

The earth resistance for pulse currents increases in comparison with its resistance for static conditions. Thus, increasing the length of earth electrodes over the, so called, critical length (Figure 7) does not cause any reduction of the earth impedance to transients.

During a lightning strike both the phenomena described above have an effect, but operate in opposite directions. The high earth current decreases resistance while the high frequency increases the impedance. The overall impedance can be higher or lower depending on which effect is dominant.

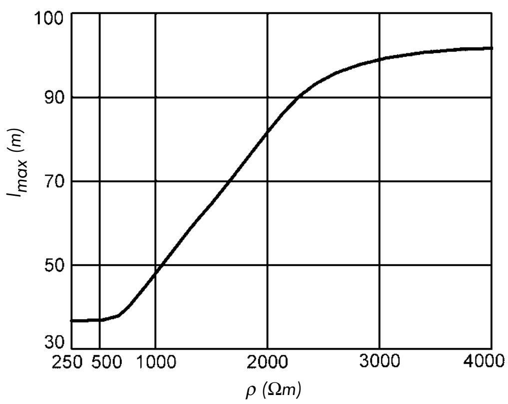

Figure 7 - Maximal length l_{max} of lightning earth electrodes as a function of earth resistivity ρ

Conclusions

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. This 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.

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