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SERIES K: PROTECTION AGAINST INTERFERENCE

Method for determining the impedance to earth of earthing systems

Recommendation ITU-T K.107

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Telecommunication
Union

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Method for determining the impedance to earth of earthing systems

Summary

Telecommunication systems are vulnerable to the earth potential rise (EPR) that can occur in power systems, and they are also vulnerable to the transfer of EPR outside the zone of influence (ZOI), which should also be considered. A quick estimate of the earth potential rise is obtained from the product ($I_e \times R_e$) of the current I_e flowing through an earth electrode and the resistance R_e to earth of that earth electrode.

Recommendation ITU-T K.107 provides methods of varying complexity for measuring the resistance to earth of earth electrodes or even complex earthing systems. The methods provide describe both simple and more sophisticated measurements through the use of computer-based earthing multimeters. Guidance is given on the relevance of each of the different methods for various purposes.

Techniques are also given for the elimination of interference and disturbance voltages for earthing measurements.

In practice it may be necessary to determine or at least estimate the impedance to earth of a power system installation already in the design phase. For these purposes, techniques of calculating the resistance/impedance to earth of isolated, as well as interconnected earthing systems are also included.

History

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Keywords

Earth electrode effect, earth fault, earth potential rise, EPR, fall-of-potential, impedance to earth, multi-earthed, screening factor.

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FOREWORD

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As of the date of approval of this Recommendation, ITU had not received notice of intellectual property, protected by patents, which may be required to implement this Recommendation. However, implementers are cautioned that this may not represent the latest information and are therefore strongly urged to consult the TSB patent database at http://www.itu.int/ITU-T/ipr/.

Table of Contents

Recommendation ITU-T K.107

Method for determining the impedance to earth of earthing systems

1 Scope

The earth potential rise (EPR) that can occur in power systems and that can be transferred to telecommunication systems is potentially dangerous to the people working in the telecommunication plant; damage to the plant itself can also occur. The impedance to earth of earthing systems of a power installation is one of the key parameters affecting the magnitude of the EPR. This Recommendation aims to provide methods of different complexities for measuring the resistance to earth of earth electrodes or complex earthing systems. Techniques for calculating the resistance/impedance to earth of isolated, as well as interconnected earthing systems are also included.

2 References

The following ITU-T Recommendations and other references contain provisions which, through reference in this text, constitute provisions of this Recommendation. At the time of publication, the editions indicated were valid. All Recommendations and other references are subject to revision; users of this Recommendation are therefore encouraged to investigate the possibility of applying the most recent edition of the Recommendations and other references listed below. A list of the currently valid ITU-T Recommendations is regularly published. The reference to a document within this Recommendation does not give it, as a stand-alone document, the status of a Recommendation.

[ITU-T K.26] Recommendation ITU-T K.26 (2008), *Protection of telecommunication lines against harmful effects from electric power and electrified railway lines*.

[ITU-T K.104] Recommendation ITU-T K.104 (2015), *Method for identifying the transfer potential of the earth potential rise from high or medium voltage networks to the earthing system or neutral of low voltage networks*.

[IEEE Std 81] IEEE Std 81 (2012), *IEEE Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Grounding System*.

[EN 50522] Cenelec EN 50522 (2010), *Earthing of power installations exceeding 1 kV a.c.*

3 Definitions

3.1 Terms defined elsewhere

This Recommendation uses the following terms defined elsewhere:

3.1.1 cable with earth electrode effect [EN 50522]: (definition 3.4.33) Cable whose sheaths, screens or armourings have the same effect as a strip earth electrode.

3.1.2 circulating transformer neutral current [EN 50522]: (definition 3.4.31) Portion of fault current which flows back to the transformer neutral point via the metallic parts and/or the earthing system without ever discharging into soil.

3.1.3 (local) earth [b-IEC IEV]: (definition 195-01-03, modified) Part of the Earth which is in electric contact with an earth electrode and the electric potential of which is not necessarily equal to zero.

NOTE – The conductive mass of the earth, whose electric potential at any point is conventionally taken as equal to zero.

3.1.4 earth electrode [EN 50522]: (definition 3.4.3) Earth electrode conductive part, which may be embedded in a specific conductive medium, e.g., in concrete or coke, in electric contact with the earth.

3.1.5 earth fault [b-IEC IEV]: (definition 151-03-40) Fault caused by a conductor being connected to earth or by the insulation resistance to earth becoming less than a specified value.

3.1.6 earth fault current, I_F [EN 50522]: (definition 3.4.28) Current which flows from the main circuit to earth or earthed parts at the fault location.

NOTE 1 – For single earth faults, this is:

– in systems with isolated neutral, the capacitive earth fault current,

– in systems with high resistive earthing, the RC composed earth fault current,

– in systems with resonant earthing, the earth fault residual current,

– in systems with solid or low impedance neutral earthing, the line-to-earth short-circuit current.

NOTE 2 – Further earth fault current may result from double earth fault and line to line to earth.

3.1.7 earth potential rise, EPR U_E [EN 50522]: (definition 3.4.12) Voltage between an earthing system and reference earth.

3.1.8 earthing conductor [b-IEC IEV]: (definition 195-02-03) Conductor which provides a conductive path, or part of the conductive path, between a given point in a system or in an installation or in equipment and an earth electrode.

NOTE – Where the connection between part of the installation and the earth electrode is made via a disconnecting link, disconnecting switch, surge arrester counter, surge arrester control gap etc., then only that part of the connection permanently attached to the earth electrode is an earthing conductor.

3.1.9 earthing system [b-IEC IEV]: (definition 604-04-02) Arrangement of connections and devices necessary to earth equipment or a system separately or jointly.

3.1.10 electric resistivity of soil, ρ_E [EN 50522]: (definition 3.4.9) Resistivity of a typical sample of soil.

3.1.11 foundation earth electrode [b-IEC IEV]: (definition 826-13-08, modified) Conductive structural embedded in concrete which is in conductive contact with the earth via a large surface.

3.1.12 high voltage (HV) [IEC 60050-151:2001, 151-15-05]: Voltage having a value above a conventionally adopted limit.

NOTE 1 – An example is the set of upper voltage values used in bulk power systems.

NOTE 2 – In the case of three phase system the voltage refers to the line-to-line voltage.

3.1.13 impedance to earth, Z_e [EN 50522]: (definition 3.4.11) Impedance at a given frequency between a specified point in a system or in an installation or in equipment and reference earth.

NOTE – The impedance to earth is determined by the directly connected earth electrodes and also by connected overhead earth wires and wires buried in earth of overhead lines, by connected cables with earth electrode effect and by other earthing systems which are conductively connected to the relevant earthing system by conductive cable sheaths, shields, PEN conductors or in another way.

3.1.14 low voltage (LV) [b-IEC IEV]: (definition 151-15-03) Voltage having a value below a conventionally adopted limit.

NOTE 1 – For the distribution of AC electric power, the upper limit is generally accepted to be 1000 V.

NOTE 2 – In the case of three phase system the voltage refers to the line-to-line voltage.

3.1.15 medium voltage (MV) [b-IEC IEV]: (definition 601-01-28) (not used in the UK in this sense, nor in Australia). Any set of voltage levels lying between low and high voltage.

NOTE 1 – The boundaries between medium and high voltage levels overlap and depend on local circumstances and history or common usage. Nevertheless, the band 30 kV to 100 kV frequently contains the accepted boundary.

NOTE 2 – The medium voltage is not a standardized term. It is specified as a system voltage class by IEEE [b-Terms].

NOTE 3 – The preferred medium nominal (line-to-line) voltages in North America: 4.16 kV, 12.46 kV, 13.8 kV, 34.5 kV and 69 kV [b-Terms]. Typical MV system voltages for public distribution: in Europe 10 kV (mainly underground) 20 kV and 35 kV (mainly overhead) [b-Lacroix], in Japan 6.6 kV.

3.1.16 multi-earthed HV neutral conductor [EN 50522]: (definition 3.4.20) Neutral conductor of a distribution line connected to the earthing system of the source transformer and regularly earthed.

3.1.17 PEN conductor [b-IEC IEV]: (definition 826-13-25) Conductor combining the functions of both protective earthing conductor and neutral conductor.

3.1.18 potential [EN 50522]: (definition 3.4.13) Voltage between an observation point and reference earth.

3.1.19 protective bonding conductor [EN 50522]: (definition 3.4.5) Protective conductor for ensuring equipotential bonding.

3.1.20 reduction factor, *r or* screening factor k_s [EN 50522]: (definition 3.4.30) Factor r of a three phase line is the ratio of the current to earth I_E over the sum of the zero sequence currents $3I_0$ in the phase conductors of the main circuit ($r = I_E / 3 I_0$) at a point remote from the short-circuit location and the earthing system of an installation, (also referred to as screening factor, k_s).

3.1.21 reference earth [b-IEC IEV]: (definition 195-01-01, modified) (remote earth) Part of the earth considered as conductive, the electric potential of which is conventionally taken as zero, being outside the zone of influence of the relevant earthing arrangement.

NOTE – The concept "earth" means the planet and all its physical matter.

3.1.22 resistance to earth, R_e [EN 50522]: (definition 3.4.10) Real part of the impedance to earth.

3.1.23 solidly earthed neutral system [IEC 601-02-25:1985]: System whose neutral point(s) is(are) earthed directly.

3.1.24 structural earth electrode [EN 50522]: (definition 3.4.8) Metal part, which is in conductive contact with the earth or with water directly or via concrete, whose original purpose is not earthing, but which fulfils all requirements of an earth electrode without impairment of the original purpose.

NOTE – Examples of structural earth electrodes are pipelines, sheet piling, concrete reinforcement bars in foundations and the steel structure of buildings, etc.

3.1.25 substation [b-IEC IEV]: (definition 605-01-01) Part of a power system, concentrated in a given place, including mainly the terminations of transmission or distribution lines, switchgear and housing and which may also include transformers. It generally includes facilities necessary for system security and control (e.g., the protective devices).

NOTE – According to the nature of the system within which the substation is included, a prefix may qualify it.

EXAMPLE Transmission substation (of a transmission system), distribution substation, 400 kV substation, 20 kV substation.

3.1.26 system with isolated neutral [b-IEC IEV]: (definition 601-02-24, modified) System in which the neutrals of transformers and generators are not intentionally connected to earth, except for high impedance connections for signalling, measuring or protection purposes.

3.1.27 system with resonant earthing [EN 50522]: (definition 3.4.26) System in which at least one neutral of a transformer or earthing transformer is earthed via an arc suppression coil and the combined inductance of all arc suppression coils is essentially tuned to the earth capacitance of the system for the operating frequency.

NOTE 1 – In case of no self-extinguishing arc fault there are two different operation methods used:
– automatic disconnection;
– continuous operation during fault localisation process.

In order to facilitate the fault localisation and operation there are different supporting procedures:

- short-term earthing for detection;
- short-term earthing for tripping;
- operation measures, such as disconnection of coupled bus bars;
- phase earthing.

NOTE 2 – Arc suppression coil may have high ohmic resistor in parallel to facilitate fault detection.

3.1.28 transferred potential [EN 50522]: (definition 3.4.17) Potential rise of an earthing system caused by a current to earth transferred by means of a connected conductor (for example a metallic cable sheath, PEN conductor, pipeline, rail) into areas with low or no potential rise relative to reference earth, resulting in a potential difference occurring between the conductor and its surroundings.

NOTE – The definition also applies where a conductor, which is connected to reference earth, leads into the area of the potential rise.

3.2 Terms defined in this Recommendation

This Recommendation defines the following terms:

3.2.1 effective earth current: The total zero sequence component of the fault current ($3I_{0sc}$) diminished by the circulating transformer neutral current, if present.

3.2.2 effective impedance to earth: This is composed of the resistance to earth, R_e of the earthing system (grid) and the parallel equivalent of the impedance to earth of the connected passive lines with earth electrode effect.

3.2.3 equivalent current to earth: The sum of the earth current (I_{EM}=$3I_{0EM}$) induced by the zero sequence component (I_M=$3I_{0M}$) of fault current of the in-feeding power lines. It can be expressed as a sum of the products of the screening factor k_i and the zero sequence current $3I_{0,i}$ relevant to the i-th line (see Figure 5).

3.2.4 length constant, $\tau = 1/\alpha$: The length τ measured along a line with an earth electrode effect, where at a distance of $x = \tau$, the voltage is reduced to 37% of the value at $x = 0$.

NOTE – This corresponds to the time constant associated with a time dependent phenomenon.

3.2.5 overall/equivalent impedance to earth: The parallel equivalent of the resistance to earth of the mesh earth electrode and input (earth wire/tower footing chain) impedance of the passive conductors of all (in-feeding and passive) lines which have an earth electrode effect.

4 Abbreviations and acronyms

This Recommendation uses the following abbreviations and acronyms:

a.c. Alternating current

CT Current Transformer

EPD Earth Potential Difference

EPR Earth Potential Rise

FOP Fall-Of-Potential

HV High Voltage

LV Low Voltage

MV Medium Voltage

OHL Overhead (power) Line

ZOI Zone Of Influence

5 Conventions

None.

6 Characteristics of the impedance to earth

6.1 General

Resistance measurements of an earthing system or earth electrode have been taken since the early 1950s. Basic technical literature published in the 1960s [b-Sunde] and 1970s [b-Sestech] are still the most popular tests in the electric utility industry. Advanced software packages are now available for soil structure, current distribution and earthing analyses (e.g., [b-Sestech]). The calculation of the magnitude and distribution of the earth fault current in the alternating current (a.c.) power system is given in ITU-T Directives Vol. V, Chapter 5 (see [ITU-T K.26]). Methods for the calculation of the conductive coupling phenomena relevant to the earth potential rise (EPR) of different earthing systems are described in ITU-T Directives Vol. II, Chapter 5 (see [ITU-T K.26]) and the recent CIGRE Technical Brochure [b-TB 592].

Recently, standards or guides describing methods of measuring the impedance to earth have been issued, for example: [IEEE Std 81] in North America, [EN 50522] in Europe and EG 0 power system earthing guide in Australia [b-ENA].

The resistance data provides a quick estimate of the EPR ($I_e \times R_e$) of the earth electrode. Due to their higher magnitude of available fault current and the higher probability of exposure, substation earth grids are typically designed to limit the surface voltage gradients to tolerable levels. There can or cannot be a limit on the substation earth grid resistance, depending on the utility's preference. Unlike substation earth grids, transmission or distribution pole earths are designed and installed based on limiting their impedances to remote earth to specified values. This practice is practical and more appropriate for improving lightning performance of transmission and distribution systems. In either case, the measurement of earth grid or earth electrode impedance can be an important part of designing or analysing an earthing system.

6.2 Impedance to earth

The impedance to earth of an earthing system largely depends on the resistivity of the surrounding soil and the extent and configuration of the buried electrode. Earth at a given location can be composed of various combinations of dry soil, clay, gravel, slate, sandstone, or other natural materials of widely varying resistivity. The soil can be relatively homogeneous over a large area, or it can be layered in granite, sand, or other high-resistivity materials and, thus, be practically insulated from the surrounding area. Consequently, the earthing impedance can vary with the season as the temperature, moisture content, and density of the soil change.

Calculations and experience show that, in a given soil, the effectiveness of an earth grid is dependent largely on the overall size of the earth grid and the resistivity of the soil. The addition of conductors and earth rods within an existing earth grid system can also aid somewhat in reducing the earth grid impedance. This reduction diminishes with the addition of each successive conductor or rod. After the installation of a substation or other earthed structure, the settling of the soil with annual cyclical weather changes tends to reduce the earth impedance during the first year or two.

The impedance of an earthing electrode is usually measured in terms of resistance because the reactance is generally negligible with respect to the resistive component. The reactive component increases with the size of the earth grid and especially when the earth grid is interconnected with earthed neutral and shield wire systems and cables with earth electrode effect. Determination of the reactive component is necessary when the analysis involves surge or impulse currents.

The resistance will not usually vary greatly from year to year after the first year or two following its installation. Although the earth grid can be buried only half a metre below the surface, the resistance of an earth grid seems to bear little relationship to the changes in the resistivity at the burial level. The lack of correlation between grid resistance and burial depth resistivity is especially true for grids equipped with long-driven rods in contact with deep soil. This obviously will not be true for earth grids buried over a high-resistivity stratum such as a rock bed or grids buried in permafrost.

7 Methods of measuring the resistance/impedance to earth

7.1 General

This clause describes the general methods of measuring impedance to earth. The measured impedance value is often called resistance, even though it contains a reactive component. The reactive component can be very significant for large or interconnected earthing systems. The resistance of an earth electrode usually is determined with alternating or periodically reversed current. This minimizes the effect of galvanic voltages that can be present at the probes and interference from direct currents in the soil from cathodic protection or telluric currents. Applying test currents that operate at a frequency different from power or harmonic frequencies will minimize interference from possible stray currents and disturbing voltages.

7.2 Measuring methods

7.2.1 Two-point method

In the two-point method [IEEE Std 81], the resistance of the subject earth electrode is measured in series with an auxiliary earth electrode. The resistance of the auxiliary earth is presumed to be negligible in comparison with the resistance of the subject earth. The measured value then represents the resistance of the subject earth.

One application of this method is to measure the resistance of a driven earth rod with respect to a nearby residential house. Typically, a residential house with a low voltage (LV) power supply network of TN-C or TN-C-S system has a low-impedance earthing system due to its tie with the neutral conductor of the power supply system. Using such an earthing system as an auxiliary earth can produce a test result with reasonable accuracy.

This method is subject to large errors when testing for low-resistance earths. If the subject and auxiliary earths are too close to each other, then the mutual resistance between the earths can also be a source of error. However, this method is a useful tool where a *go or no-go* type of test is all that is required. (See also clause 7.2.5)

7.2.2 Three-point method

The three-point method [IEEE Std 81] involves the use of two auxiliary electrodes with their resistances designated as r_2 and r_3.The resistance of the subject electrode is designated r_1. The resistance between each pair of electrodes is measured and are designated r_{12}, r_{13}, and r_{23}, where

$$r_{12} = r_1 + r_2, \quad r_{13} = r_1 + r_3 \text{ and } r_{23} = r_2 + r_3$$

Solving the three simultaneous equations, it follows that

$$r_1 = \frac{r_{12} - r_{23} + r_{13}}{2} \tag{1}$$

By measuring the series resistance of each pair of earth electrodes and substituting the resistance values in the equation, the value of r_1 can be established. If the two auxiliary electrodes are of materially higher resistance than the electrode under test, then the errors in the individual measurements will be greatly magnified in the final result. For accurate measurement, the electrodes need to be at a far enough distance from each other so as to minimize the mutual resistances between them. In cases involving inadequate distances between the electrodes, absurdities such as zero or negative resistances can arise. In measuring the resistance of an earth rod, separate the three electrodes by at least three times the depth of the subject rod. In providing this guidance, the assumption is also made that the auxiliary electrodes are driven to the same or less depth as the subject earth rod. This method becomes more difficult to apply as the earthing electrode system becomes large and complex and other methods are preferred, especially if higher accuracy is desired.

7.2.3 Fall-of-potential method with earth tester

The fall-of-potential (FOP) method involves passing a current between an earth electrode (E) and a current probe (CP), and then measuring the voltage between E and a potential probe (PP), as shown in Figure 1. To minimize inter-electrode influences due to mutual resistances, the current probe is generally placed at a substantial distance from the earth electrode under test.

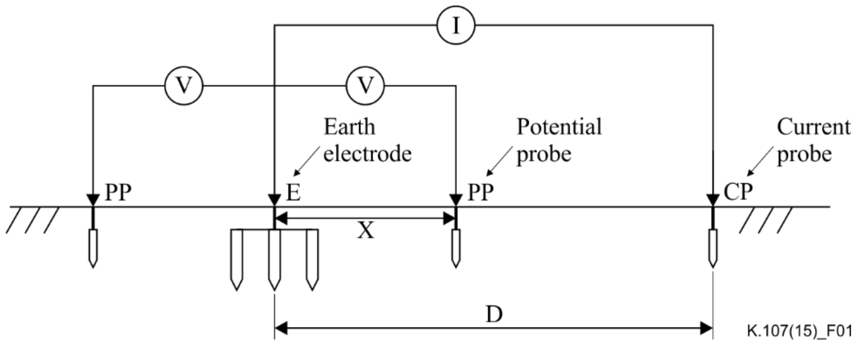


Figure 1 – Arrangement of the fall-of-potential method [IEEE Std 81]

According to [EN 50522] the earth electrode under test E, current probe CP and auxiliary potential electrode PP shall lie on a straight line as far apart as possible. The distance of the probe PP from the earth electrode under test should be at least 2.5 times the maximum extension of the earth electrode under test (in measuring direction), but not less than 20 m; the distance of the auxiliary electrode CP must be at least four times the maximum extension, but not less than 40 m.

According to [IEEE Std 81] the current probe is generally placed at a substantial distance from the earth electrode under test. Typically, this distance is at least five times the largest dimension of the earth electrode under test. The potential probe is typically placed in the same direction as the current probe, but it can be placed in the opposite direction, as shown in Figure 1. In practice, the distance "X" for the potential probe is often chosen to be 62% of the distance of the current probe, i.e., $X=0.62\ D$, when current and potential probes are in the same direction (62% rule). This distance is based on the theoretically correct position for measuring the exact electrode impedance for a soil with uniform resistivity ([b-Curdts]), assumes a sufficient distance between the earth electrode under test and the test probes that are present to allow test probes to be considered as being a hemisphere, and further assumes that the earth electrode has no external interconnections.

Once the criteria for the current probe are satisfied, the location of the potential probe is critical to measuring accurately the resistance of the earth electrode. The location needs to be free from any influence from both the earth electrode under test and the current probe. A practical way to determine whether the potential probe is free from other electrodes' influences is to obtain several resistance readings by moving the potential probe between the earth grid and the current probe. Two to three consecutive constant resistance readings can be assumed to represent the true resistance value (flat slope method, FOP).

The FOP theory suggests that, for a soil with uniform resistivity. The required separation distance is greater when using probes on opposite sides. Also, the variations due to soil non-uniformity are greater when the PP and CP are located in opposite directions.

Additional limitations of the FOP method prevent it from yielding a true impedance value. An accurate measurement of impedance is obtained only when the subject earthing system can be represented as an equivalent hemisphere with an electrical centre for measuring various probe distances (see Table 1). An effective electrical centre is defined as a point on an earthing system where most of the test current flows. Most isolated earth grids with simple geometries can be represented by equivalent hemispheres. For complex earthing systems such as a large substation earth grid (or even a small substation earth, [b-Tagg] described a method known as the "slope method." In his method, the assumptions of uniform soil resistivity and representation of the earthing electrode system as an equivalent hemispherical electrode remained as before. However, his method allowed measuring the probe distances from a convenient point such as from the edge of an earthing electrode system by introducing the error distances in the FOP equation (see [IEEE Std 81]).

To apply the FOP method with the 62% rule the following conditions should exist:

a) a fairly uniform soil;

b) large distances between the earth grid under test and reference electrodes so that all the electrodes can be assumed to be hemispherical;

c) the electrode under test has no external earth connections.

Also, the reference origin for measuring the distances of the auxiliary electrodes (current and voltage probes) is needed. For hemispherical earths, the origin is the centre of the earth. For large earth systems, some authors introduce the concept of *electrical centre* and describe the method of determining the impedance of the extensive earthing systems imbedded in a uniform soil ([b-Thug]). It should be noted that for a large and complex earth grid system, the *electrical centre* might not be the same as the geometrical centre of the earth grid. Unlike the geometrical centre, the location of the electrical centre largely depends on the current density profile in and around the earth grid conductors.

The FOP test measures the resistance between a point in the earth grid and remote earth. When the measurement aims at to determine the resistance to earth relevant to the EPR at that point of the substation area where the telecommunication circuit entering the substation is terminated, the potential should be measured between this point (earthing at the telecom room) and the remote earth.

In general, the best way to obtain a satisfactory measurement is to achieve spacing between the earth grid and the current probe (Figure 1) so that all mutual resistances are sufficiently small. The main advantage of the FOP method is that the potential and current electrodes can have a substantially higher resistance than the earth electrode tested without significantly affecting the accuracy of the measurement.

Nevertheless, ***the main areas of application*** of the FOP method are for earth electrodes and earthing systems of small or medium extent, for example, single rod earth electrodes, strip earth electrodes, earth electrodes of overhead line (OHL) towers with lifted off or attached earth wires, medium voltage (MV) earthing systems and separation of the low-voltage earthing systems. The frequency of the used alternating voltage should not exceed 150 Hz [EN 50522].

7.2.4 High frequency measurements with earth tester [EN 50522]

The *use of the high frequency measurement is* to measure the impedance to earth of such earthing which is connection to distributed-like line(s), *typically earth wire*. This instrument facilitates, without lifting off the earth wire, the measurement of the resistance to earth of a single tower. The frequency of the measuring current shall be so high (up to 5 kHz) that the chain impedance of the earth wire and the neighbouring towers becomes high, representing a practically negligible shunt circuit to the earthing of the single overhead line tower.

7.2.5 Resistance measurements by clamp-on method [IEEE Std 81]

In contrast to the high frequency measurements in clause 7.2.4 the clamp-on measurement method assumes the availability of low chain impedance earthing, such as multi-earthed neutral. The method is based on an assumption that the impedance of the multi-earthed neutral (or screen) system, excluding the earth electrode under test, is so small compared to the earth electrode under test, that it can be assumed to be zero ($Z_{eq} = 0$), i.e., the potential of both the current probe and the voltage probe are considered as reference earth. With this assumption, the indicated reading approximates the resistance of the earth electrode when properly used.

The clamp-on meter measures the resistance of an earthing electrode by clamping onto the down lead wire, as illustrated in Figure 2 [IEEE Std 81].

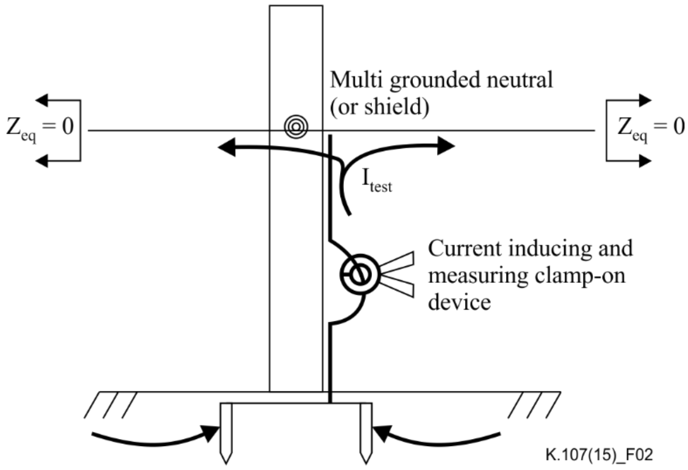


Figure 2 – Resistance measurements by clamp-on method [IEEE Std 81]

When turned on, the clamp-on meter induces a voltage with a defined frequency, usually between 1 kHz and 3.4 kHz, into the integrated earth system, including the earth electrode under measurement. The induced voltage causes a current (I_{test}) to flow into the multi-earthed system, which is measured by the meter. The voltage-to-current ratio (impedance) is then determined and displayed in digital format by the meter.

The accuracy of the clamp-on device is predicated on the proper mating and alignment of the jaws. Clamp-on meters require frequent calibration to assure proper operation.

Although this method is practical and widely used for transmission and distribution lines, its theory lends itself to some application limitations. The application is limited to an earth electrode connected to a relatively low impedance earthing system.

A large error can be introduced into the test measurement if the inductive reactance of the multi-earthed shield or neutral system under test is significant compared to the resistance being measured. This is particularly true of clamp-on devices that require high test frequencies of 1 kHz to 3.4 kHz to maintain their compact shapes, assuming no effort is made to account for the reactance in the test circuit. The high frequency injected into the test circuit will increase the reactive impedance of the circuit and can greatly distort the test readings if the inductance is significant.

The applicability area of the clamp-on method can be extended by the use of measurement with two clamps (Figure 3).

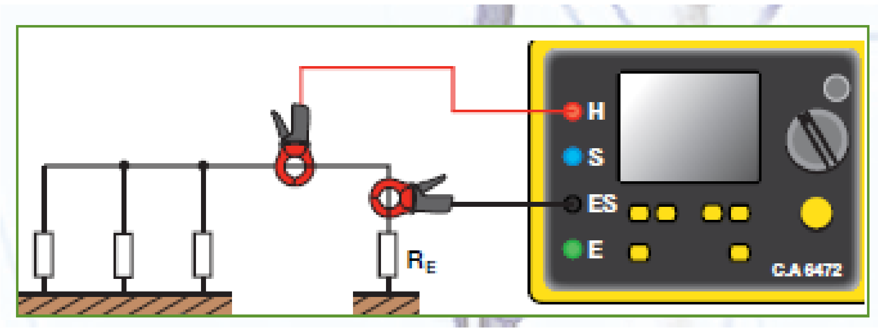


Figure 3 – Measurement with two clamps

The principle of this method involves placing two clamps around the earth conductor to be tested and connecting each of them to the instrument. One clamp injects a known signal (e.g., 32 V/1367 Hz) while the other clamp measures the current circulating in the loop. This method saves considerable time when earth testing because it is no longer necessary to set up auxiliary rods or to disconnect the earth connections.

The method is not applicable to a multiple-connected earth electrode system, such as a substation earth grid, multi-connected pole, or structure earths. Disconnect a multi-connected pole or structural earth electrode, except at the measuring leg. Be sure that any earth lead is disconnected in a safe manner.

7.2.6 Resistance measurements by FOP/clamp-on method [IEEE Std 81]

A stand-alone resistance of an earth electrode can also be measured by combining the FOP method and clamp-on method, as shown in Figure 4 [IEEE Std 81]. The current and voltage probes are placed in the same way as required for the FOP method. In addition to passing the current into the earthing system, a clamp-on (flexible) current transformer (CT) measures the portion of the test current that flows into the earthing system. A ratio of the measured voltage to measured earth current then determines the stand-alone resistance of the earthing system.

The FOP/clamp-on method is often used when measuring the resistances of multi-legged or guyed transmission line structures that do not have dedicated earth electrode systems. For measuring the current flowing in the earth, a large split-core CT is used, as shown in Figure 4. In the case of a four-legged tower, the resistance of each leg is measured separately before combining them to determine the overall resistance of the structure. Recently, a device has been developed that allows the measurement of all four resistances simultaneously.

Similar to the clamp-on method, high-frequency noise in the system can influence the reading. A high noise-to-signal ratio can also occur during the measurement of a high-resistance earth.

A single measurement is sufficient to acquire all the essential quantities:

– overall earth resistance of the line;

– resistance of the pylon under consideration;

– resistance of each pylon footing;

– resistance of the earth cable between pylons.

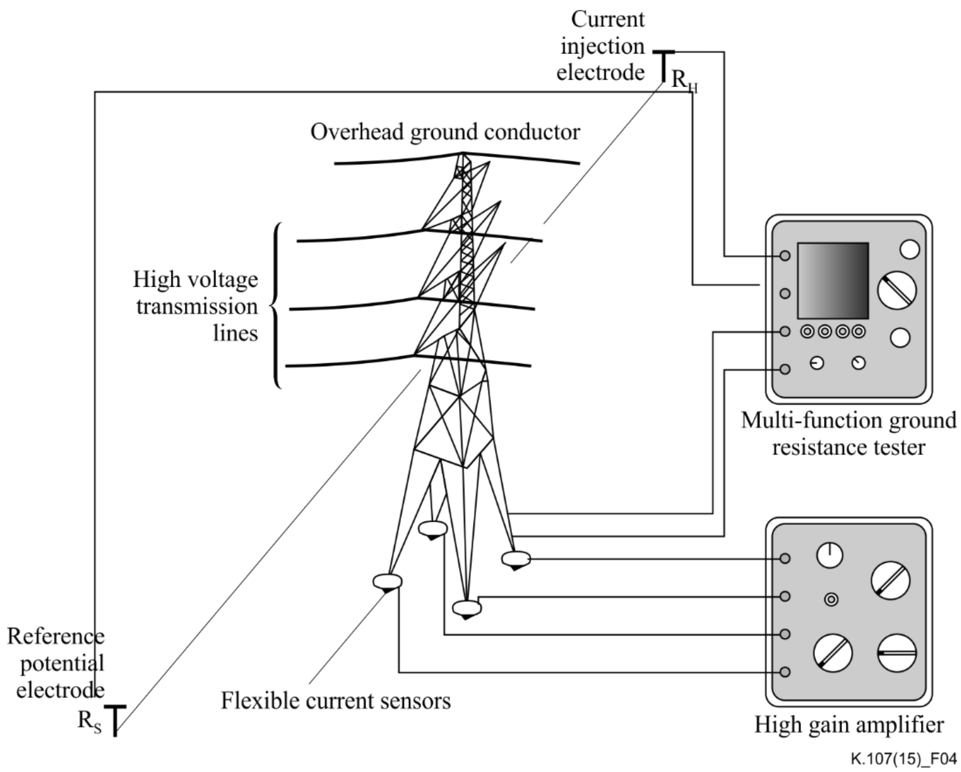


Figure 4 – Tower footing measurement using FOP and leakage current measurements [IEEE Std 81]

7.2.7 Heavy-current injection method [EN 50522]

7.2.7.1 Description of the method

The heavy-current injection method illustrated in Figure 5 is used particularly for the measurement of the impedance to earth of large earthing systems.

By applying an alternating voltage of approximate system frequency between the earthing system and a remote earth electrode, a test current I_M is injected into the earthing system, leading to a measurable potential rise of the earthing system.

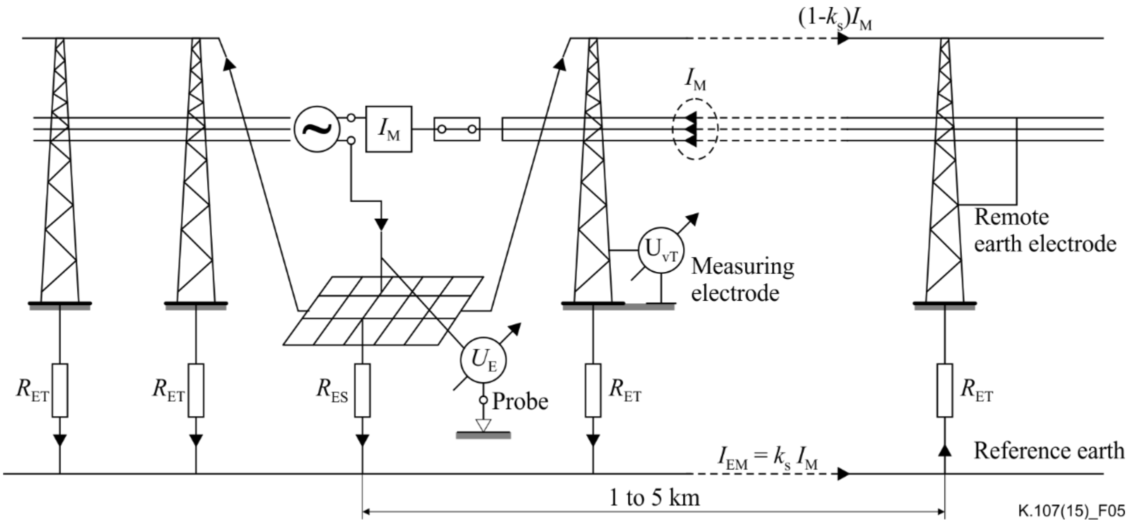
Earth wires and cable sheaths with earth electrode effect, which are operationally connected to the earthing system, shall not be disconnected for the measurement.

The modulus of the impedance to earth is given by:

$$Z_E = \frac{U_{EM}}{I_M \cdot k_s} \qquad (2)$$

where:

- U_{EM} is the measured voltage between the earthing system and a probe in the area of the reference earth (remote earth) in volts
- I_M is the measured test current in amperes
- k_s is the screening (reduction) factor of the line to the remote earth electrode. The screening factor may be determined by calculation or by measurement. For the screening factor for overhead lines without earth wires and cables without shield or armouring is k_s = 1



I_M Test current (generally only the modulus of the voltage and the current is determined)

I_{EM} Current to earth during the measurement (in this case not directly measurable)

k_s Screening factor of the line to the remote earth electrode

R_{ES} Resistance to earth of the mesh earth electrode

R_{ET} Resistance to earth of the tower

U_E EPR during measurement

U_{vT} Prospective touch voltage during measurement

Figure 5 – Illustration of the determination of the impedance to earth by the heavy-current injection method [EN 50522]

The Z_E given by equation (2) is the overall/equivalent impedance to earth (defined by the term in clause 3.2.4). Earth wires of lines which run on a separated support parallel to the test line between earthing system and remote earth electrode, have to be taken into account, if they are connected to the earthing system under test and the remote earth electrode. If the measuring current is fed by a cable with low-resistance metal sheath, earthed on both sides, then the greatest part of the test current will return via the sheath. The above-mentioned line(s) is (are) the in-feeding line(s) indicated at the left side of the substation grid. It should be noted that the measured Z_E is relevant to the EPR calculation only in the case where all in-feeding lines have identical screening factors.

If there is an insulating covering around the sheath it can be suitable to disconnect the earthings of the sheath. This kind of measurement will provide the effective impedance to earth (see the definition given in clause 3.2.3) assuming that the only in-feeding line is the cable used in the measurement.

The lines connecting from the left side to the substation grid are the so called passive lines. Their passive conductors with earth electrode effect are contributing (reducing) the impedance to earth, i.e., both to the effective and the overall/equivalent impedance.

However, for such in-feeding cables the sheaths of which perform the function of an earth electrode, the earthing of the metal sheaths shall not be disconnected.

The distance between the tested earthing system and the remote earth electrode should be large enough to ensure separate zones of influence, e.g., 5 km for extended earthing systems. The test current should be, as far as possible, selected at least so high that the measured voltages (EPR as well as touch voltages, referred to the test current) are greater than possible interference and disturbance voltages. This is generally ensured for test currents above 50 A. The internal resistance of the voltmeter should be at least 10 times the resistance to earth of the probe.

Possible interference and disturbance voltages have to be eliminated (see clause 7.2.7.2).

7.2.7.2 Elimination of interference and disturbance voltages for earthing measurements

For the determination of the EPR in accordance with the above clause, distortions of the measured values due to interference and disturbance voltages of every type (for example inductive interference of the test circuit by parallel systems in operation) may occur.

Examples for methods proved useful in practice for the elimination of such disturbing effects are:

a) Beat method

In this case a voltage source (for example emergency generating set) is used, whose frequency deviates some tenth of a Hertz from the system frequency.

NOTE – There is computer-based earthing generating with the use of power electronic 55 Hz measuring current and measuring the voltages highly selective way thus suppressing the disturbing voltages.

The voltages caused by the test current are added vectorially to possible disturbance voltages U_d', whose modulus and phase angle for sufficiently short duration of a measuring cycle may be regarded as constant. Due to the asynchronous superposition the pointer or the display of the voltmeter swings between a maximum value U_1 and a minimum value U_2. The voltage caused by the test current is determined by:

$$\boldsymbol{U = \frac{U_1+U_2}{2}} \quad \text{for } 2U_d' < U_1 \tag{3}$$

$$\boldsymbol{U = \frac{U_1-U_2}{2}} \quad \text{for } 2U_d' > U_1 \tag{4}$$

$$\boldsymbol{U = \frac{U_1}{2}} \quad \text{for } 2U_d' = U_1 \tag{5}$$

b) Polarity reversal method

For this purpose a system synchronous voltage source (transformer) is used, whose voltage is reversed 180° electrically in the phase angle after a dead interval. During the flow of the test current the occurring voltages U_a before the reversal, U_b after the reversal and the disturbance voltage U_d for the test current switched off are measured. Because of vectorial relations the voltage caused by the test current is calculated by

$$U = \sqrt{\frac{U_a^2 + U_b^2}{2} - U_d^2} \tag{6}$$

c) Vector measurement

Long measuring leads should be laid rectangular to the test line, as far as possible. If this is not possible because of space conditions, the part of the voltage induced in the measuring line by the test current can partly be eliminated by vector measurement equipment.

d) Blocking of direct currents

If the disturbance voltages have high direct voltage contents, a decoupling element blocking direct current (d.c.) or a voltmeter which blocks the direct voltage may be required.

7.2.8 Earth impedance measurement by computer-based earthing multimeter [IEEE Std 81]

A computer-based earthing multimeter was developed by different researchers (e.g., [b-Meliopoulo]) with the ability to characterize the impedance of an isolated or integrated earth system. The test involves installing one current returning and six voltage-sensing electrodes (via a pair of tri-coaxial leads, each connected to three electrodes), as shown in Figure 6. The current return electrode is placed at a distance of at least two times the longest substation dimension. The first voltage probe in each string is typically placed at a 15 m distance from the substation fence. The distances of the remaining voltage probes are then automatically (determined by the length of the connecting conductors) fixed from the first probe. For better accuracy, voltage probes are located as far from other earth structures (e.g., pole earths, pipes) as possible.

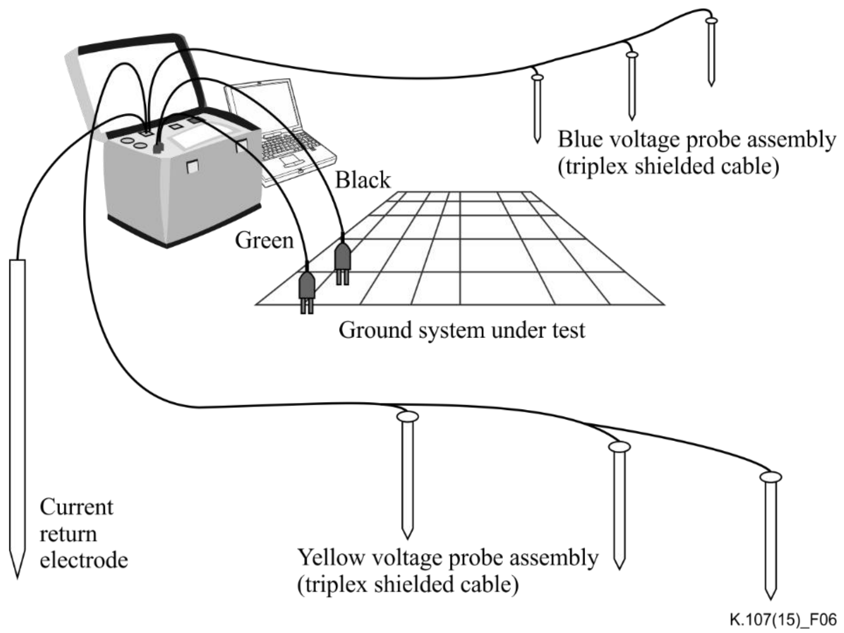


Figure 6 – Illustration of earth impedance measurement by computer-based earthing multimeter

Generally, these types of multimeters present the user with the following measurement options:

a) earth impedance (isolated or interconnected earthing system of a tower, pole, or substation);

b) soil resistivity;

c) tower earth impedance (stand-alone tower/pole earth impedance without disconnecting shield or neutral wires);

d) touch voltage;

e) step voltage;

f) earth mat impedance (stand-alone substation earth impedance without disconnecting shield and neutral wires);

g) transfer voltage;

h) low impedance/continuity (substation earth grid conductor integrity test).

Based on the selected measurement option, the user then inputs several parameters, including the type and size of the earthing system (earth rods, counterpoises, or earth grid) and approximate coordinates for current and voltage electrodes. During the test, the power supply unit injects continuous pulses (white noise) between the earthing electrode under test and the return electrode. The current pulses are injected for a short duration, typically for 0.5 s. In the earth impedance mode, earth potential differences (EPDs) are measured by six voltage electrodes. The computer software then processes the measured current and EPDs and performs the following:

– noise filtering;

– corrections of the voltage and current transducer errors;

– estimation of the earth electrode impedance and soil factor by solving a 2 by 6 equation matrix using weighted least square method;

– display an earthing impedance (magnitude and phase angle) versus frequency plot on the screen.

In other areas, as follows, the computer method has similar limitations as the FOP method that can influence the accuracy of the data:

– voltage and current probe distances are measured from an assumed electrical centre, and as a result, the impedance of an interconnected earthing system is not accurately determined;

– the measured impedance value can vary with changes in voltage and/or current probe locations. However, the method provides a range of error along with the impedance value. The method claims that the true value of impedance is enclosed by this range.

8 Methods of determining the resistance/impedance to earth by calculation

In practice it may be necessary to determine the impedance to earth of a power system installation already in the design phase. This can be determined or at least estimated by calculation.

This clause describes techniques for estimating the resistance/impedance to earth by the calculation of isolated, as well as interconnected, earthing systems. To avoid confusion, the term "resistance" will be alternatively used to mean the impedance as well.

The equations for calculating the impedance to earth of a stand-alone earth electrode are given. A more complex earthing system is composed of these stand-alone electrodes, thus its overall resistance can be determined as their electrically parallel connected equivalent.

8.1 Equations for calculating impedance to earth of a stand-alone earth electrode

8.1.1 Resistance of the equivalent hemisphere

It is well known from technical literature, [b-Tagg], that the resistance of a hemisphere on the surface homogeneous soil (see Figure 7) is:

$$R_e = \frac{\rho}{2\pi r_e} \tag{7}$$

where:

ρ is the resistivity of soil

r_e is the radius of the hemisphere.

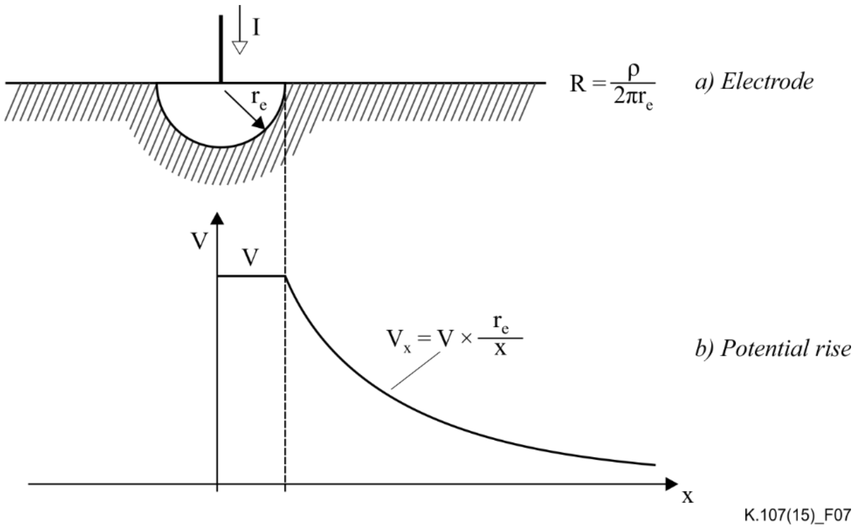


Figure 7 – Resistance and potential rise of equivalent hemisphere

8.1.2 Resistance R_e and equivalent radius r_e for three common electrode shape

The equivalent hemisphere of a real electrode, e.g., tower footing, having the resistance of R_e, is defined in such a way that the resistance of the hemisphere electrode and the real ones should be equal to each other:

$$r_e = \frac{\rho}{2\pi R_e} \tag{8}$$

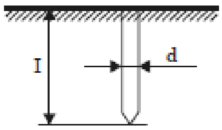
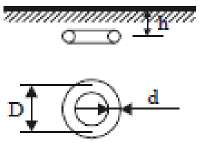
where:

R_e is the earth resistance of the electrode to be replaced by equivalent hemisphere. Its value may be given as measured or can be calculated for a typical shape of electrodes by relevant formulae.

The formulae of resistance R_e and equivalent radius r_e are given in Table 1 for three common electrode shapes [b-Tagg].

These equations can be used for calculating the impedance to earth of electrodes with different shapes and sizes.

Table 1 – Formulae for the earth resistance R_e and radius r_e of equivalent hemisphere

Electrode		Earth resistance	Radius of equivalent hemisphere
Type	Shape and size	R_e	r_e
Driven rod		$\frac{\rho}{2\pi\ell}\left[\ln\frac{8\ell}{d}-1\right]$	$\frac{\ell}{\ln\frac{8\ell}{d}-1}$
Ring of wire	 DIR-V.II_Table1-5	$\frac{\rho}{\pi^2 D}\ \ln\frac{4D}{\sqrt{dh}}$	$\frac{\pi D}{2\ \ln\sqrt{\frac{4D}{dh}}}$
Earth plates	Area of the plate A	$\frac{\rho}{4}\sqrt{\frac{\pi}{A}}$	$\frac{2}{\pi\cdot\sqrt{\pi}}\sqrt{A} = 0.3592\ \sqrt{A}$

8.1.3 The impedance to earth of different power network elements

The equations given in Table 1 can be used for calculating the approximate value of the impedance to earth of different power network elements such as those given in the following clauses.

8.1.3.1 Equations for tower footing and/or small-sized earth

The resistance of a tower footing and/or a small-sized earth electrode is given by:

The resistance to earth of tower footing can be obtained as a first approximation:

$$R_e = \frac{\rho}{30} \tag{9}$$

This can be calculated in more precise way by the following expression:

$$R_e = \frac{\rho}{4}\sqrt{\frac{\pi}{A}} \tag{1}$$

8.1.3.2 Meshed earth electrode (grid)

The approximate value of the resistance to earth of a meshed electrode (grid) is given by the following expression:

$$R_e = \frac{\rho}{2D} \tag{11}$$

where:

D is the diameter of a circle with the same area as the area of the meshed electrode.

8.1.3.3 Resistance to earth of horizontal earth electrodes

The resistance of horizontal strip earth electrodes can be calculated by the following expressions:

Strip earth electrode:

$$R_{EB} = \frac{\rho}{\pi L} ln \frac{2L}{d} \tag{12}$$

Ring earth electrode:

$$R_{ER} = \frac{\rho}{\pi^2 D} ln \frac{2\pi D}{d} \tag{13}$$

where:

L Length of the earth strip in m

$D = \frac{L}{\pi}$ Diameter of the ring earth electrode in m

d Diameter of the stranded earth electrode or half width of an earth strip in m (here 0.015 m assumed)

NOTE – In case of a cable bundle, the diameter should be replaced by twice that of the geometric mean radius (GMR) of the bundle.

ρ soil resistivity in Ω m

The numerical values are illustrated in Figure 8.

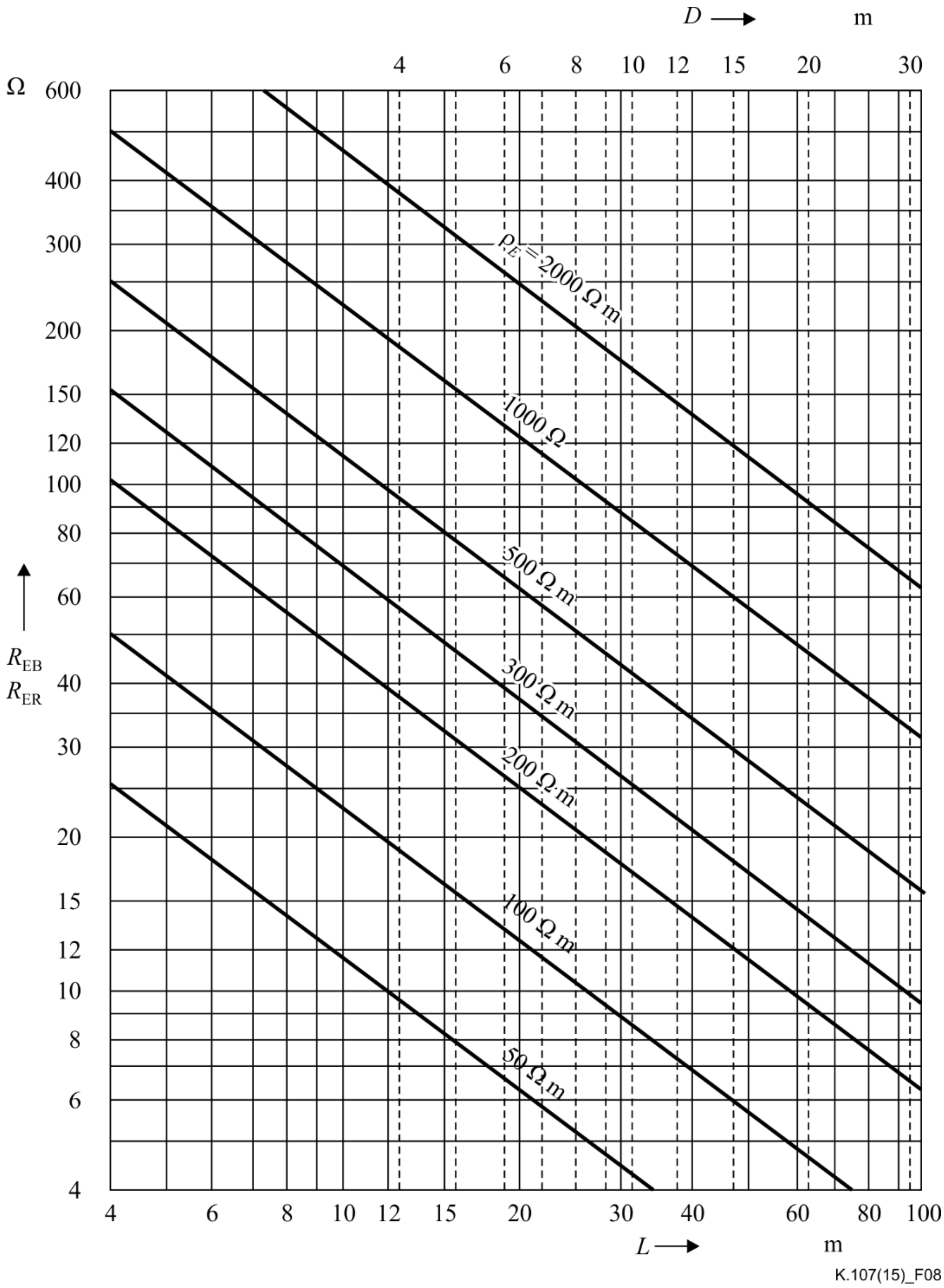


Figure 8 – Resistance to earth of horizontal earth electrodes (made from strip, round material or stranded conductor) for straight or ring arrangement in homogeneous soil

Typical values for the resistance to earth of a cable with earth electrode effect depending on the length of the cable and the soil resistivity are plotted in Figure 9 [EN 50522].

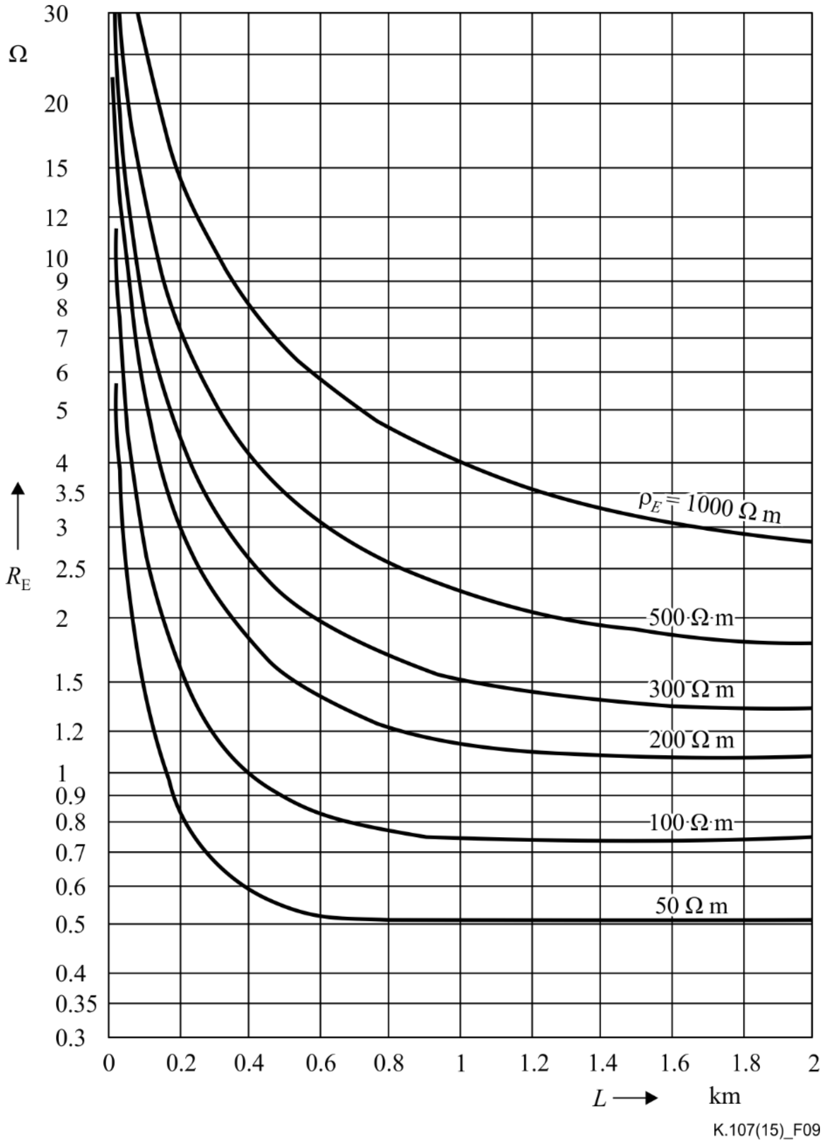


Figure 9 – Typical values for the resistance to earth of a cable with earth electrode effect depending on the length of the cable and the soil resistivity

8.1.3.4 Input chain impedance of the earth wire

The impedance of the earth wire and tower-footing chain, as seen from the start of a span is [b-Endrenyi]:

$$Z_c = 0.5\left[z_s + \sqrt{z_s\left(4R_t + z_s\right)} \right] \approx 0.5 z_s + \sqrt{R_t z_s} \tag{14}$$

where:

Z_s is the impedance of the earth wire with earth return, per span

R_t is resistance of the tower footing.

The overlapping of tower footing resistances is neglected.

The calculated chain impedance is demonstrated versus the length in Figure 10, flag is the resistance of the tower footing.

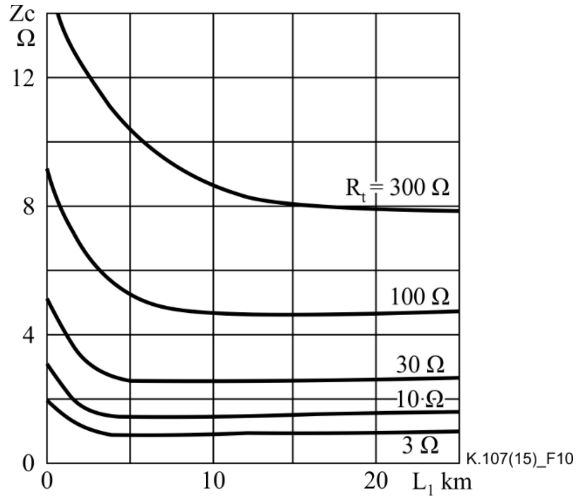


Figure 10 – Calculated dependence of the chain impedance on R_t and Length L

8.1.4 Determination of the resistance to earth from the individual resistances

If the earthing system consists of separate earth electrodes, which practically do not interfere with each other, but which are interconnected via connecting conductors, for example earthing conductors or earth wires of overhead lines, then the impedance to earth Z_E can be determined in the following way.

The resistance to earth of each earth electrode is determined for disconnected connecting conductors by the FOP method, the impedance of the connecting conductors are calculated, and the impedance to earth is determined from the equivalent circuit of the resistance to earth and the impedances of the connecting conductors.

8.1.5 Determination of the resistance to earth of a complex earthing system

The following circumstances result in a complex earthing system:

– large size of the earthing grid;

– the complex structure, i.e., grid in combination with vertical rods and/or strip like earth electrodes such as cable with earth electrode effect;

– layered earth structure;

– earthing system composed of close coupled grids [b-Varju].

A series of computer models are used to simulate earthing systems of different sizes and structures in various soil structures [b-Ma]. Appropriate software tools are also available for evaluating these adequate computer models [b-Sestech**]**.

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