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OF ITU

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SERIES K: PROTECTION AGAINST INTERFERENCE

## Protection measures for radio base stations sited on power line towers

ITU-T Recommendation K.57

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## Protection measures for radio base stations sited on power line towers


### Summary

This Recommendation specifies measures to be taken with respect to safety and risk of damage to equipment through earth potential rise, when power line towers are used for locating radio base stations. It also considers the special lightning protection scheme, which is needed for this type of installation.

This is of special concern when power is fed from the low-voltage network, which is the most common situation. Different options are described.

Three appendices are attached:

Appendix I, titled "Guide on the coordination of the isolation level required for the power supply circuit and the potential rise of power line towers", gives information on how to determine the required isolation voltage level due to the EPR at an earth fault in the tower.

In Appendix II, titled "Guide on the LV feeding arrangement", more details on the low-voltage feeding options are given.

Finally, Appendix III, titled "Characterization and control of the EPR zone of tower earthing and estimation of the minimum length of the junction section", presents simple calculations for estimation of the EPR for the determination of the length of the so-called junction cable.

It also shows graphs of the EPR and touch voltage when grading frame earths around the equipment cabinet are installed.



### Source

ITU-T Recommendation K.57 was approved by ITU-T Study Group 5 (2001-2004) under the ITU-T Recommendation A.8 procedure on 6 September 2003.

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## Protection measures for radio base stations sited on power line towers

### 1 Scope

This Recommendation specifies measures to be taken with respect to safety and risk of damage to equipment through earth potential rise, when power line towers are used for locating radio base stations.

Special arrangements for lightning protection at these installations are also covered.

It considers both the power feeding and the connection to the telecommunication network.

It also mentions the risk of disturbances to the transmitting antenna.

Lightning protection of radio base stations is treated in ITU-T Rec. K.56.

### 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 Recommendation K.8 (1988), *Separation in the soil between telecommunication cables and earthing system of power facilities*.

– ITU-T Recommendation K.33 (1996), *Limits for people safety related to coupling into telecommunications system from a.c. electric power and a.c. electrified railway installations in fault conditions*.

– ITU-T Recommendation K.52 (2000), *Guidance on complying with limits for human exposure to electromagnetic fields*.

– ITU-T Recommendation K.56 (2003), *Protection of radio base stations against lightning discharges*.

– IEC 61643-1 (2002-01), *Surge protective devices connected to low-voltage power distribution systems – Part 1: Performance requirements and testing methods*.

– IEC 61643-12 (2002-02), *Low-voltage surge protective devices – Part 12: Surge protective devices connected to low-voltage power distribution systems – Selection and application principles*.


### 3 Definitions and abbreviations

#### 3.1 Definitions

This Recommendation defines the following terms:

**3.1.1 potential grading earth (PGE)**: An electrode system laid at small depth around the equipment cabinet(s) for controlling the step and touch voltages. It is bonded to both the tower and the cabinet(s) earth.

**3.1.2 directly earthed power system**: HV and MV power systems, whose neutral is connected to earth through a low impedance or directly.

**3.1.3 non-directly earthed power system**: HV and MV power systems, whose neutral is connected to earth through a high impedance (resistor or inductor), or arc extinguishing (Petersen) coil or isolated.

## 3.2 Abbreviations

This Recommendation uses the following abbreviations:

EPR Earth Potential Rise

HV High Voltage (Voltage levels exceeding 100 kV a.c.)

LV Low Voltage (Voltage levels not exceeding 1000 V a.c.)

MOV Metal Oxide Varistor

MV Medium Voltage (Voltage levels lying between LV and HV)

RBS Radio Base Station

SPD Surge Protective Device

T-EPR Tower-earthing potential rise

Z-EPR Zone of the earth potential rise

# 4 General

Locating radio base station antennas in power line towers is mainly of interest in rural areas, where there are no tall buildings, where antennas may be installed. At the same time, some precautions have to be taken in order to make the installation safe and not to cause damage to the equipment.

At every power line tower with a radio base antenna, there is a cabinet located near the tower or between the tower legs. This cabinet is sometimes elevated, if possible. The location of the equipment cabinet is not a safety issue, but rather a question of accessibility to the tower.

This cabinet is hosting equipment for transmitting and receiving and has cable connections for power feeding and signal transmission.

There is a transformer cabinet for power supply in close proximity to the equipment cabinet or in a dedicated part of the cabinet.

The antenna may be mounted below or above the phase conductors or even above the overhead earth wire(s), if any.

The power line may belong to a directly or non-directly earthed power system.

There are two phenomena that have to be considered:

- Earth potential rise in case of earth fault at the tower – This problem is treated by isolating that part of the RBS equipment, which has external metallic connection, against its cabinet and equipment, which is bonded to the tower.
- Lightning hitting the tower – This problem is handled by bonding the above-mentioned parts of the RBS equipment through suitable SPDs in order not to jeopardize the isolation for EPR.

For further information, see II.2.

### 4.1 Earth fault characterization of directly earthed power systems

When an earth fault occurs in a power system with directly earthed neutral, there will be an earth potential rise, EPR, at the feeding substations, and also at the fault location, which may be the tower, where the radio base station is installed. In most cases the EPR will be much higher at the fault location because the equivalent impedance to the earth at this point is much higher than at the substations.

For further information, see Appendix I.

### 4.2 Earth fault characterization of non-directly earthed power systems

When an earth fault occurs in a power system with non-directly earthed neutral, the EPR will be very small due to the small amplitude of the fault current. However, double earth faults may also occur. In that case the fault current will be much higher and result in a substantial EPR at both fault locations.

### 4.3 Earth potential rise (EPR)

When a single earth fault on a power line of a network with directly earthed neutral or a double earth fault on power line(s) of a network with non-directly earthed neutral occurs, a large EPR will appear at the tower, maybe tens of kVs. The EPR, as a general term, involves the two kinds of potential rise as explained in the following.

#### 4.3.1 Tower-earthing potential rise (T-EPR)

The tower potential rise is the potential of the earthing (footing) of tower with respect to the remote earth occurring during earth fault.

The amplitude of the T-EPR depends on a number of different factors such as:

a) earth fault current amplitude;

b) earth resistance of the pole;

c) aerial and underground earth wires, if applied;

d) distance to the feeding power stations;

e) span between the towers.

The factors mentioned in items d) and e) have of secondary importance.

NOTE 1 – When the power line is equipped with aerial or underground earth wires, the majority of the fault current returns through these wires and only a fraction of the earth fault current flows through the tower footing. The T-EPR can be characterized by the product of that fraction ($3I_0E$) of the zero-sequence component ($3I_0$) of the earth fault current that is passing through the tower footing, and the earthing resistance (R) of the tower, i.e., $3I_0ER$.

The T-EPR may be calculated or preferably measured in order to determine, whether special arrangements are not needed, which is unusual; see Appendix I.

NOTE 2 – When the power line is not equipped with earth wires, the whole of the fault current flows through the tower footing. The T-EPR can be calculated by the product of the zero-sequence component ($3I_0$) of the earth fault current, and the earthing resistance (R) of the tower, i.e., $3I_0R$.

The T-EPR shall be calculated for each given case by considering the actual conditions of the tower holding the base station.

#### 4.3.2 Zone of the earth potential rise (Z-EPR)

The zone of the earth potential rise (Z-EPR) is that area surrounding the tower of the power line where earth potential with respect to the remote earth occurs in case of single phase to earth fault, or in case of non-directly earthed network, double earth fault. This potential falls more or less rapidly in the earth ("potential funnel") as the distance from the tower footing increases. The magnitude and the way of decrease of the potential depends on the following factors:

a) the magnitude of the T-EPR causing the Z-EPR;

b) the geometry (size and structure) of the earthing system;

c) soil characteristics (geological nature, stratification, etc.).

More detailed characterization of the Z-EPR is given in Appendix III.

## 5 Power supply

The RBS equipment may be powered in the following ways:

1) From the LV network through an isolating transformer in order to separate the EPR area from the surrounding: This is most commonly used.

2) From a MV power network: In this case you can use the MV/LV transformer as isolation between the EPR area and the surrounding.

3) From the HV power line itself for example through capacitive voltage divider or inductively coupled loop: This method is expensive and hardly used.

For further information, see Appendix II.

### 5.1 Feeding from the LV network

Figure 1 shows the arrangement, when the equipment cabinet is powered from the LV network.

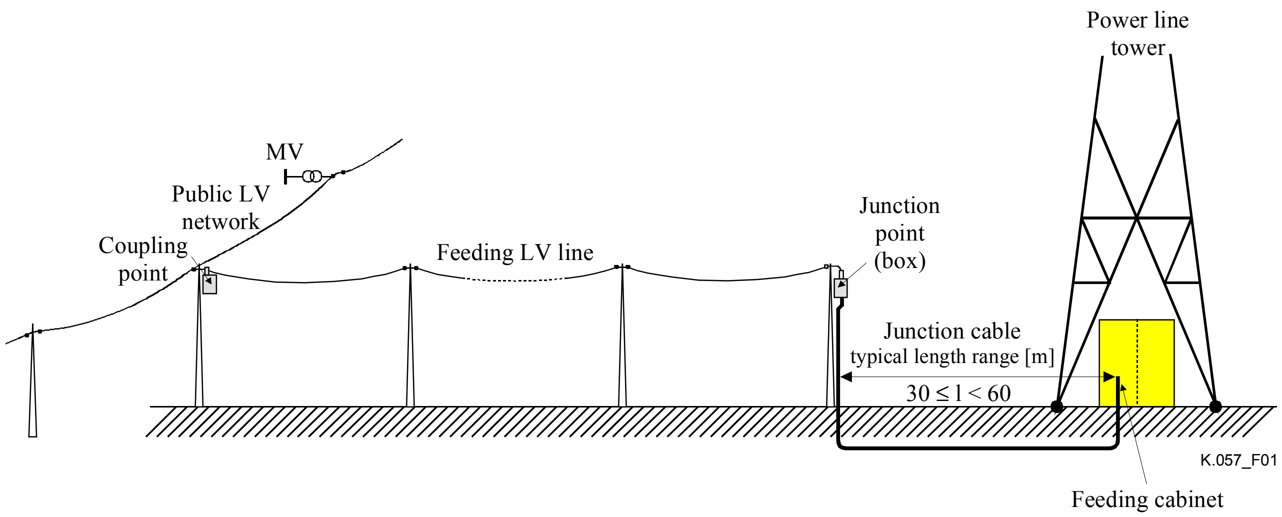



**Figure 1/K.57 – Typical arrangement of LV feeding**

Apart from what is described in the different options below, the following shall be observed:

- The cable shall not be stapled towards earthed parts in the transformer cabinet.
- The cable shall approach the cabinet perpendicular to the power line in order to avoid induced voltages.
- If the ground does not allow buried cable, aerial cable may be used.
- In order to protect the LV network, other measures have to be fulfilled that may be required by the LV network operator.
- As an alternative to a LV cable in plastic pipe, a MV cable which has the required insulation level, may be used for power supply. This shall be installed at least 50 m nearest to the tower. The MV cable shall not contain screen, i.e., MV cable manufactured without screen for this purpose is required.

The applicable protection practice, such as the way of connecting and selecting SPDs, is significantly affected by the feeding arrangement, especially the structure of the junction cable that together with the isolating transformer are commonly protected with the SPDs applied at the feeding cabinet of the RBS.

### 5.1.1 Options for the junction cable structure

The junction cable can be classified in two main categories according to the absence or presence of screen. It is preferred to be underground, but it may be overhead.

#### 5.1.1.1 Junction cable without metallic screen and neutral

In this case the metallic parts of the cable are only the three phase conductors. The voltage stresses (lightning impulse and 50-Hz potential rise) occur between the phase conductors and the earth. Regarding the ways of providing the appropriate insulation with respect to the earth, the options are the following:

a) LV three-core cable with additional increase of isolation to earth: The additional isolation shall be provided by insulating jacket on the cable or placing the junction cable in watertight insulating tube.

b) MV cable without metallic screen: In this case, the required isolation to earth is provided by essentially the core insulation itself, which is further increased by the plastic sheath (jacket) of the cable.

NOTE 1 – MV cables with the required voltage level (10 kV or above) are generally manufactured with metallic screened cores. Therefore, the cable without screen may be manufactured by special order.

NOTE 2 – The required MV cable may be three single-core cables (typical for voltage levels of 20 kV or above).

#### 5.1.1.2 Junction cable with metallic screen or neutral

In this case the typical cable is the LV three-conductor cable with concentric copper wire screen around the core bundle. When a four-core screened LV cable is used, the neutral conductor shall be bonded to the screen at the terminals of the junction cable. According to the protection principle, the screen is earthed at the junction point (outside the EPR zone), thus the voltage stresses (lightning impulse and 50-Hz potential rise) occur between the screen and the earth especially in the vicinity of the tower. The required isolation to earth shall be provided by additional insulating jacket on the cable or placing the junction cable in watertight insulating tube.

NOTE – The screen carries the surge current diverted by the MV SPD; thus, its total cross-sectional area shall be at least 35 $mm^2$.

### 5.1.2 Options of protection schemes at the feeding cabinet and junction point

Three options are recommended corresponding to the different feeding arrangements.

#### 5.1.2.1 Scheme for junction cable without metallic screen and neutral

The type and ways of connection of SPDs are in case of junction cable without metallic screen and neutral (see Figure 2, Option 1):

1) At the feeding cabinet, MV SPD (e.g., MOV) is connected between each phase conductor and the tower earthing.

2) At the junction point, LV SPD is connected between each phase conductor and the earth.

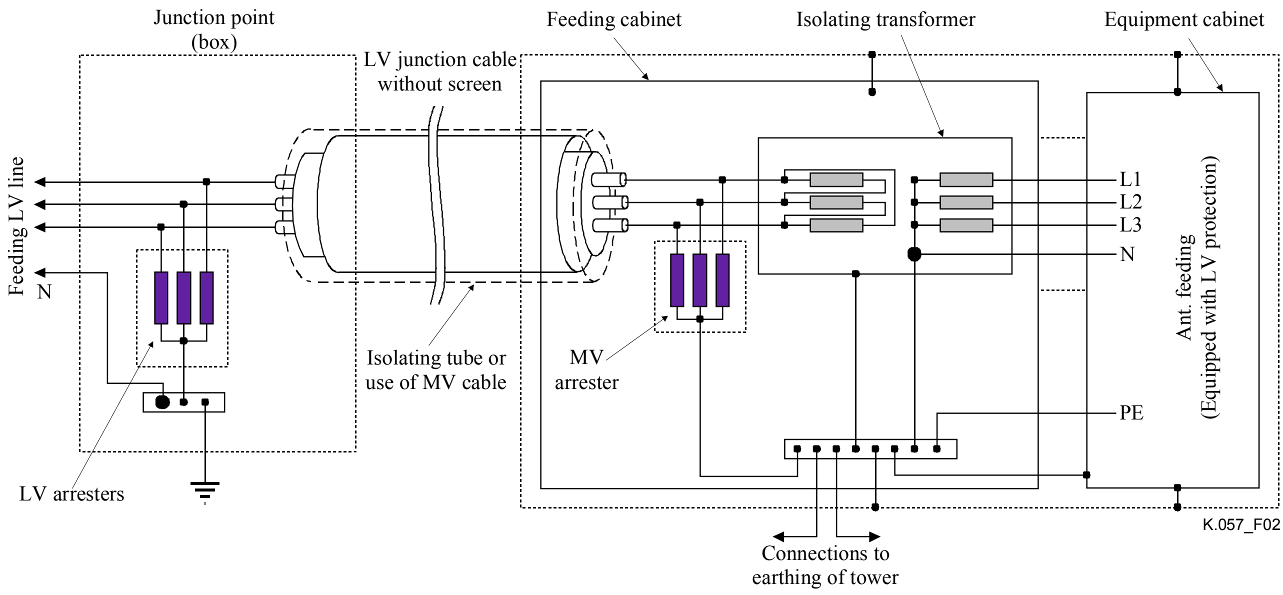



**Figure 2/K.57 – Junction cable without screen protected by MV arresters at the feeding cabinet and LV SPD at the junction box connected between each phase conductor and the earth: Option 1**

#### 5.1.2.2 Scheme for junction cable with metallic screen or neutral

In case of junction cable with metallic screen with or without neutral, the type and ways of connection of SPDs are classified in the following two options:

a) *Applying MV SPD arrester only to the screen*

According to this protection scheme the type and ways of connection of SPDs are as follows (see Figure 3, Option 2):

1) At the feeding cabinet a single MV SPD arrester is connected between the screen and the tower earthing.

2) At the junction point the screen is directly earthed and no LV SPD at all is applied.

NOTE 1 – When applying this protection scheme, it is assumed that the voltages of the phase conductors are, practically, equalized with the voltage of the screen due to the close inductive and capacitive coupling between the screen and the phase conductors.

b) *Applying the combination of MV SPD arrester and LV SPDs*

According to this protection scheme the type and ways of connection of SPDs are as follows (see Figure 4, Option 3):

1) At the feeding cabinet a single MV SPD arrester is connected between the screen and the tower earthing, and LV SPDs are connected between each phase conductor and the screen.

2) At the junction point the screen is directly earthed, and LV type SPD is connected between each phase conductor and the screen.

NOTE 2 – When applying this protection scheme, the voltage equalizing between the screen and the phase conductors is ensured by the LV SPDs.

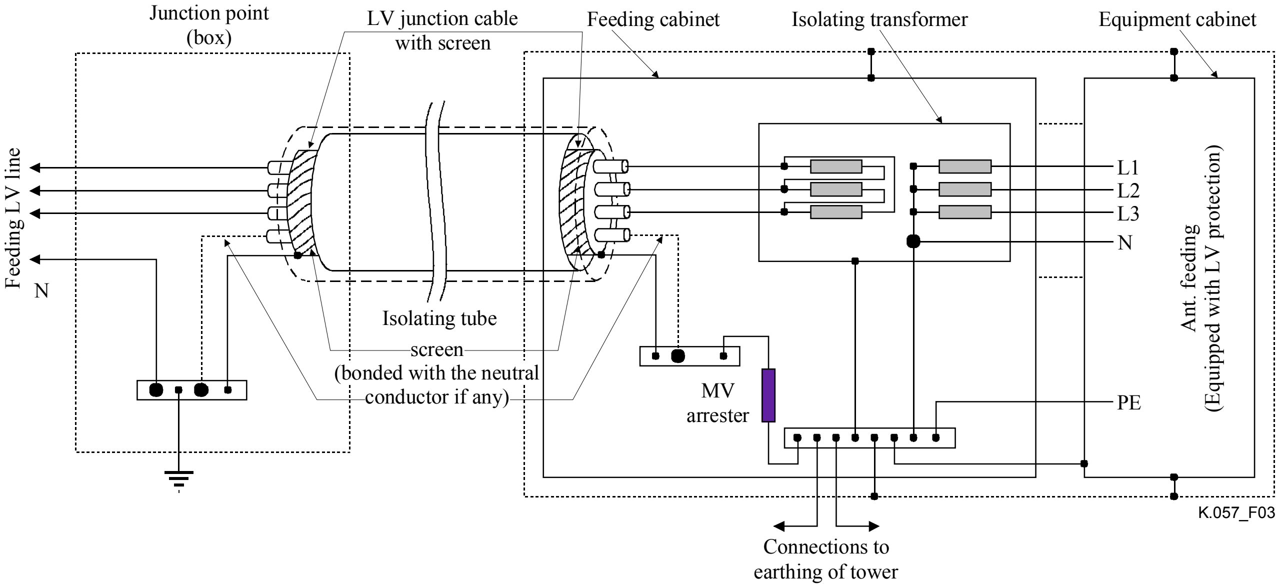



**Figure 3/K.57 – Junction cable with screen protected by a single MV arrester connected between the screen and the tower earthing at the feeding cabinet and the screen is directly earthed at the junction point: Option 2**

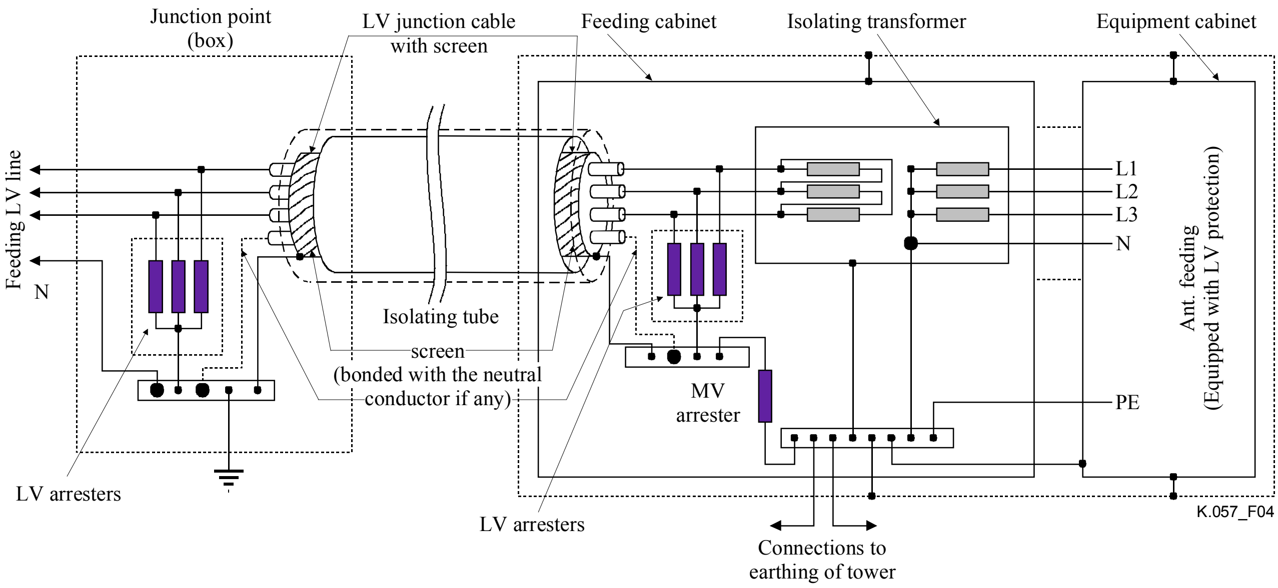



**Figure 4/K.57 – Junction cable with screen protected by a single MV arrester connected between the screen and the tower earthing at the feeding cabinet and the screen is directly earthed at the junction point; in addition LV arresters are connected between each phase conductor and the screen at both the feeding cabinet and the junction box: Option 3**

### 5.1.3 Protection of the feeding line including the coupling point

The connecting line, between the junction and coupling points including the coupling point itself, should be protected according to the requirements of low-voltage power distribution systems such as given in IEC 61643-1 and IEC 61643-12. The protection scheme, especially the bonding and earthing conditions, shall also comply with the requirements for subscriber premises given in ITU-T Rec. K.31.

### 5.1.4 Protection of MV/LV transformer located in the zone of EPR

In case of RBS fed from MV/LV transformer located in the zone of EPR, the following means of protection shall be applied:

a) Equalizing through a copper wire of at least 35 $mm^2$ between the HV tower earthing and the earthing bar at the transformer;

b) MV SPD (e.g., MOV or similar) arrester connected between each phase conductor on the MV side and the earthing bar at the transformer;

NOTE 1 – This is normally applied to protect the transformer against lightning surges coming from the MV line.

c) LV-type SPD is connected between each phase conductor and the tower earth in the feeding cabinet of the RBS.

NOTE 2 – This LV-type SPD is applied for the protection of the equipment of the radio base station.

### 5.1.5 Protection when feeding from MV/LV transformer located outside the EPR zone and only serving the RBS

In case of RBS fed from MV/LV transformer located out of the EPR zone, but not very far (less than 50-60 m), the applicable protection scheme is the following:

a) The LV/LV isolating transformer shall be installed in the feeding cabinet.

b) The LV feeding line is considered as junction section; therefore it shall be protected according to point 5.1.2 using that option, which corresponds to the actual installation.

NOTE 1 – The protection scheme given in 5.1.2.2 a) is not recommended especially when the power metering facilities are installed at the location of the MV/LV transformer.

c) MV SPD shall be connected between each phase of the MV side and the earthing at the MV/LV transformer.

NOTE 2 – This is normally applied to protect the transformer against lightning surges coming from the MV line. The MV SPD may not be necessary when the transformer is fed by well-shielded MV cable.

## 5.2 Feeding from a MV network

As an alternative the equipment cabinet may be powered from a distribution network, typically 10 to 20 kV. In this case you get a higher insulation level on cables and transformer automatically. The isolating transformer is then substituted with a distribution transformer; see Figure 5. However, the screen of the MV cable should be isolated and protected by MV-type SPD against the tower earthing according to 5.1.2.2 and Figure 3. The required screen-to-earth isolation shall be provided by additional insulating jacket on the MV cable or placing the cable in watertight insulating tube along the junction section (see Table III.2).

## 5.3 Feeding from the HV line

No method is known at present that is justified technically and economically. This method of feeding the RBS is therefore not recommended.

# 6 Requirements on the antenna system

Following are the requirements on the installation of the RBS.

- Coaxial cables between equipment cabinet and antenna(s) shall be placed in a suitable way in dedicated cable ducts or clamped to the tower structure, in order that maintenance and fault repair of the equipment and the towers are not complicated.
- Underground cables between equipment cabinet and tower shall be laid in isolated pipes.

- Communication equipment, antenna and accessories shall be type-approved according to national regulations and requirements.
- The antennas will be placed in strong electric fields, where they may be exposed to corona and sparks. The owner of the antennas must be aware of this in order to avoid degraded function of the antennas.
- Depending on the type of tower and the location of the antenna(s), the levels of electric and magnetic field strengths from the power line may be achieved from the power company.
- If antennas are placed above the overhead earth wires, they shall be provided with lightning protection; see ITU-T Rec. K.56.

## 7 Telecommunication cables

In order to avoid problems of induction and EPR at earth faults, the telecommunication should use metal-free fibre optic cables or radio links; see Figures 6 and 7.

If metallic cables are used for the telecommunication, they shall be constructed and connected under the same conditions as the LV power supply. It means that they shall:

- have an adequate isolation level;
- be laid in an insulating, water-tight, plastic tube;
- be terminated via a transformer;
- be provided with feasible over-voltage arrestors.

The transition point should not be closer than the point, where the EPR is expected to be 650 V. This voltage level is the limit for short-term overvoltage with a duration of $\leq$0.5 s. Other levels may be chosen with reference to ITU-T Rec. K.33.

See also ITU-T Rec. K.8.

## 8 Earthing arrangements

The earthing arrangements are important for the safety and protection of the equipment. The following shall be applied:

- Metallic parts of the antenna shall be bonded to the coaxial screen and earthed to the metallic structure of the tower.
- The other end of the screen shall be connected to the earth of the equipment cabinet.
- PGE system shall be laid about 0.3 m deep around the equipment cabinet for the control of the touch and step voltages. This can be implemented as either single or double frame system corresponding to the actual potential level to be controlled. The grading electrodes shall be bonded both to the cabinet earth and to the legs of the tower at least at two corners (see Figure III.14). The bonding shall be applied diagonally, when the cabinet is located between the legs (see thick line bonds in Figure III.15). Guidance is given for the proposed locations of the grading frames in Appendix III (see III.2.2 b) and the above-referred figures).
- The earthing system of the equipment and transformer cabinets shall be bonded to the earthing of the tower through a copper wire of at least 35 $mm^2$. Note that this may require cathodic protection when different metals are used in the earthing network.

## 9 Installation and maintenance

Installation and maintenance of the equipment located in the tower such as antennas and cables, are restricted to people specially trained with knowledge about electric and magnetic fields from power lines, normally linesmen of the power company. However, special caution has to be observed concerning the risk of exposure to electromagnetic fields from the RBS antenna(s). For guidance, see ITU-T Rec. K.52.

The installations on ground are normally done by specially instructed RBS people.

National regulations may require further restrictions on this type of work.

## 10 Examples of installations

Figures 5 to 7 give examples of installations.

Figure 8 shows an installation where unauthorized access is prevented.

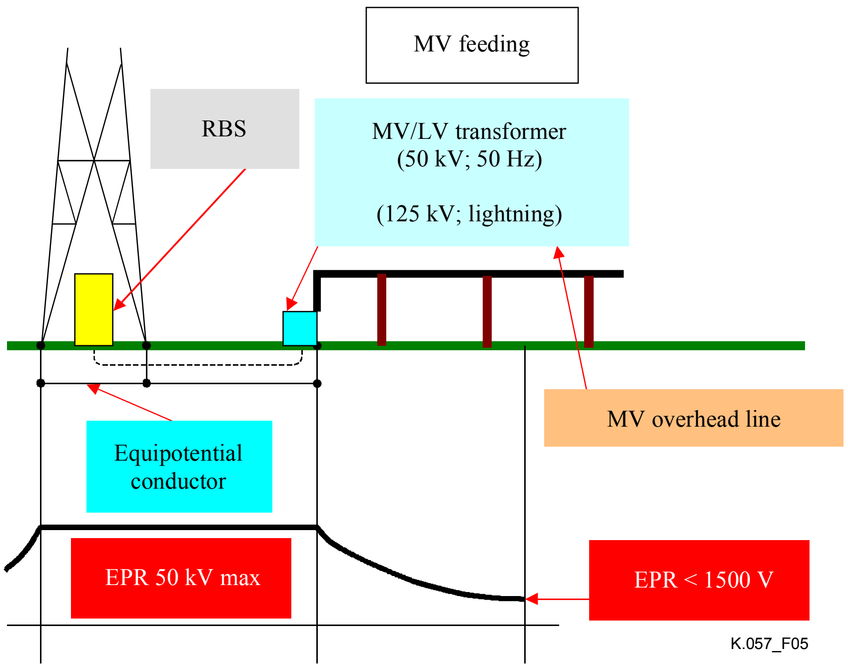



**Figure 5/K.57 – MV power feeding of RBS**

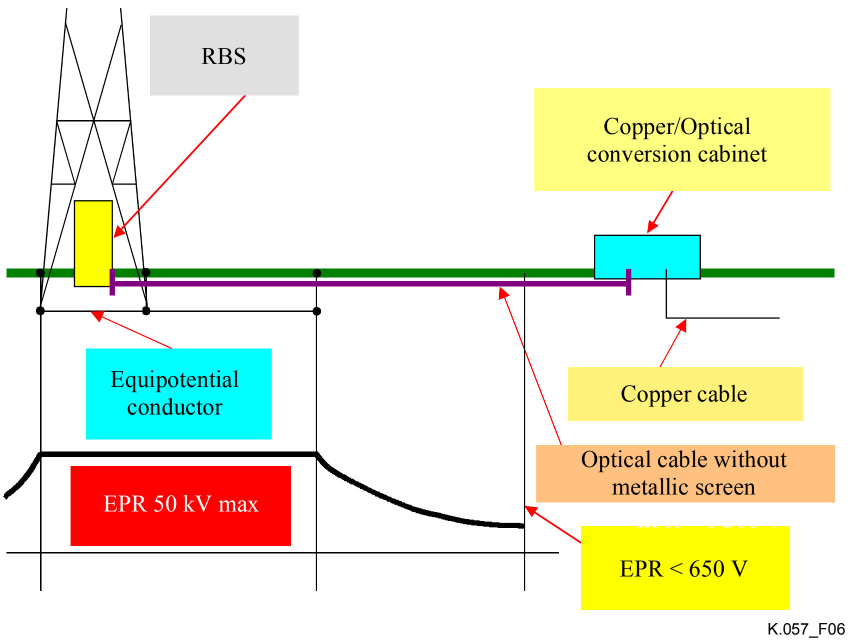



**Figure 6/K.57 – Connection to a telecommunication network via optic fibre**

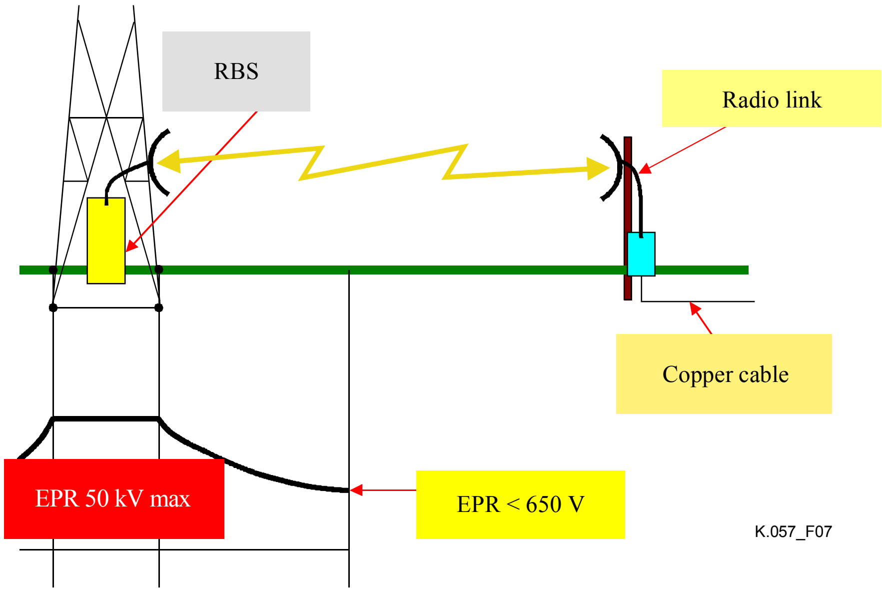



**Figure 7/K.57 – Connection to a telecommunication network via radio link**

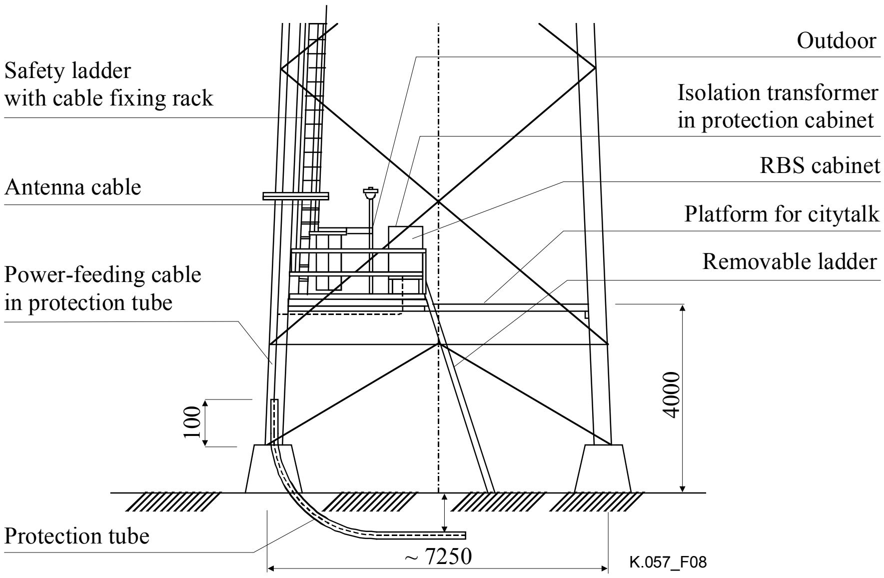



**Figure 8/K.57 – Elevated location of RBS in power tower**

# Appendix I

## Guide on the coordination of the isolation level required for power supply circuit and the potential rise of power line towers

### I.1 Scope of the investigation

The tower-earthing potential rise (T-EPR) investigations presented in this appendix aim at sensitivity analysis performed by a multiconductor solution technique [I.1], to provide guidance on the identification of the potential relevant to given conditions in practice.

The analysis performed covers the following optional conditions:

1) Length, L, of the power line (km): 15 or 60;
2) Location of the fault: near the origin (km 1), middle (km L/2) or near the end (km L – 1) of the line, and also step-like varying;
3) Earthing resistance of the substations at the lines origin/end (Ω): 0.1/0.1 or 0.1/1;
4) Way of supply: single end (1 × 10 kA) or both ends (2 × 5 kA);
5) Shield-wire (sw) and counterpoise (cp) options: two sw, only one sw or one sw + cp;
6) Earthing resistance of the tower (Ω)/soil resistivity (Ωm): 8/50, 25/500 or 50/2500;
7) Mean span between the towers.

The results are related to phase-to-earth fault current with a magnitude of 10 kA, which is considered as a base. Considering that the investigated phenomenon is practically linear, the obtained T-EPR values can be recalculated to any actual earth fault current proportionally to the ratio of that earth fault current and the 10-kA basic current.

### I.2 Investigated options, parameters

#### I.2.1 Line structure options

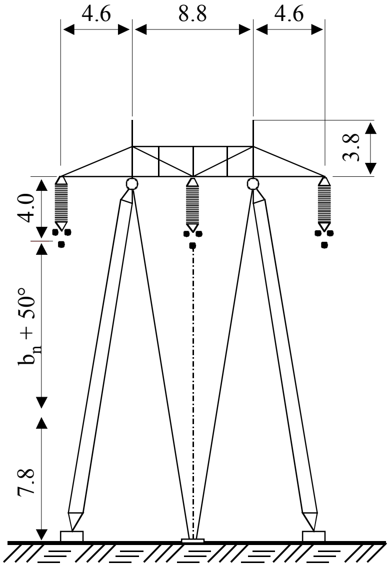
The conductor arrangements of the investigated 400-kV power lines are identified in Figure I.1. The shown two-line arrangements are investigated according to the following three options:

A Horizontal phase conductor arrangement with ***two shield-wires (sw)*** (Figure I.1 a);

B Compact triangular phase conductor arrangement with ***one shield-wire (sw)*** (Figure I.1 b);

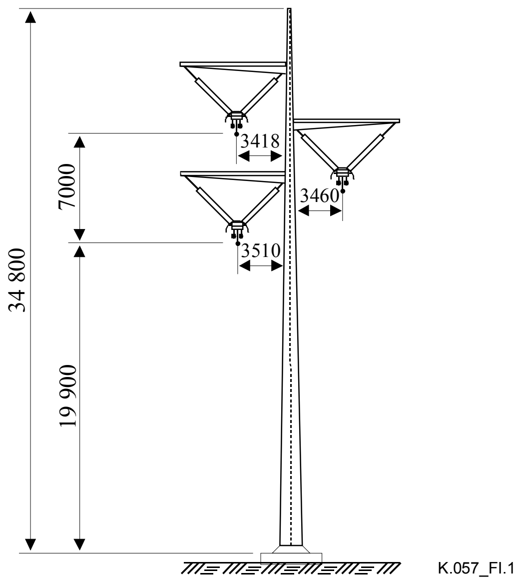
C As in point B but with ***one shield-wire and one counterpoise (cp)***.

The counterpoise is a bare copper wire of 35 $mm^2$ laid along the route of the line in about 0.5-m depth. The towers are not metallically connected to the cp. However, the spark gaps, installed between the tower earthing and the cp, are striking and connecting the tower to the cp when T-EPR exceeds about 3 kV. Thus, for this condition, no connection is assumed between the tower earthing and the cp, except at the faulty tower.




Structure of the phase conductor system: $3 \times (3 \times 593)\ mm^2$
Structure of the shield (earth) conductor system: $2 \times 142\ mm^2$
$b_n + 50° = 12.72$ m

**a) Arrangement of line with twin shield-wires (case A)**




Structure of the phase conductor system: $3 \times (3 \times 593)\ mm^2$
Structure of the shield (earth) conductor system: $1 \times 241\ mm^2$
Counterpoise can additionally be applied in a depth of 50 cm.

**b) Arrangement of line with single shield-wire (case B) which may be equipped with counterpoise as well (case C)**

**Figure I.1/K.57 – Line structures assumed in the investigations (normal span: 333 m)**

The assumed mean span between the towers is 333 m (1/3 km). Investigations have also been made for mean spans of 200 m and 500 m for the checking of the effect of the span length.

The simulation calculations have been performed for line lengths of:

– Code L15: "short line" of 15 km;
– Code L60: "long line" of 60 km.

### I.2.2 Parameter options

#### I.2.2.1 Substation earthing

The following two options are simulated regarding the earthing resistances of the substations at the line ends:

– Case code S1: low resistance at both ends, i.e., 0.1 Ω/0.1 Ω;

– Case code S2: low resistance at the origin (S end at km 0) and higher impedance at the other (R at km L) end, i.e., 0.1 Ω/1 Ω.

#### I.2.2.2 Tower-earthing resistance and specific earth resistivity

The specific resistivity of the earth is affecting two kind of parameters used in the simulations. The specific resistivity of the surface soil layer essentially influences the resistance of the tower earthing. The earthing resistance – assuming a given earthing electrode structure – is, in principle, proportional to the specific resistivity of the soil embedding the electrode system.

The specific resistivity of the deeper earth layer has a certain effect on the series self- and mutual impedances, both with earth return, of the line. The effect is quite small for self-impedance and also for mutual impedance, when the span between the conductors is not big, such as the spacing between the phase and shield-wires.

It follows that no strict but certain correlation should be assumed between tower-earthing resistance and the specific earth resistance. Therefore, the following options are considered in the simulation study:

| Case code | Resistivity | |
|---|---|---|
| | Tower earthing [Ω] | Specific [Ωm] |
| R1 | 8 | 50 |
| R2 | 25 | 500 |
| R3 | 50 | 2500 |

#### I.2.2.3 Fault locations

The calculations have been performed for every simulated option for fault location at the middle (km L/2) of the line.

In case of one-sided (1 × 10 kA) current injection, the following fault locations have also been studied:

– at 1-km distance from each line end;

– varying with 1-km steps for the 15-km long line and 2-km steps for the 60-km long line.

#### I.2.2.4 Magnitude and way of fault current injection

The potential rise is linked with the $I_0$ zero-sequence current component. In case of phase-to-earth fault, the $3I_0$ zero-sequence current is equal to the fault current at the faulty point. In the studies $3I_0 = 10$ kA fault current magnitude is assumed at the faulty point. Along the line, $I_0$ current is assumed in each phase, thus the effects of the positive and negative sequence current components are neglected. Practically it means the consideration of the "average" effects between the phase and shield-wires, or in other words the neglecting of the small differences due to the fault occurrences in different phases.

Regarding the current distribution between the line sections at both sides of the faulty point, the following two extreme conditions are simulated:

– 1 × 10 kA current flow only in one direction, i.e., between km 0 and the faulty point;

– 2 × 5 kA current flow half-by-half, i.e., $3I_0 = 5$ kA both between km 0 and the faulty point, and the faulty point and km L line sections.

In an actual case, the current distribution is affected by the relative location of the faulty point, but it is basically determined by the zero-sequence impedances of the substations, which is highly influenced by the transformers with earthed neutral located in the substations at the line ends. However, the one-side current flow occurs, at least temporarily, during the tripping process, due to the non-simultaneous switch-off at both ends of the faulty line.

## I.3 Analysis of the results

### I.3.1 Qualitative analysis

First of all, a qualitative analysis of the results on the tower potential rise has been made to identify the relative importance of the different conditions listed in I.1. The key result is the potential of the shield-wire(s), because, due to the metallic connection between tower and shield-wires, the potential rise of a given tower is identical with the potential of the shield-wire at the place of the tower in question.

This qualitative analysis is mainly made by the use of plots containing the most representative results of the simulations.

The highest potential rise occurs, of course, at the faulty tower (see Figures I.2, I.3 and I.4). The shield-wire potential is decreasing with increase of the distance from the faulty point. The shield-wire potential tends to drop to zero in that side of the line from where no zero-sequence current is fed to the fault (see the right side plots in Figures I.2 and I.3). In contrast to this, the shield-wire potential tends to drop to zero at first, and behind this section it is increasing, when approaching the substation, which feeds zero-sequence current to the fault (see the left side plots in Figures I.2 and I.3 and also both side plots in Figure I.4).

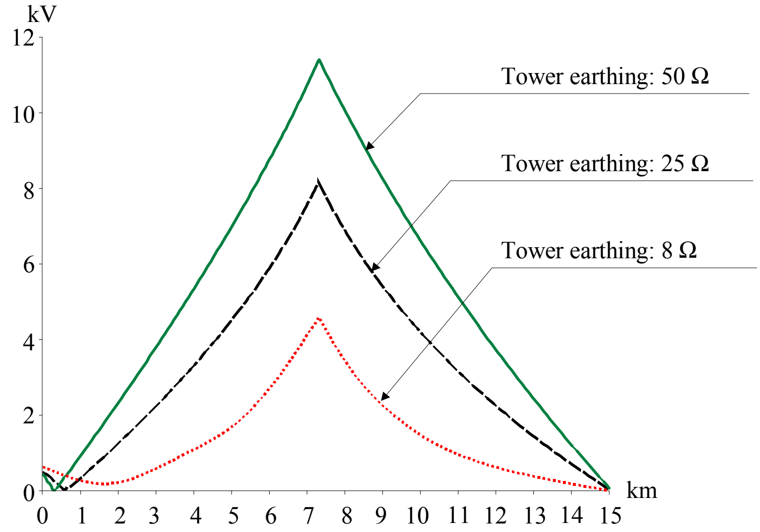
Regarding the effect of the fault location, it can be stated that the potential rise of the faulty tower practically does not vary except near the line ends (in the end-effect zones), where the potential decreases to approach the potential rise relevant to the substation earthing (see Figure I.5). It is worth mentioning that this decreasing tendency is strictly valid only with the assumption that the earth fault current magnitude is constant. In practice, magnitude of the earth fault current increases when the fault occurs closer to the substation. These counter-effects can mainly compensate each other in practical cases.

The effect of the mean span on the tower potential rise of the faulty tower vs. the fault location is demonstrated for line structure having only one shield-wire in Figure I.6. It can be seen that the tower potential rise increases with the increase in the mean span.

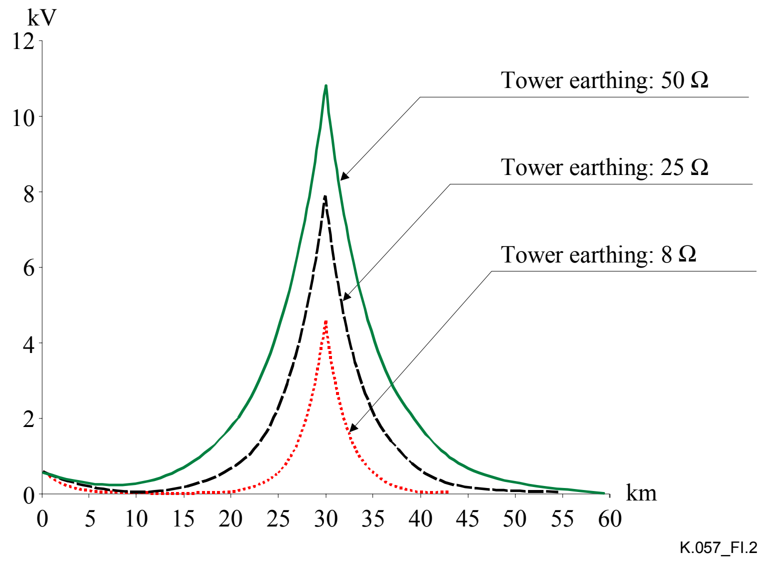
For the sake of completeness, the shield-wire current profile is plotted in Figure I.7. The following tendencies can be observed, when zero-sequence current ($3I_0$ = 10 kA) is fed only from one (left) side:

- Shield-wire current is flowing in both directions, but significantly higher on the feeding side.
- Shield-wire current tends to drop to zero in that side of the line from where no zero-sequence current is fed to the fault.

The shield-wire current decreases to its induced steady value first, and behind this, generally increases in the end-effect zone close to the substation, which feeds the zero-sequence current to the fault.



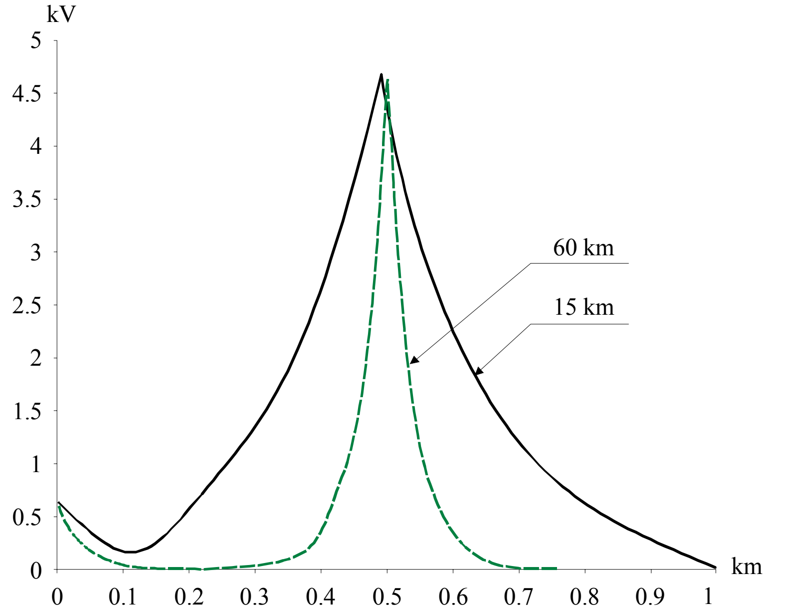

**a) Line length: L = 15 km**




**b) Line length: L = 60 km**

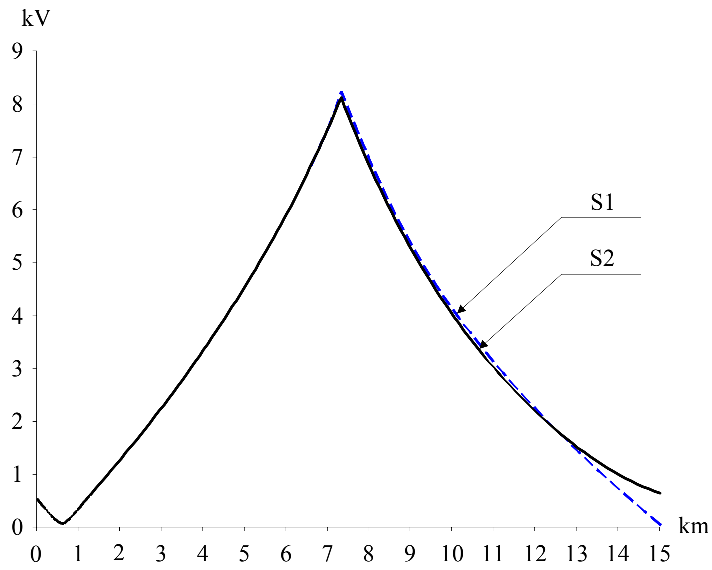
B 400-kV line with 1 shield-wire without counterpoise
S1 Substation earthing: 0.1 Ω/0.1 Ω
F2 Fault location: L/2 km (F2)
1 × 10 kA current flow, only from the left side of the faulty point

**Figure I.2/K.57 – Shield-wire potential profile vs. length, parameter: Tower-earthing resistance**

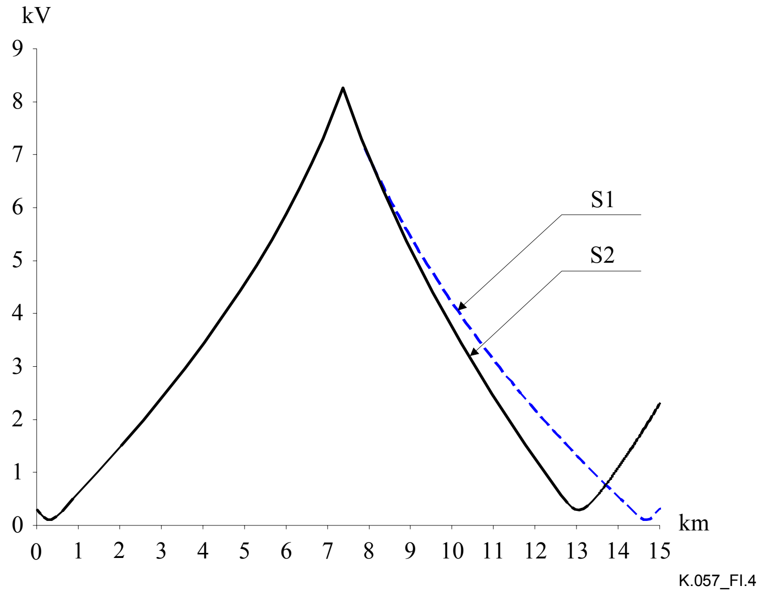



B 400-kV line with 1 shield-wire without counterpoise
S1 Substation earthing: 0.1 Ω/0.1 Ω
F2 Fault location: L/2 km (F2)
R1 Tower-earthing resistance: 8 Ω
1 × 10 kA current flow, only from the left side of the faulty point

**Figure I.3/K.57 – Shield-wire potential profile vs. length, with normalized length scale parameter: Line length**



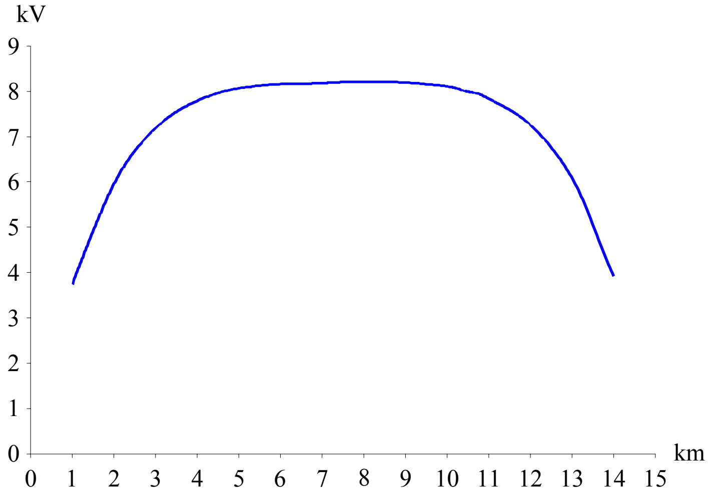

**a) 1 × 10 kA current flow, only in the left side of the faulty point**



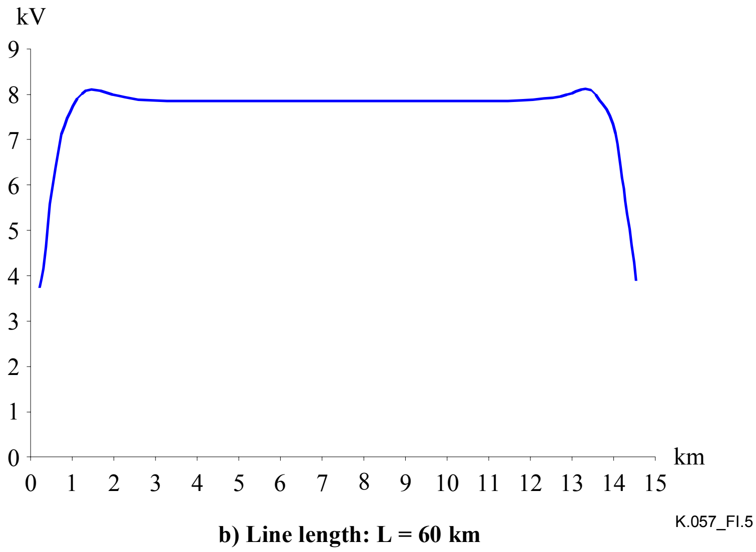

**b) 2 × 5 kA current flow, in both sides of the faulty point**

| | |
|---|---|
| B | 400-kV line with 1 shield-wire without counterpoise |
| F2 | Fault location: L/2 km (F2) |
| R2 | Tower-earthing resistance: 25 Ω |

**Figure I.4/K.57 – Shield-wire potential vs. length profile, parameter: Earthing resistances of the substations S1 = 0.1 Ω/0.1 Ω, S2 = 0.1 Ω/1 Ω**



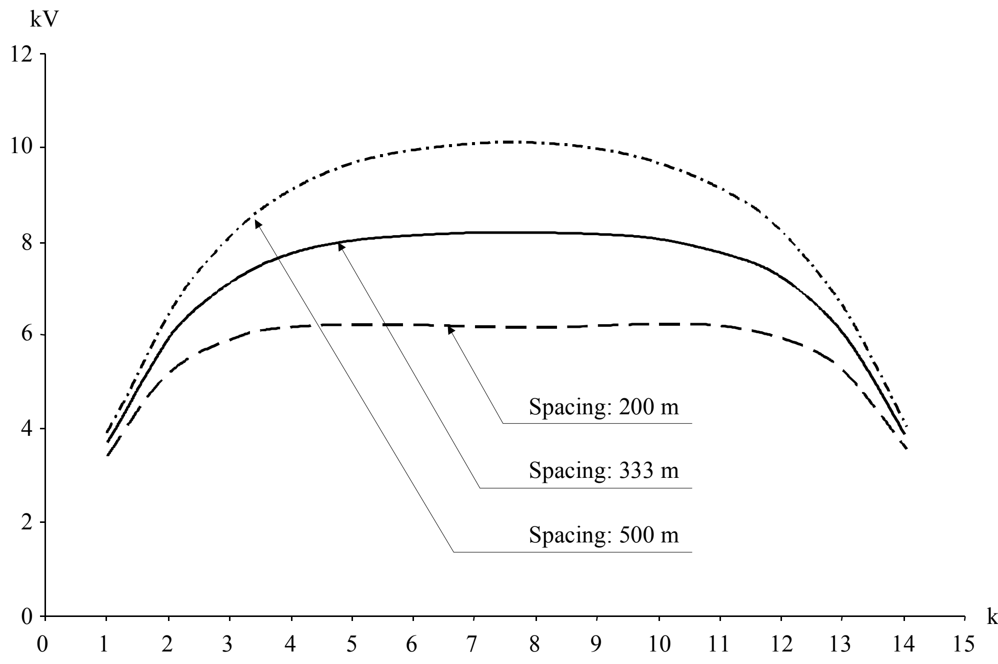

**a) Line length: L = 15 km**



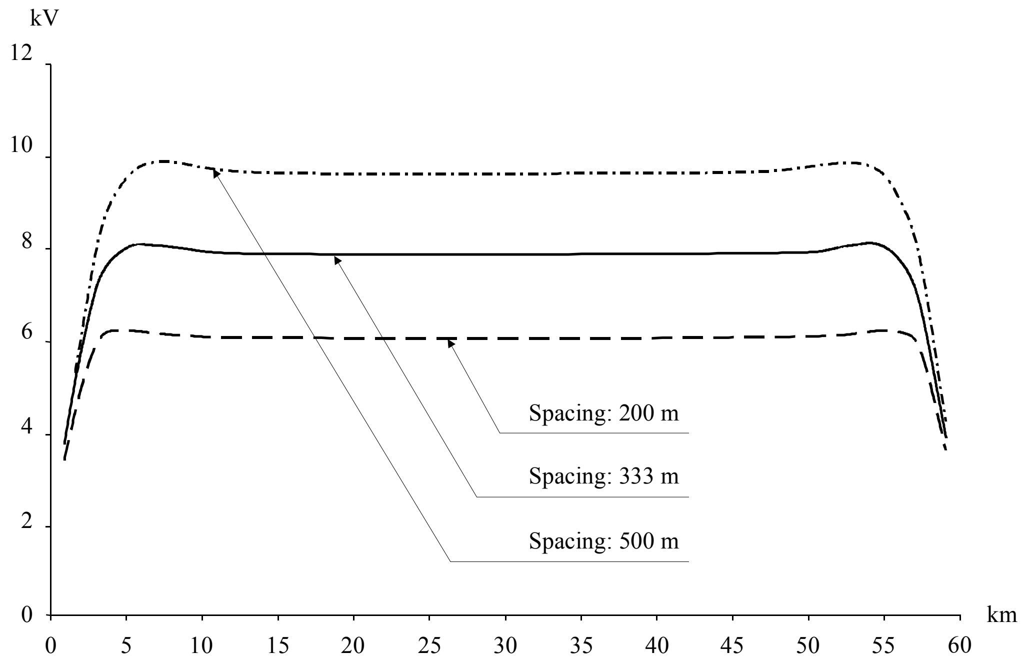

**b) Line length: L = 60 km**

B 400-kV line with 1 shield-wire without counterpoise
S1 Substation earthing: 0.1 Ω/0.1 Ω
R2 Tower-earthing resistance: 25 Ω
1 × 10 kA current flow, only from the left side of the faulty point

**Figure I.5/K.57 – Tower potential rise of the faulty tower vs. the fault location**



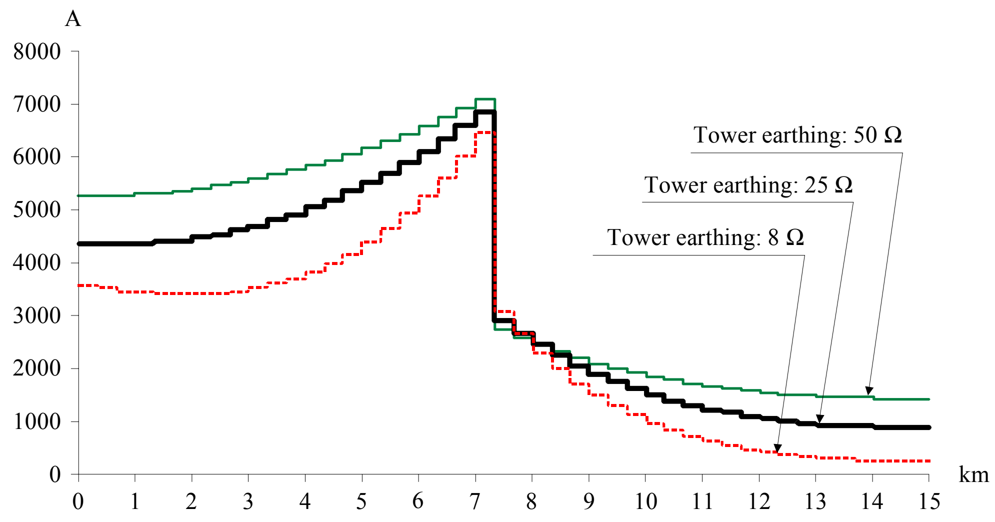

**a) Line length L = 15 km**



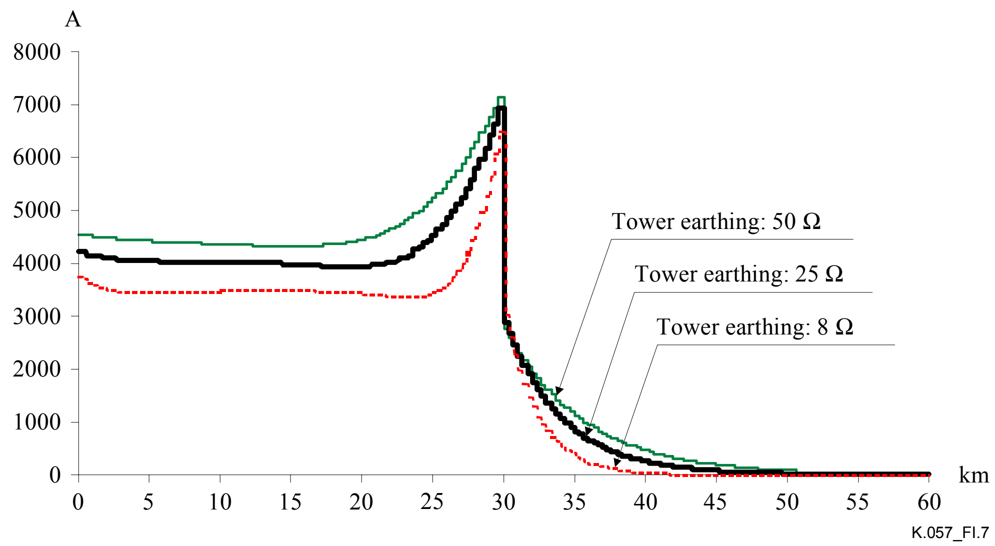

**b) Line length L = 60 km**

B 400-kV line with 1 shield-wire without counterpoise
S1 Substation earthing: 0.1 Ω/0.1 Ω
R2 Tower-earthing resistance: 25 Ω
1 × 10 kA current flow, only from the left side of the faulty point

**Figure I.6/K.57 – Effect of the mean span (parameter of the curves) on the tower potential rise of the faulty tower vs. the fault location**




**a) Line length: L = 15 km**




**b) Line length: L = 60 km**

B 400-kV line with 1 shield-wire without counterpoise

S1 Substation earthing: 0.1 Ω/0.1 Ω

F2 Fault location: L/2 km (F2)

1 × 10 kA current flow, only from the left side of the faulty point

**Figure I.7/K.57 – Shield-wire current profile vs. length**

### I.3.2 Quantitative analysis

The studied conditions and parameters can be classified accordingly to their relative importance on the tower potential rise magnitudes into the following three classes:

a) Negligible conditions and parameters are:

- Length of the line;

  (See Figures I.3 and I.8, which indicate only a very small increase in T-EPR for shorter line.)

- Earthing resistance of the substations;

  (See Figures I.4 and I.9.)

- Single (1 × 10 kA) or double (2 × 5 kA) sided fault (zero-sequence) current flow.

  (See Figure I.10.)

b) Deciding conditions and parameters are:

- Earthing resistance of the towers (average);

  (See Figures I.2 and I.8.)

- Shield-wire number (one or two) and use of counterpoise.

  (See Figure I.8.)

It is worth mentioning that the magnitude of the fault current belongs also to the deciding parameter. However, it is a design parameter, which should correspond to the actual value (range) when estimating the T-EPR relevant to a given case.

c) Corrective condition is the span between the towers. Its relative importance is demonstrated in Figures I.11 and I.12 for line lengths of 15 km and 60 km, respectively. The values of correction factor for the calculations of the tower potential of lines with different spans are given in Table I.2.

It is worth mentioning that the corrections needed in the tower potential rise due to the differences in the span are less than ±5% for lines equipped with shield-wire(s) and counterpoise, and less than ±25% for lines equipped only with shield-wire(s).

The tower potential rise values obtained from the simulations are given for the deciding conditions in Table I.1. These values are related to 10-kA earth fault current and span of 333 m as reference conditions. They can be recalculated to currents other than 10 kA proportionally to the current magnitude. Similarly, tower potential rise can be recalculated to span values other than the mean of 333 m, by its multiplication with the correction factors given in Table I.2.

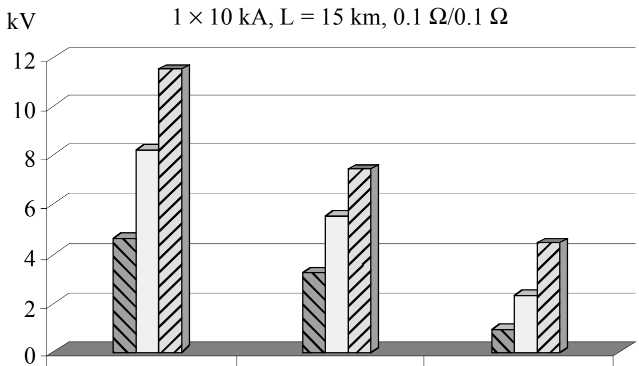
**Table I.1/K.57 – Potential rise of the faulty tower for the deciding conditions and parameters per 10-kA earth fault current**

| Earthing resistance [Ω] | Shield-wire configuration | | | | | |
|---|---|---|---|---|---|---|
| | 1 sw | | 2 sw | | 1 sw + cp | |
| | [kV] | [Deg.] | [kV] | [Deg.] | [kV] | [Deg.] |
| 8 | 4.663 | 31.40 | 3.237 | 22.62 | 0.872 | 19.68 |
| 25 | 8.208 | 32.45 | 5.589 | 25.13 | 2.290 | 20.08 |
| 50 | 11.413 | 37.70 | 7.432 | 31.32 | 4.316 | 22.63 |
| sw shield-wire<br>cp counterpoise | | | | | | |

**Table I.2/K.57 – Correction factors for the tower potential rise of lines with different spans (Base: The tower voltage for a 333-m span)**

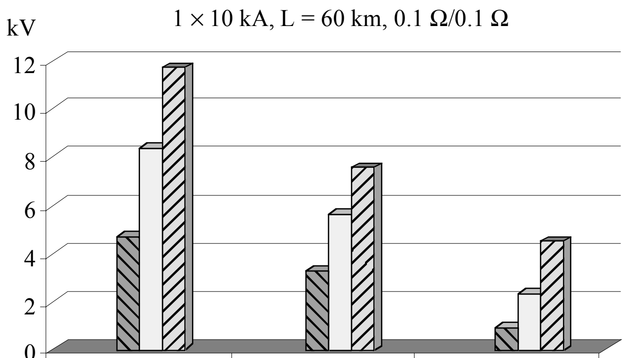
| Earthing wire structure | Spacing [m] | Line lengths [km] | | | | | |
|---|---|---|---|---|---|---|---|
| | | 15 | | | 60 | | |
| | | Tower-earthing resistance [Ω] | | | Tower-earthing resistance [Ω] | | |
| | | 8 | 25 | 50 | 8 | 25 | 50 |
| 1 sw | 200 | 0.77 | 0.76 | 0.77 | 0.78 | 0.77 | 0.77 |
| | 333 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| | 500 | 1.23 | 1.24 | 1.18 | 1.22 | 1.22 | 1.22 |
| 2 sw | 200 | 0.77 | 0.76 | 0.80 | 0.77 | 0.77 | 0.77 |
| | 333 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| | 500 | 1.24 | 1.21 | 1.14 | 1.22 | 1.22 | 1.22 |
| 1 sw + 1 cp | 200 | 0.95 | 0.92 | 0.89 | 0.95 | 0.92 | 0.89 |
| | 333 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| | 500 | 1.03 | 1.06 | 1.08 | 1.03 | 1.05 | 1.08 |

NOTE – 1) 400-kV line configuration.
2) Fault location: L/2 km.
3) 2 × 5 kA current flow, only from the left side of the faulty point.
4) Substation earthing: 0.1 Ω/0.1 Ω.




| | 1 sw | 2 sw | 1 sw + cp |
|---|---|---|---|
| 8 Ω | 4.663 | 3.237 | 0.872 |
| 25 Ω | 8.208 | 5.589 | 2.29 |
| 50 Ω | 11.413 | 7.432 | 4.316 |

**a) Line length: L = 15 km**



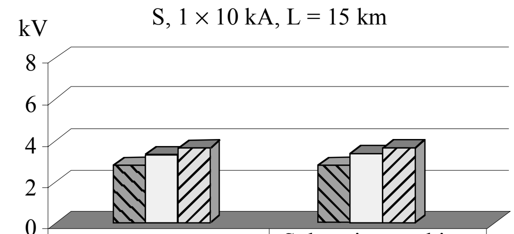

| | 1 sw | 2 sw | 1 sw + cp |
|---|---|---|---|
| 8 Ω | 4.64 | 3.2 | 0.87 |
| 25 Ω | 7.86 | 5.342 | 2.259 |
| 50 Ω | 10.803 | 7.28 | 4.157 |

K.057_FI.8

**b) Line length: L = 60 km**

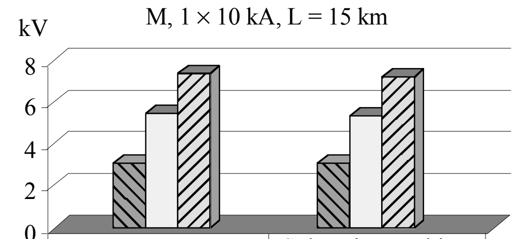
S1 Substation earthing: 0.1 Ω/0.1 Ω
F2 Fault location: L/2 km (F2)
1 × 10 kA current flow, only from the left side of the faulty point

**Figure I.8/K.57 – Potential rise of the faulty tower for different tower-earthing resistances and shield-wire/counterpoise options**



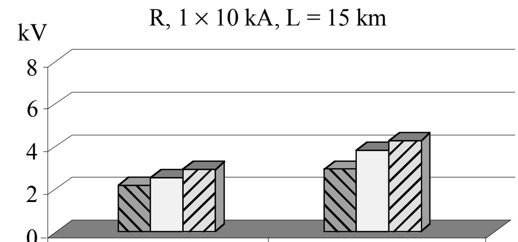

| | | Substation earthing resistance: 0.1/0.1 | Substation earthing resistance: 0.1/1 |
|---|---|---|---|
| ▧ | 8 Ω | 1.914 | 1.914 |
| □ | 25 Ω | 2.259 | 2.258 |
| ▨ | 50 Ω | 2.423 | 2.419 |

**a) Fault location at km 1**




| | | Substation earthing resistance: 0.1/0.1 | Substation earthing resistance: 0.1/1 |
|---|---|---|---|
| ▧ | 8 Ω | 3.237 | 3.232 |
| □ | 25 Ω | 5.589 | 5.492 |
| ▨ | 50 Ω | 7.432 | 7.273 |

**b) Fault location at the middle of the line**



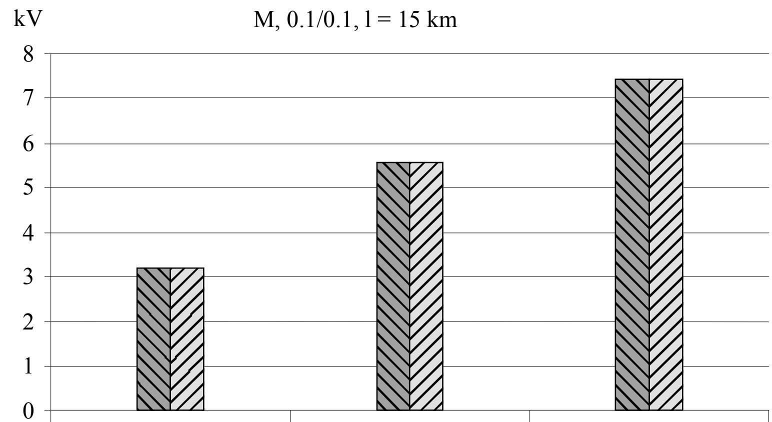

| | | Substation earthing resistance: 0.1/0.1 | Substation earthing resistance: 0.1/1 |
|---|---|---|---|
| ▧ | 8 Ω | 2.062 | 2.914 |
| □ | 25 Ω | 2.414 | 3.768 |
| ▨ | 50 Ω | 2.571 | 4.140 |

K.057_FI.9

**c) Fault location at km 14**

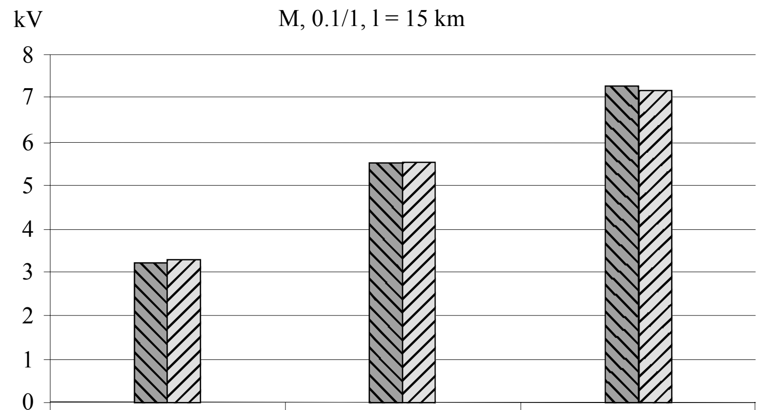
A 400-kV line with 2 shield-wires without counterpoise
R2 Tower-earthing resistance: 25 Ω
L15 Line length L = 15 km
1 × 10 kA current flow, only from the left side of the faulty point

**Figure I.9/K.57 – Potential rise of the faulty tower for different tower-earthing resistance and substation earthing resistance options**




| | 8 Ω | 25 Ω | 50 Ω |
|---|---|---|---|
| 1 × 10 kA | 3.237 | 5.589 | 7.432 |
| 2 × 5 kA | 3.236 | 5.589 | 7.431 |

**a) Substation earthing resistances S1 = 0.1 Ω/0.1 Ω**



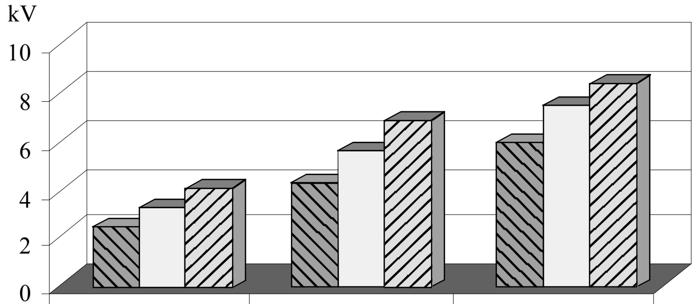

| | 8 Ω | 25 Ω | 50 Ω |
|---|---|---|---|
| 1 × 10 kA | 3.232 | 5.492 | 7.273 |
| 2 × 5 kA | 3.275 | 5.512 | 7.217 |

K.057_FI.10

**b) Substation earthing resistances S2 = 0.1 Ω/1 Ω**

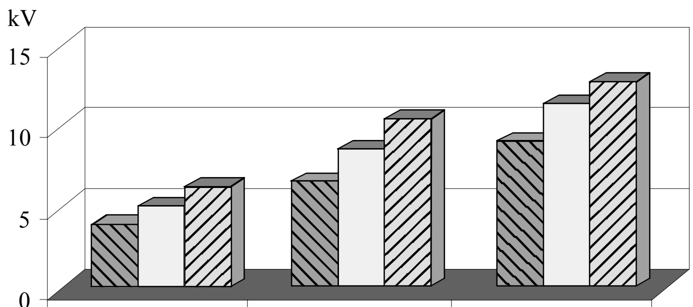
A 400-kV line with 2 shield-wires without counterpoise
F2 Fault location: L/2 km (F2)

**Figure I.10/K.57 – Potential rise of the faulty tower for single (1 × 10 kA) or double (2 × 5 kA) sided fault current flow and tower-earthing resistance options**



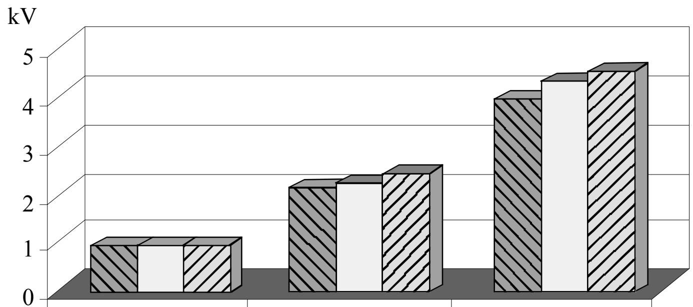

| | 8 Ω | 25 Ω | 50 Ω |
|---|---|---|---|
| Spacing: 200 m | 2.489 | 4.262 | 5.928 |
| Spacing: 333 m | 3.236 | 5.589 | 7.431 |
| Spacing: 500 m | 4.007 | 6.771 | 8.479 |

**a) 1 shield-wire**




| | 8 Ω | 25 Ω | 50 Ω |
|---|---|---|---|
| Spacing: 200 m | 3.599 | 6.196 | 8.803 |
| Spacing: 333 m | 4.659 | 8.203 | 11.405 |
| Spacing: 500 m | 5.750 | 10.170 | 13.427 |

**b) 2 shield-wires**



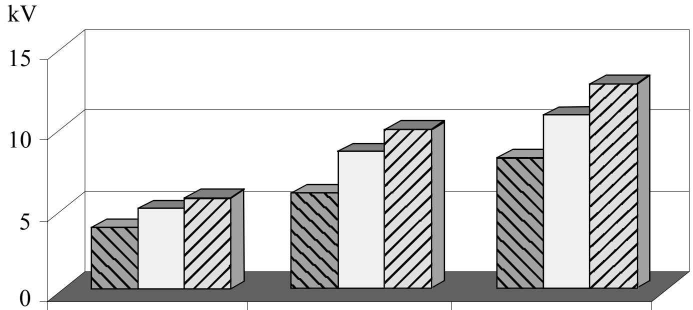

| | 8 Ω | 25 Ω | 50 Ω |
|---|---|---|---|
| Spacing: 200 m | 0.829 | 2.102 | 3.821 |
| Spacing: 333 m | 0.872 | 2.289 | 4.316 |
| Spacing: 500 m | 0.901 | 2.417 | 4.645 |

K.057_FI.11

**c) 1 shield-wire and counterpoise**

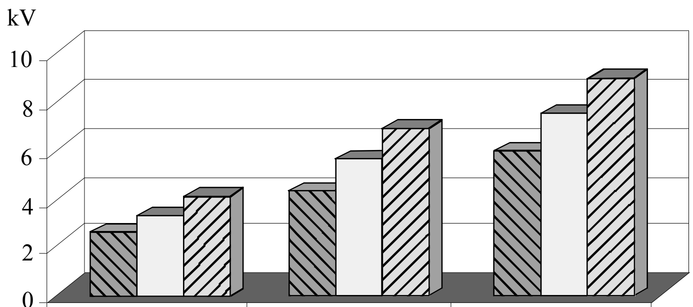
B 400-kV line
L15 Line length: L = 15 km
F2 Fault location: L/2 km
2 × 5 kA current flow, only from the left side of the faulty point
S1 Substation earthing: 0.1 Ω/0.1 Ω

**Figure I.11/K.57 – Tower potential rise of the faulty tower for different tower spans**



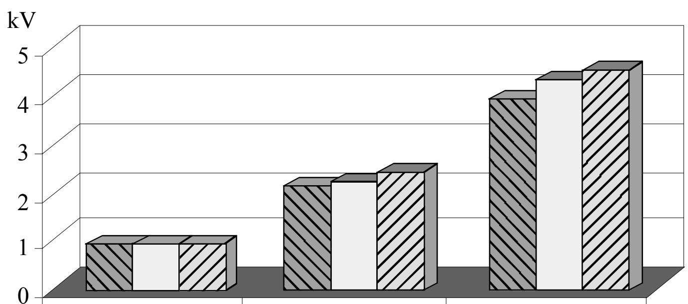

| | 8 Ω | 25 Ω | 50 Ω |
|---|---|---|---|
| Spacing: 200 m | 3.596 | 6.089 | 8.367 |
| Spacing: 333 m | 4.640 | 7.858 | 10.801 |
| Spacing: 500 m | 5.679 | 9.622 | 13.227 |

**a) 1 shield-wire**




| | 8 Ω | 25 Ω | 50 Ω |
|---|---|---|---|
| Spacing: 200 m | 2.479 | 4.138 | 5.638 |
| Spacing: 333 m | 3.200 | 5.342 | 7.279 |
| Spacing: 500 m | 3.916 | 6.542 | 8.916 |

**b) 2 shield-wires**




| | 8 Ω | 25 Ω | 50 Ω |
|---|---|---|---|
| Spacing: 200 m | 0.828 | 2.088 | 3.715 |
| Spacing: 333 m | 0.870 | 2.259 | 4.157 |
| Spacing: 500 m | 0.897 | 2.378 | 4.480 |

K.057_FI.12

**c) 1 shield-wire and counterpoise**

B 400-kV line
L60 Line length: L = 60 km
F2 Fault location: L/2 km
2 × 5 kA current flow, only from the left side of the faulty point
S1 Substation earthing: 0.1 Ω/0.1 Ω

**Figure I.12/K.57 – Tower potential rise of the faulty tower for different tower spans**

## I.4 Estimation of the required isolation level

The coordination of the isolation level required for the power supply circuit and the potential rise of power line towers can be made on the basis of the potential rise of the faulty tower for the deciding conditions and parameters contained in Table I.1.

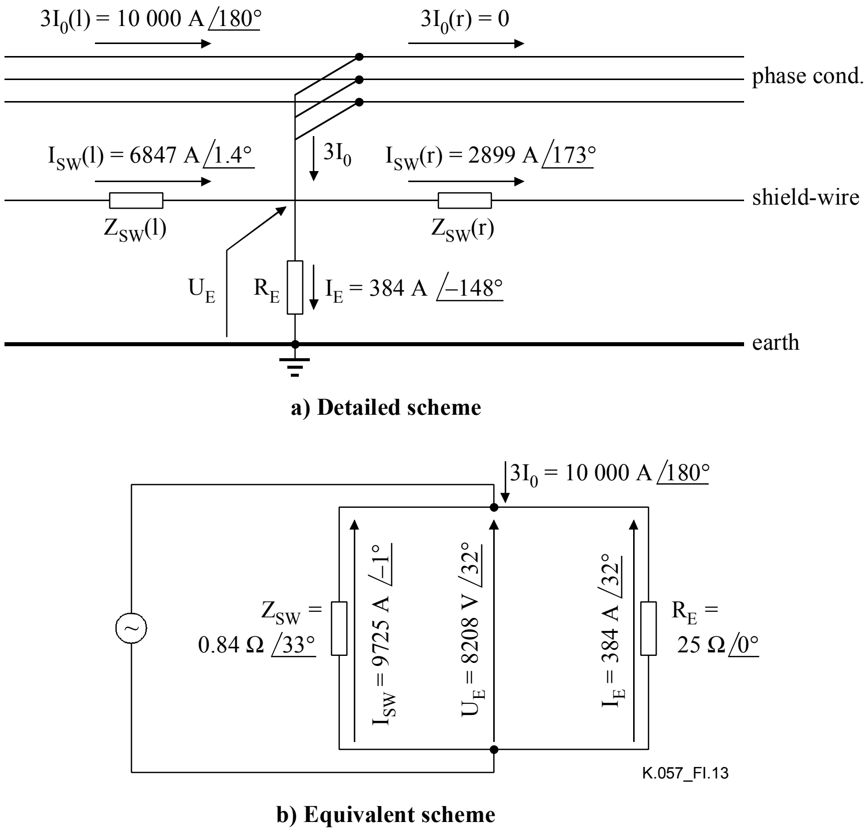
### I.4.1 Circuit representation of the faulty tower

From the simulation of the power line – including the shield-wire system – not only the potential of the tower but also the current distribution at the faulty tower is obtained as shown in the detailed scheme of part a) of Figure I.13. These voltage and current values allow the identification of the input impedance of the shield-wire(s) seen in both directions, i.e., $Z_{sw}(l)$ and $Z_{sw}(r)$, and their parallel equivalent, i.e., equivalent driving point impedance of the shielding-wire system seen from the faulty tower (see part b) of Figure I.13). The phasor values $Z_{sw}$ are listed in Table I.3. These are related to the one-side faulty current flow (1 × 10 kA) but identical values were obtained for the two-side (2 × 5 kA) faulty current flow in spite of the significant difference in the shield-wire current distribution.

The driving point impedance is in the range of 0.1 to 1.2, which is quite low compared to the resistance of the tower earthing. As a conclusion, the potential rise of a given tower is determined by the average value of the earthing resistances of the neighbouring 5 to 10 towers, rather than the tower in question itself. In other words, the T-EPR of a given tower cannot be significantly reduced by the improvement of resistance of that tower only.

**Table I.3/K.57 – Driving-point impedance seen from the faulty tower**

| Earthing resistance [Ω] | Shield-wire configuration | | | | | |
|---|---|---|---|---|---|---|
| | 1 sw | | 2 sw | | 1 sw + cp | |
| | [Ω] | [Deg.] | [Ω] | [Deg.] | [Ω] | [Deg.] |
| 8 | 0.491 | 33.2 | 0.336 | 23.5 | 0.090 | 19.9 |
| 25 | 0.844 | 33.5 | 0.570 | 25.7 | 0.232 | 20.3 |
| 50 | 1.162 | 38.5 | 0.752 | 31.8 | 0.435 | 22.8 |
| sw shield-wire<br>cp counterpoise | | | | | | |




| | |
|---|---|
| B | 400-kV line with 1 shield-wire without counterpoise |
| R2 | Tower-earthing resistance: 25 Ω |
| L15 | Line length: L = 15 km |
| S1 | Substation earthing: 0.1 Ω/0.1 Ω |

1 × 10 kA current flow, only from the left side of the faulty point

**Figure I.13/K.57 – Circuit representation of the faulty tower**

### I.4.2 Coordination of the isolation and earth fault current levels

Potential rise of the faulty tower for the deciding nine conditions and parameters are given in Table I.1 for 10-kA earth fault current. The modulus of these T-EPR values are reproduced in Table I.4 and these are considered as $U_b$ base values for isolation level coordination.

**Table I.4/K.57 – Base tower potential rise (T-EPR) values for isolation level coordination**

| Earthing resistance [Ω] | Shield-wire configuration | | |
|---|---|---|---|
| | 1 sw [kV] | 2 sw [kV] | 1 sw + cp [kV] |
| 8 | 4.663 | 3.237 | 0.872 |
| 25 | 8.208 | 5.589 | 2.290 |
| 50 | 11.413 | 7.432 | 4.316 |
| sw shield-wire<br>cp counterpoise | | | |

By the use of $U_b$ base T-EPR values the following two kinds of design values can be determined:

1) The ***required isolation voltage***, $U_{is}$ for a given earth fault current can be determined by the following expression:

$$U_{is} = U_b \frac{I_{ef}}{10} \qquad \text{[kV]}$$

where:

$U_b$ is the base voltage, corresponding to the average earthing resistance and shield-wire configuration of the line under study, taken from Table I.3;

$I_{ef}$ is the earth fault current, in kA, of the power line tower containing the base station in question.

For example, let us assume the following conditions for the power line, the tower of which contains the base station:

a) the power line is equipped with two shield-wires;

b) the average value of the earthing resistance of the towers is around 25 Ω;

c) the phase-to-earth fault current relevant to the tower holding the base station: $I_{ef}$ = 21 kA.

The base voltage corresponding to the first two conditions is: $U_b$ = 5.589 kV. Considering the third condition too, the isolation voltage required for the power feeding facilities (isolating transformer, cabling) is given as:

$$U_{is} = 5.589 \frac{21}{10} = 11.737 \qquad \text{[kV]} \qquad \text{(I-1)}$$

The required isolation voltage level – as a rounded value – is 12 kV.

2) The ***permissible phase-to-earth fault current***, $I_{ef}$ corresponding to different pre-defined isolation voltage levels ($U_{is}$) can be determined by the following expression:

$$I_{ef} = 10 \frac{U_{is}}{U_b} \qquad \text{[kA]} \qquad \text{(I-2)}$$

where:

$U_b$ is the base voltage, corresponding to the average earthing resistance and shield-wire configuration of the line under study, taken from Table I.4;

$U_{is}$ is the pre-defined isolation voltage levels of the power feeding facilities (isolating transformer, cabling), e.g., those listed in the first column of Table I.5.

From an engineering design point of view, it can be assumed that a series of isolation transformers are manufactured with given isolation voltage levels. In this case, the permissible earth faults, classified according to the isolation levels, can be identified for the average earthing resistance and shield-wire configuration of the line under study by using expression I-2.

For example, let us assume the following conditions for the power line, the tower of which contains the base station:

1) the power line is equipped with two shield-wires;

2) the average value of the earthing resistance of the towers is around 25 Ω.

Furthermore, as a third condition:

3) the isolation voltage level of the power feeding facilities (isolating transformer, cabling) $U_{is}$ = 20 kV.

The base voltage corresponding to the first two conditions is: $U_b$ = 5.589 kV. Considering the third condition too, in the tower holding the base station is given as:

$$I_{ef} = 10 \frac{20}{5.589} = 35.785 \qquad \text{[kA]}$$

The rounded value of the permissible earth fault current is 36 kA according to the value given in the 8th row and 4th column of Table I.5.

**Table I.5/K.57 – Permissible earth fault current corresponding to different isolation levels**

| 0 | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| | **Isolation voltage levels of the power feeding [kV]** | **Average earthing resistance of the towers [Ω]** | **Permissible earth fault current [kA] for shield-wire configuration** | | |
| | | | **1 sw [kA]** | **2 sw [kA]** | **1 sw + cp [kA]** |
| 1 | 10 | 8 | 21 | 31 | 115 |
| 2 | | 25 | 12 | 18 | 44 |
| 3 | | 50 | 9 | 13 | 23 |
| 4 | 15 | 8 | 32 | 46 | 172 |
| 5 | | 25 | 18 | 27 | 66 |
| 6 | | 50 | 13 | 20 | 35 |
| 7 | 20 | 8 | 43 | 62 | 229 |
| 8 | | 25 | 24 | 36 | 87 |
| 9 | | 50 | 18 | 27 | 46 |
| 10 | 50 | 8 | 107 | 154 | 573 |
| 11 | | 25 | 61 | 89 | 218 |
| 12 | | 50 | 44 | 67 | 116 |
| sw | shield-wire | | | | |
| cp | counterpoise | | | | |

The permissible earth fault currents are determined for 10-kV, 15-kV, 20-kV and 50-kV isolation voltage levels and the above identified power line parameter options and the results are listed in rows 1 to 12 and columns 3 to 5 of Table I.5.

The selection of the required isolation voltage level shall be made on the basis of the real earth fault current magnitudes. The magnitudes of the earth fault currents are generally available as maximum and average values for each HV level of a national grid.

The maximum fault currents are relevant to a fault in the substation; thus, such high currents never occur in cases of power line faults.

# Appendix II

# Guide on the LV feeding arrangement

## II.1 LV feeding arrangement

The low-voltage feeding is composed of the following elements (when proceeding from the tower to feeding network, see Figure 1):

1) Isolating transformer, installed in the feeding cabinet, is LV/LV type, i.e., 400 V/(400/230) V, preferably delta/why ($D/Y_0$) connected.

   NOTE 1 – The delta connection has the advantage that there is no neutral conductor, thus no 4th MV SPD (medium voltage type surge protective device) is needed and it can feed unbalanced loads as well.

2) Junction cable is the last section of the LV feeding line, entering the Z-EPR zone, between the cabinet of the isolating transformer and the junction point. Its minimum length shall be greater than the measure of the Z-EPR zone and right of way (falling distance) of the HV power line (at least 30 m).

   NOTE 2 – The junction section might be an aerial line in that exceptional case, where the national regulations allow the use of aerial lines in the right of way zone of the HV lines.

3) Junction point is the connection of the junction cable and connecting LV line section. The junction shall be equipped with:
   - a low-voltage type surge protective device, LV SPD;
   - low-resistance (below 10 Ω) earthing;
   - power-metering facilities, if appropriate.

4) The connecting line is the section of the LV feeding line between the point of coupling to the feeding network and the junction point.

   NOTE 3 – The connecting lines may feed a few customers too, especially if the lines are long (many hundreds of metres). In this case, very good earthing is required at the junction point or each customer shall be equipped with LV SPD.

5) The coupling point can be at any point of a LV public network or the LV terminals of a MV/LV transformer used only for the RBS but located outside the zone of Z-EPR. The coupling shall be equipped with:
   - a SPD

     NOTE 4 – The SPD is not necessary when customers equipped with SPD are fed from the connecting line and no power-metering facilities are installed at the junction point.
   - low resistance (below 10 Ω) earthing

     NOTE 5 – In case of TN(-C-S) LV network the resultant impedance seen at the coupling point to the earth can be low enough without the application of additional earthing electrodes.
   - power-metering facilities, if appropriate

     NOTE 6 – The power metering can be made at the coupling point only in that case when no customer is fed from the connecting line.

     NOTE 7 – In case of RBS fed from MV/LV transformer located in the zone of Z-EPR and equipped with potential equalizing conductor (see Figure 5), the feeding transformer acts as an isolating transformer as well. Thus, low-voltage type SPD shall be applied in the feeding cabinet of the RBS and MOV in the MV side (this is normally applied to protect the transformer against lightning surges coming from the MV line).

### II.2 Protection principles

The protection of LV feeding system involves the protection against power frequency (50 Hz) overvoltages due to earth faults and the impulse stresses caused by the lightning strokes to the tower hosting the RBS.

#### II.2.1 Protection against power frequency EPR

The earth fault current causes a power frequency (50 Hz) electrode potential rise (T-EPR) on the tower earthing itself and a progressively decreasing earth potential rise (Z-EPR) around the tower. The magnitude of the T-EPR can be estimated according to the "Guide on the coordination of the isolation level required for power supply circuit and the potential rise of power line towers" given as Appendix I.

The principle of the protection is isolation of the LV feeding system, entering the Z-EPR, against the potential rise. The potential of the conductors of the feeding line is fixed to remote earth. (The phase conductors are earthed through the neutral earthing (assuming TN system) whilst the neutral and the cable screen, if applied, are directly earthed.) The primary winding of the isolating transformer is also on the potential of remote earth due to its metallic connection to the feeding line. On the other hand, the neutral of the secondary winding is bonded to the tower earthing.

Under the above conditions, the protection can be provided by the appropriate:

1) isolation of the primary (delta) winding of the isolating transformer with respect to the secondary winding and to the iron core and to any other metallic part of the cabinet;
2) isolation of the phase conductors and any metallic part (neutral screen) of the LV junction cable with respect to any earthed part of the cabinet and tower and to the earth in the Z-EPR zone;
3) power frequency withstand of the SPD (MOV or similar device), i.e., appropriate selection of its rated voltage ($U_r$).

   NOTE – Rated voltage ($U_r$) is the rms value of the power frequency voltage, which can be applied during 10 consecutive seconds between the surge arrester terminals after maximum prior duty. It characterizes the surge arrester withstand to power frequency overvoltages (temporary overvoltages).

   The continuous operating voltage ($U_c$), i.e., the maximum rms value of power frequency voltage, which can be continuously applied between the arrester terminals, is 80% of $U_r$.

#### II.2.2 Protection against lightning-generated surges

When lightning strikes a tower hosting an RBS, the majority of the lightning current is flowing to the earth through the earthing of the tower. Thus a similar, but impulse type, EPR occurs as the EPR due to earth fault currents as described above. The magnitude of the impulse type tower T-EPR is essentially determined by the product of the magnitude of the lightning current and earthing impedance of the tower. Their ranges are for the lightning current 10 to 100-kA peak and for the earthing impedance 5 to 20 Ω. Therefore, the tower potential rise ranges from 50 to 2000 kV (Typical value: 50 kA × 10 Ω = 500 kV peak).

##### II.2.2.1 Protection of the isolating transformer

The above impulse type overvoltage could occur between the windings and between the primary winding and earthed parts of the isolating transformer. It is not feasible to design the isolating transformer for such a high insulation level. For example, an isolating transformer designed for 20-kV power frequency insulation level can withstand around 70-kV impulse voltages. Therefore, the impulse overvoltage should be equalized by SPDs, connected between primary side terminals and the tower earthing to which the neutral of the secondary winding is connected as well.

The SPD shall comply with the following requirements:

1) Maximum residual voltage lower than the lightning impulse withstand of the isolating transformer.

   NOTE – The maximum residual voltage is the maximum peak value of the voltage between the surge arrester terminals at nominal discharge current. It characterizes the ability of the surge arrester to limit the overvoltage level.

   The maximum residual voltage is typically three times $U_r$.

2) Voltage ($U_r$) rated high enough to ensure that the surge arrester withstands the highest power frequency tower potential rise. Considering the possible magnitude of the tower potential rise (10 to 40 kV) MV SPD surge arresters are needed for the protection of the isolating transformer (typically metal oxide varistor, MOV).

   The fulfilment of this requirement is very important to guarantee the recovery of the isolation state for power frequency subsequent to discharging the lightning impulse.

3) Nominal discharge current, corresponding to the largest lightning current for which protection is intended. The current ($I_{LV}$) entering the LV feeding line through the protectors is a fraction of the lightning current ($I_L$) and may roughly be approximated according to the parallel connected impedance of the earthing resistance of the tower (R) and the surge impedance of the LV line ($Z_{LV0}$) as:

$$I_{LV} = \frac{R}{R_E + Z_{LV0}} I_L \cong \frac{R}{100} I_L$$

   In the last part of the formula it is assumed that the surge impedance of the cable-like LV feeder ranges from 80 to 90 Ω; thus, $Z_{LV0} + R \cong 100$ Ω.

### II.2.2.2 Protection of the junction cable

The MV SPDs connected to the primary side terminals of the isolating transformer inject lightning impulse into the junction cable. The magnitude of the injected surge voltage with respect to the tower and also to the earth in the vicinity of the tower is equal to the residual voltage of the MV SPDs. Consequently the voltage stress across the cable, i.e., phase conductors to earth in case of unscreened cable or screen to earth in case of screened cable, is equal to the residual voltage of the MV SPDs in the vicinity of the tower.

The identification of the voltage stress of the junction cable is more difficult farther away from the tower. The magnitude of the injected surge voltage with respect to remote earth is the lightning impulse potential of the tower diminished by the residual voltage through the MV SPDs. This represents a surge having a few hundreds kV peak. However, the peak value of the impulse wave would appear in the cable only in the case when the wave could travel such a distance, that the peak of the wave would be at a point in the LV feeding cable, which is out of the EPR zone. The geometrical extension along the LV line of the front of the wave is about 300 m, even assuming a very steep wave with front time of 1 μs. The junction cable is typically 50-150 m in length (see Appendix III). Its conductors are terminated to the earth by either LV SPDs (phase conductors) or directly earthed (neutral conductor and screen if applied), which are providing practically short circuit at the junction point. This short-circuit-type termination causes negative reflected voltage wave, which tends to diminish the incoming wave. The resulted voltage remains below about 1/10th of the peak as far as the junction cable remains short.

With the above conditions it can be assumed that the voltage stress of the LV cable is not higher even to the remote earth, i.e., outside the EPR zone, than the residual voltage of the MV SPDs protecting the isolating transformers. However, the high insulation level should be maintained along the whole length of the junction cable.

Finally, it should be noted that the explanations above are of a qualitative kind, neglecting the effects of a couple of factors, i.e., the potential rise at the earthing of the junction point, and the effect of the connecting feeding line section. Precise design values for actual conditions can be obtained from quantitative analyses, e.g., by ElectroMagnetic Transient Program (EMTP) simulation.

### II.3 Selection of the design values for the protection

The design values for the characterization of the protection elements can be identified in the following way and logical order.

#### II.3.1 Voltage level of the isolating transformer

a) The insulation voltage level at 50 Hz of the primary winding of the isolating transformer shall be higher than the maximum rms value of the tower potential rise due to earth fault. It is essentially determined by the magnitude of the earth fault current, the average value of earthing resistances of the towers, the shield-wires and counterpoise. For the selection of the required isolation level, guidance is given in Appendix I.

b) However, the following power frequency voltage levels of isolation between the windings and between the primary winding and earthed parts are relevant for the most practical applications:

- 10 kV rms, for the most practical cases up to 20-kA earth fault current;
- 20 kV rms, when the average value of the earthing resistances are high and for severe earth fault current, i.e., up to 40 kA.

c) In addition, the impulse voltage dielectric strength of the primary winding shall be higher than the residual voltage of the applied MV SPDs (MOV or similar). Informative values for characteristics of typical MV SPD are given for the above isolation levels in Table II.1.

#### II.3.2 MV SPD (MOV or similar) characteristics

a) Rated voltage ($U_r$) of the MV SPD shall be equal to or higher than the maximum rms value of the ERP of the tower concerned, due to earth fault.

**Table II.1/K.57 – The characteristics of MV SPD (MOV or similar) corresponding to two typical voltage levels of the isolation transformer**

| Isolation level of the transformer [kV rms] | MV SPD (MOV) arrester characteristics | | | |
|---|---|---|---|---|
| | Rated voltage, $U_r$ [kV rms] | Continuous operating voltage, $U_c$ [kV rms] | Residual voltage with 8/20 μs wave | |
| | | | at 10 kA [kV peak] | at 20 kA [kV peak] |
| 10 | 10 | 8 | 28 | 32 |
| 20 | 20 | 16 | 56 | 64 |

b) Nominal discharge current shall correspond to the highest lightning current, which should be diverted by the arrester.

NOTE – The nominal discharge current is the peak value of the lightning current impulse having a 8/20 bi-exponential impulse wave shape, which is used to classify surge arresters. The energy absorption capacity, given in kJ/$kV_{Uc}$, is also used to characterize the discharge capability of the protector.

The diverted current is a fraction of the lightning current. Its value, in per cent, is roughly equal to the earthing resistance, in ohms, of the tower, where the RBS is installed (see II.2.2.1 b)).

A MOV with nominal discharge current of 20 kA can provide protection for a lightning current of at least 100-kA peak, when the earthing resistance is below 20 Ω. In case of lower earthing resistance, MOVs with nominal discharge current lower than 20 kA can provide appropriate protection.

### II.3.3 LV SPD characteristics

The nominal discharge current of the LV SPDs shall be equal to or higher than that of the MV SPDs in case of LV SPDs connected between each phase conductor and earth at the junction point according to II.3.2 b).

NOTE – Considering II.3.2 b), the applied LV SPD shall have at least the nominal discharge current of 20 kA.

In other cases the selection and application of LV SPDs shall comply with the requirements specified in the IEC standard series of IEC 61643 especially IEC 61643-1, [II.1], and IEC 61643-12, [II.2].

### II.3.4 Junction cable

#### II.3.4.1 Isolation withstand voltage

The isolation withstand voltage of the junction cable to earth shall be higher than the rated voltage and the residual voltage of the applied MV SPD (MOV) for power frequency and surge voltage (see the informative values given in Table II.2).

These withstand voltages shall be ensured between the metallic structures and earth between which the MV SPD are applied, i.e., between the phase conductors and earth in case of Option 1, whilst between the screen and the earth in cases of Options 2 and 3.

NOTE – The required voltages withstand between the isolated fittings and earthed parts of the feeding cabinet can be ensured by sufficient clearance distances. The minimum clearances for the maximum apparatus voltages and the respective insulation levels according to IEC 71 are as follows:

**Table II.2/K.57 – Informative values for the required voltage withstand and clearances**

| Maximum voltage for apparatus [kV rms] | Rated lightning impulse withstand voltage [kV peak] | Minimum clearance (indoors) [mm] |
|---|---|---|
| 12 | 75 | 90 |
| 24 | 125 | 160 |

#### II.3.4.2 Length of the junction cable

The minimum length of the junction cable shall be greater than the measure of the EPR zone and right of way (falling distance), where applicable, of the HV power line (at least 30 m; for more details, see Appendix III).

On the other hand, unnecessary extension of the junction cable should be avoided as far as possible, to reduce the cost of this section having increased isolation level and to prevent the occurrence of overvoltage due to the travelling wave phenomenon (see II.2.2.2 and also Appendix III).

### II.4 Options for the feeding of multiple RBSs

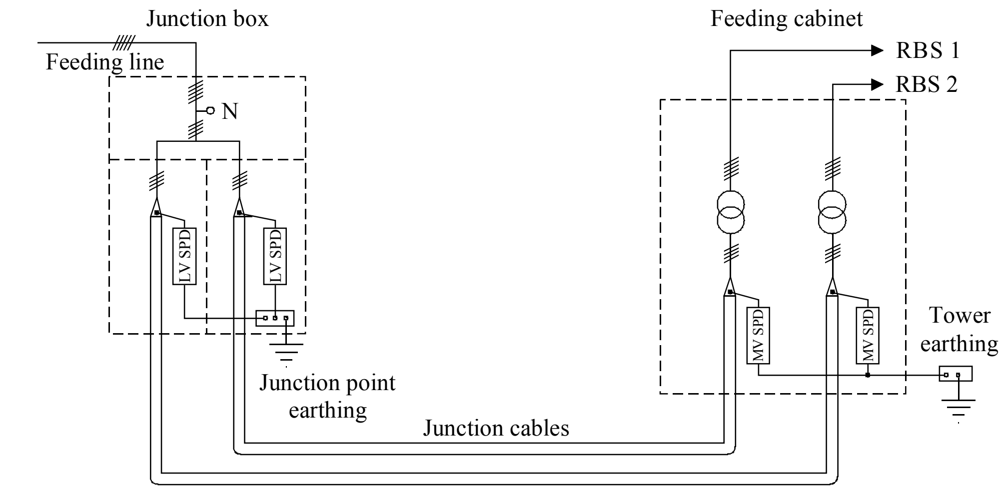
In some cases more than one RBS – e.g., operated by different service providers – may be mounted in the same power line tower. The possible feeding options of this multiple RBS operation are demonstrated in Figure II.1 with the assumption of two RBSs. More and more elements of the feeding system become commonly used, when proceeding from options a) to c) thus resulting in the less installation cost, but on the other hand less flexibility in the operation and maintenance.

The different feeding arrangements (see Figure II.1) can be characterized by the following main features:

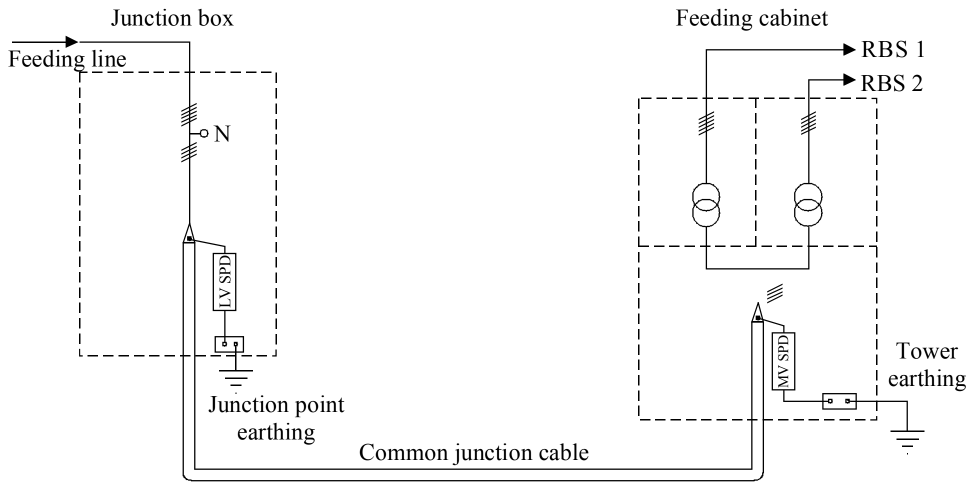
a) Each circuit element is separated, i.e., duplicated from the junction point to the feeding cabinet. A separate consumption (kWh) meter for each RBS can be installed either at the junction point or at the separate compartment of the feeding cabinet. It is worth mentioning that the LV SPDs could, in principle, be combined and replaced by a single set connected to the common (feeding line) branch.

b) The junction cable, the MV SPD and LV SPD at the feeding cabinet and the junction point respectively are common for the two RBSs. Separate consumption meters for each RBS can only be installed at the separate compartments of the feeding cabinet.

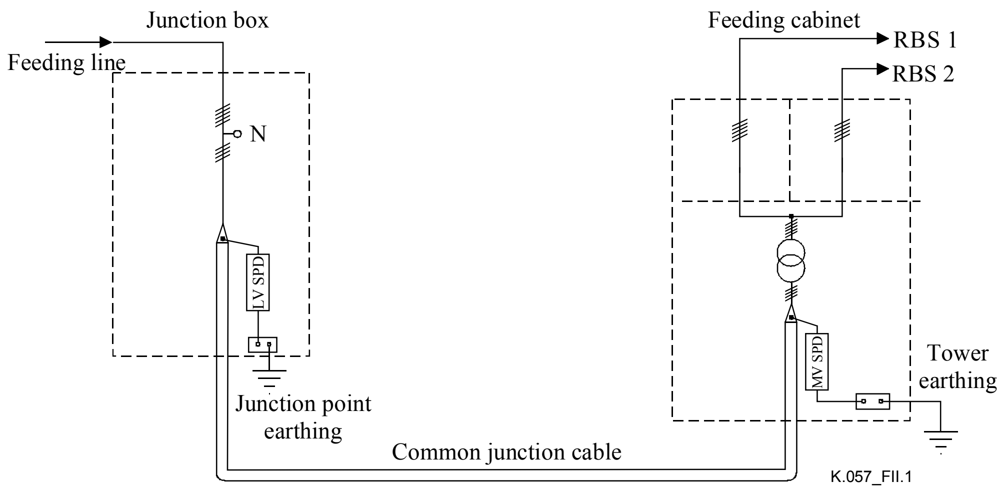
c) The junction cable, the SPDs and the isolating transformer are used commonly. The feeding is separated only on the secondary side of the isolating transformer. The consumption of each RBS can be measured by subsidiary meters installed in separate compartments on the feeding cables at the secondary side. A meter for common consumption – including the loss of the isolating transformer – can be installed either in the primary side compartment of the feeding cabinet or at the junction point.




**a) Separate feeding**




**b) Common junction cable and SPDs (both MV and LV types)**




**c) Common junction cable, SPDs and isolating transformer**

**Figure II.1/K.57 – Options for the feeding of multiple RBSs mounted in the same tower**

# Appendix III

## Characterization and control of the EPR zone of tower earthing and estimation of the minimum length of the junction section

### III.1 Characterization of the zone of EPR of the tower earthing

#### III.1.1 EPR for actual tower footings

This clause describes characteristics of the zone of the earth potential rise (Z-EPR) occurring around the tower footing due to the current injected to the earth through the earthing electrode system of a high-voltage power line tower. It also presents a collection of figures obtained on the one hand from field measurements and on the other hand by simulation studies.

The profile curves of Z-EPR vs. distance in per cent, normalized to the earthing potential ($V_e$), are given in Figure III.1. These profiles were obtained from measurements made in the field around the footing of a 220-kV power line, the measures of which are given in part b) of Figure III.1. Part a) of the referred figure shows measured Z-EPR profiles vs. distance at the surface of the earth in the specified four directions [III.1].

Part b) of Figure III.1 shows the normalized potential profiles with log-log scaling, thus providing better comparison between the profiles of different directions indicated in the figure for further distances.

3D plots of Z-EPR are given in Figure III.2 in two different scalings. These were obtained from simulation [III.2] of the earthing system of a 220-kV line, the structure of which is given in Figure III.3.

Profiles of Z-EPR normalized to the tower potential, at a depth of 0.5 m, perpendicular to the route of the line, through the centre point between the legs of the tower, are plotted for two different earth resistivities in Figure III.4. This is a case where no ring conductor is installed.

On the base of the information provided, the following main conclusions can be made for practical purposes:

– In the close vicinity of the tower footing, the change in the EPR is quite rapid. Therefore, the bonding for potential equalization of the different cabinets, e.g., feeding and RBS equipment, is of essential importance.

– The specific resistivity of the earth affects the magnitude of the earthing potential, T-EPR and Z-EPR, but does not affect the magnitude and the profile of the normalized Z-EPR (see Figure III.4).

– The differences of the Z-EPR profiles in different directions are only significant in the close vicinity of the tower footing. At further distances from the tower footing, the Z-EPR profiles in different directions are practically identical and decrease with the distance $x$ according to $1/x$ (hyperbolic) pattern. The later statement allows for the equivalent hemispheric representation of the tower earthing for practical purposes.

#### III.1.2 Representation of the Z-EPR by equivalent hemisphere concept

It is well known from the technical literature [III.3] that the Z-EPR can be described with very simple expressions, when a hemisphere or an equivalent hemisphere replaces the actual electrode.

These simple formulae also assume homogeneous soil at least in the surface layer.

The Z-EPR of a hemispheric electrode at a distance $x$ is given by:

$$V_x = \frac{\rho}{2\pi x} I \qquad \text{(III-1)}$$

where:

- ρ is the resistivity of the soil; and
- $I$ is the current flowing through the earthing electrode

The earthing potential $V_e$ of the tower becomes:

$$V_e = R \cdot I \qquad \text{(III-2)}$$

where $R$ is the earthing resistance of the power tower.

Making the ratio of $V_x/V_e$ the following expression is obtained:

$$\frac{V_x}{V_e} = \frac{\rho}{2\pi R}\frac{1}{x} \qquad \text{(III-3)}$$

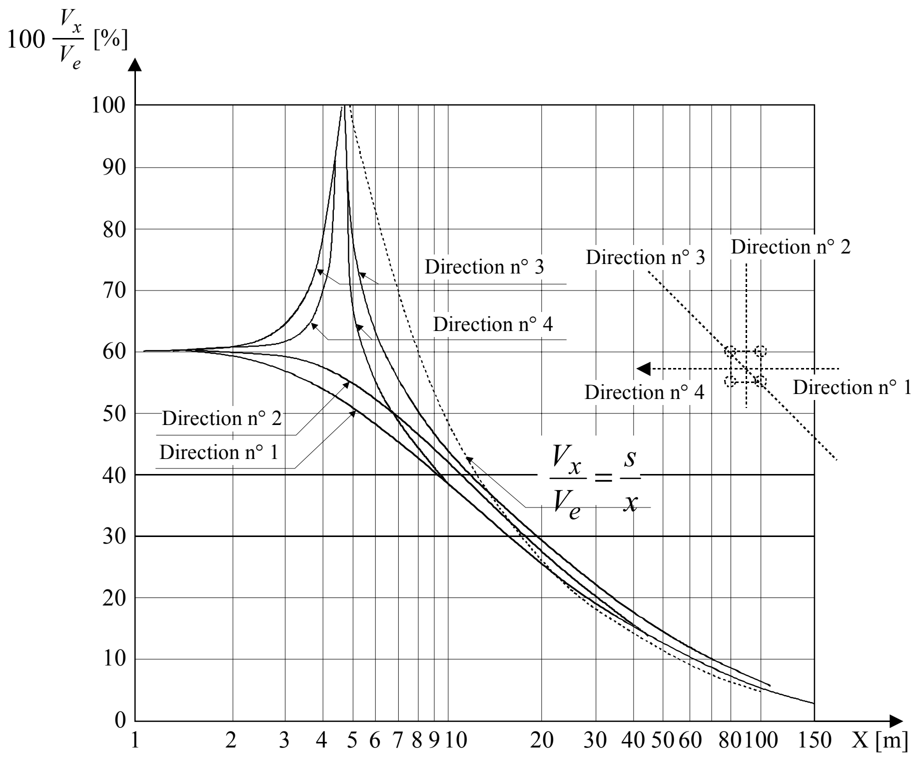
Finally, the minimum distance $x_{min}$ from the centre of the electrode, where the earth potential $V_x$ is equal to a stipulated value can be obtained as:

$$x_{\text{min}} = \frac{1}{2\pi}\frac{\rho}{R}\frac{V_e}{V_x} \qquad \text{(III-4)}$$

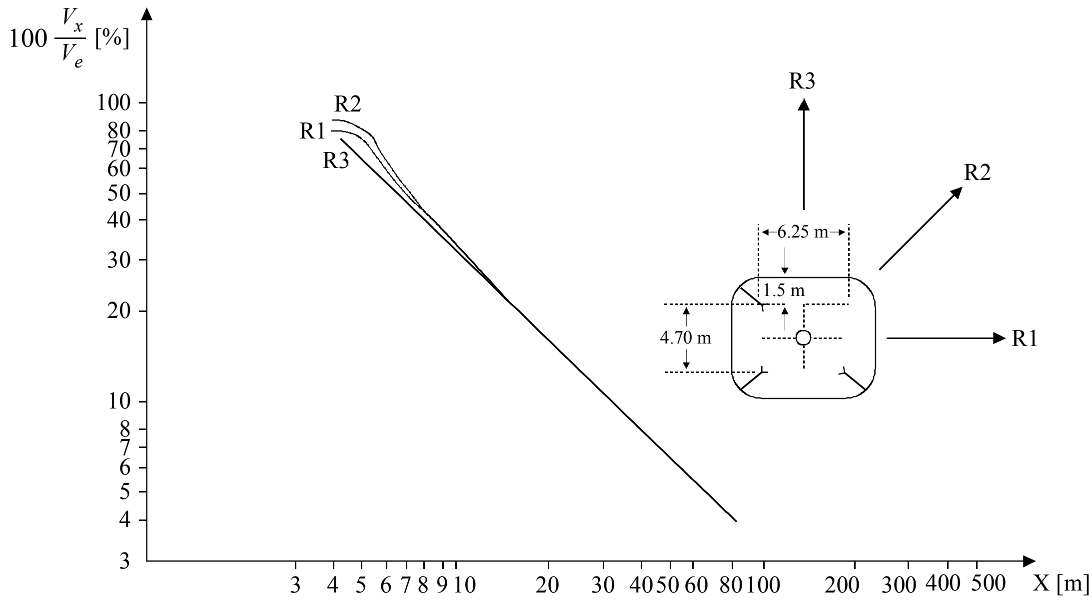
where the following values are assumed to be known:

- ρ the specific resistivity of the surface soil at the location of the tower holding the RBS
- $R$ earthing resistance of the tower holding the RBS (the value considered in Appendix I)
- $V_e$ potential rise of the tower holding the RBS (the value obtained according to Appendix I)
- $V_x$ admissible no load earth potential at the remote end of the junction section, i.e., at the junction point.

When the junction cable is laid along a straight route, then $x_{min}$ is equal to the required minimum length of the junction section.



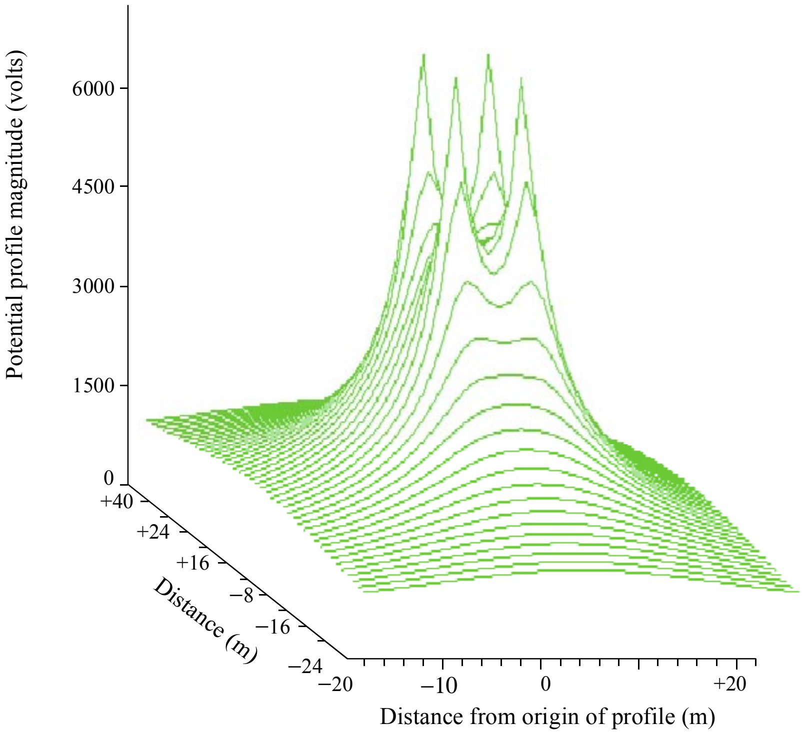

**a) Normalized potential profiles near the tower footing in different directions indicated in the figure (the label *s* is the radius of the equivalent hemisphere representing the tower earthing)**



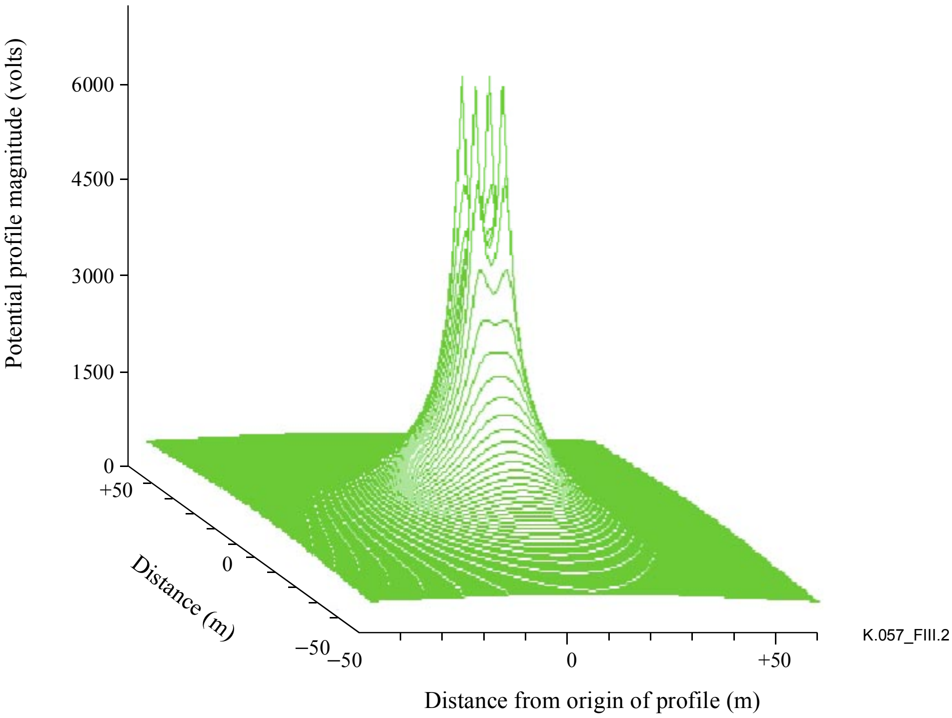

**b) Normalized potential profiles with log-log scaling for further distances from tower footing to different directions indicated in the figure**

K.057_FIII.1

**Figure III.1/K.57 – Z-EPR normalized by the earthing potential (in per cent) measured around the footing of a 220-kV power line with the measures given in Figure III.1 b)**




**a) Shown area: 40 × 40 m**




**b) Shown area: 100 × 100 m**

**Figure III.2/K.57 – 3D plots of Z-EPR at a depth of 0.5 m, ρ = 1500 Ωm, earth fault current: 10 kA, number of earth wire: 1, earthing structure according to Figure III.3**

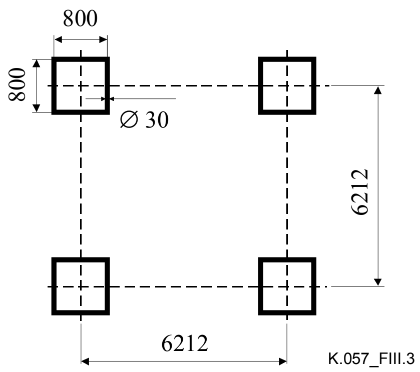



**Figure III.3/K.57 – Arrangement and sizes (in mm) of earthing electrodes of a 220-kV power line considered in the EPR simulation – Depth of electrodes: 1.7 m**

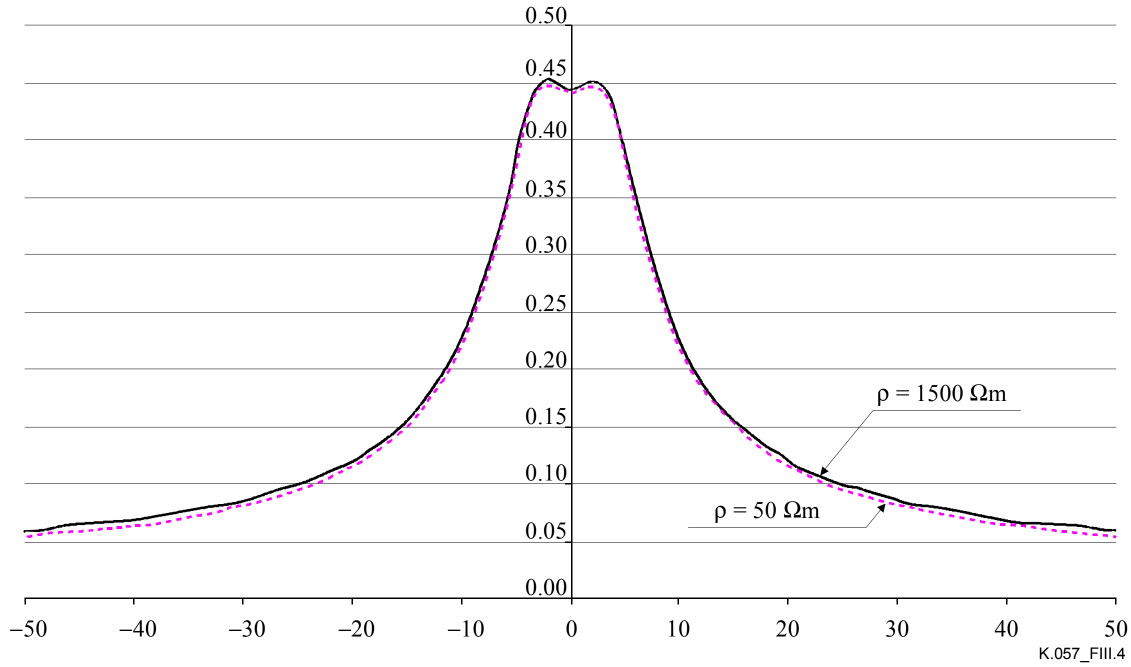



**Figure III.4/K.57 – Profiles of Z-EPR normalized by the tower potential, at a depth of 0.5 m, perpendicular to the route of line through the centre point between the legs of the tower**

## III.2 Control of touch and step voltages by potential PGE

The investigation of the Z-EPR has show significant difference in the potential between the legs of the tower and also beside the tower (see Figures III.1, III.2 and III.4). This difference causes touch and step voltages which can affect the staff working in the vicinity of the cabinet of RBS. The possible control of touch and step voltages by PGE is investigated below.

### III.2.1 Effectiveness of the PGE

a) *Applied simulation technique and basic parameters*

The simulation calculations have been made by the CDEGS software package (see ref. [III.2]). This technique allows the consideration of the actual earthing electrode arrangement and the soil resistivity and structure (even stratified earth).

In the calculations, the following general conditions were considered:

- homogenous earth (specific resistivity of ρ = 50 Ωm);
- frequency: 50 Hz (current injection: 1000 A to the tower, including the legs).

It is worth mentioning that only normalized values are considered in the evaluations, which are affected neither by the specific resistivity of the earth nor by the magnitude of the injected current.

b) *Arrangement of the tower earth and the potential grading earth electrodes simulation*

The earthing electrode arrangement of the tower is the one specified in Table III.1 under case code 9. The sizes are reproduced in Figure III.7. In fact, the tower earth system is composed of four square-form electrodes placed at the bottom of the tower foundation and bonded together through the tower body (see Figure III.14). The structure and the sizes of the tower earth are characterized by:

- electrode material: steel, circular with a diameter of 30 mm;
- depth: 2.0 m;
- lateral size of the square-form electrode of each leg: 1.7 × 1.7 m;
- spacing between the centre line of the tower leg electrodes: 6.5 × 6.5 m.

The electrode arrangements and grading earth electrode frames are shown for the cabinet beside the tower in Figure III.5, and for the cabinet between the legs of the tower in Figure III.6.

The structure and arrangement of the simulated voltage grading earth frame electrode systems are as follows:

- electrode material: steel, circular with a diameter of 20 mm;
- depth: 0.3 m;
- positions:
  – beside the tower (see Figure III.5);
  – between the tower legs centrally located (see Figure III.6);
- sizes of the PGE (see Figure III.7):
  – outer frame 3.6 × 3.6 m;
  – inner frame 2.4 × 2.4 m.

The sizes of the PGE frames are identical for the cabinet beside the tower and between the legs of the tower. If only a single frame is assumed, it is the outer one.

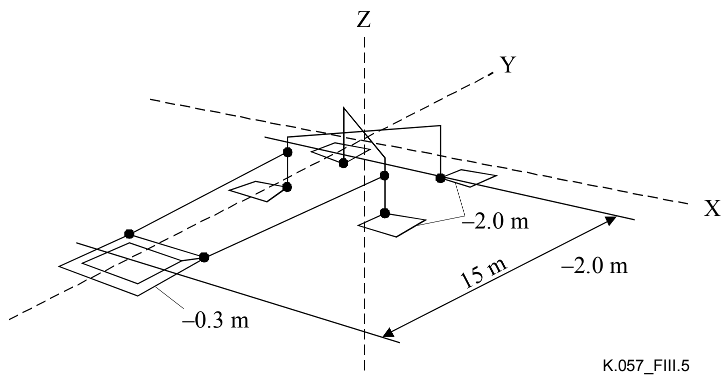



**Figure III.5/K.57 – Arrangement of the tower-earthing electrodes and potential grading double frame earth electrodes. Cabinet location: beside the tower**

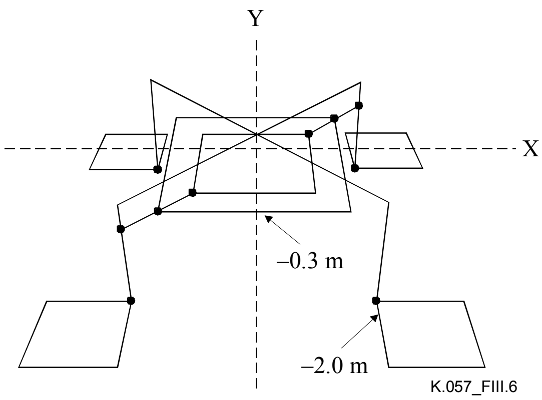



**Figure III.6/K.57 – Arrangement of the tower-earthing electrodes and potential grading double frame earth electrodes. Cabinet location: between the tower legs**

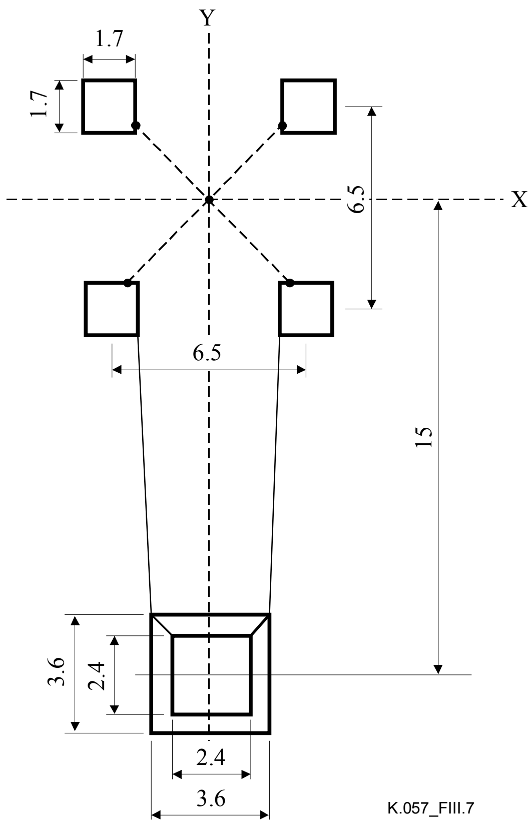



**Figure III.7/K.57 – Sizes of the tower-earthing electrode and PGE double frame electrode, in m**

c) *Surface potential and touch voltage profiles*

The CDEGS code provides a complete EMF solution of the electrode system providing, e.g., the potential, current distribution, electric and magnetic field in any place of the surrounding area. This result can be further processed, thus resulting in the touch and step voltages, etc.

A general overview is provided by the 3D plot of the potential at a given level of the earth, like the one shown in Figure III.2.

For the quantitative analysis of the results, the profiles of the earth surface potential to remote earth and the touch voltage between the cabinet earthing (bonded with the tower earthing) and the earth surface near the cabinet are given vs. length in three representative directions for the following two cabinet locations:

- beside the tower (see Figures III.8, III.9 and III.10);
- between the tower legs (see Figures III.11, III.12 and III.13).

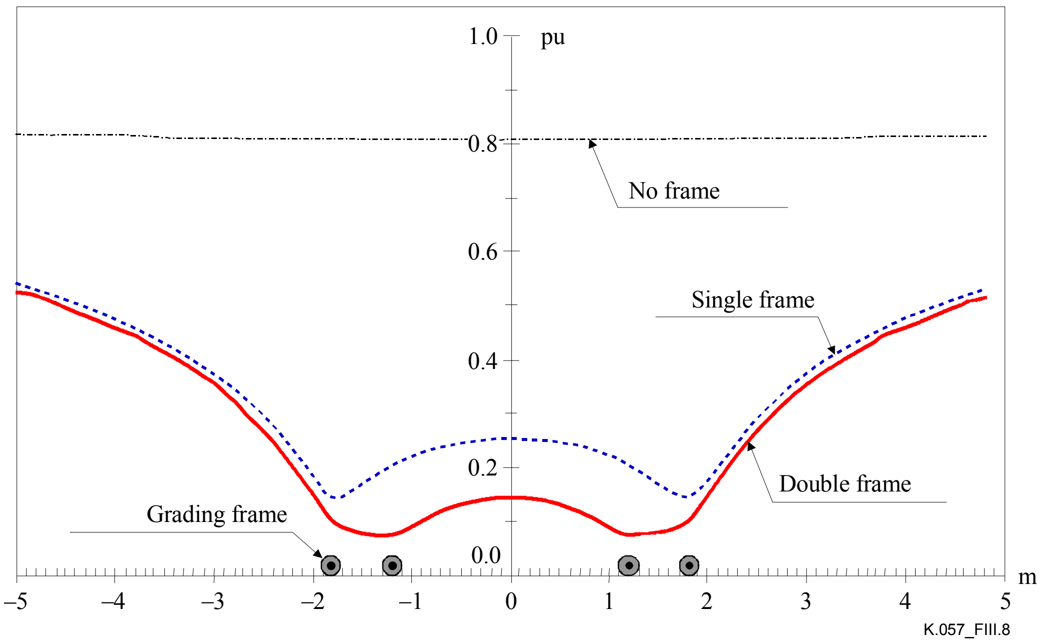



**Figure III.8/K.57 – Profile of touch voltage (pu, Base: T-EPR) for cabinet beside the tower. Profile: X direction, in centre line of the grading electrode frame**

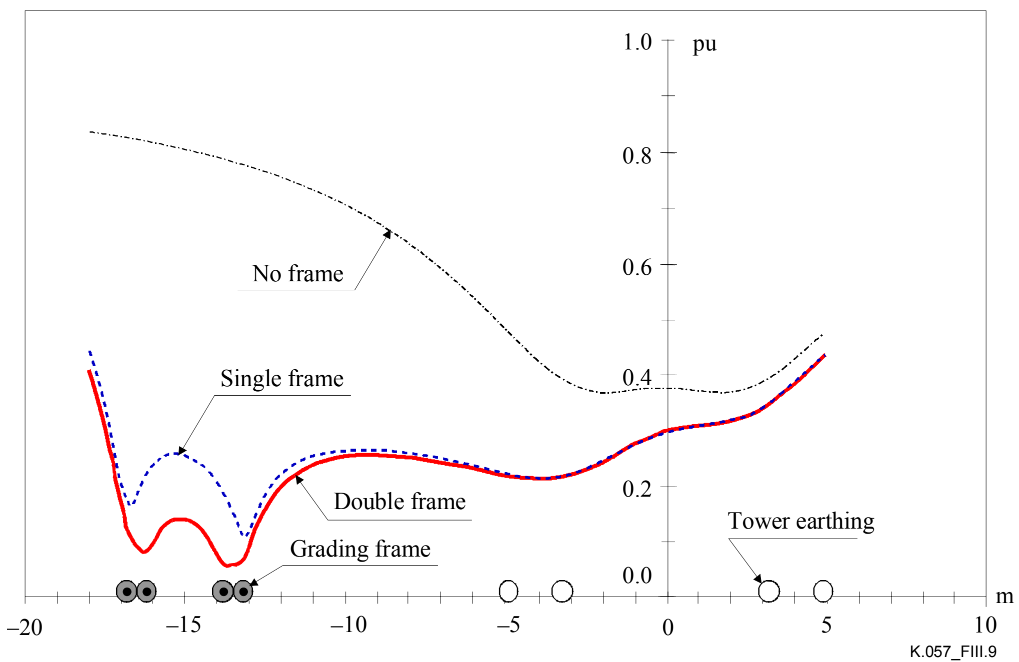



**Figure III.9/K.57 – Profile of touch voltage (pu, Base: T-EPR) for cabinet beside the tower. Profile: Y direction, in centre line of the grading frame and tower-earthing electrodes**

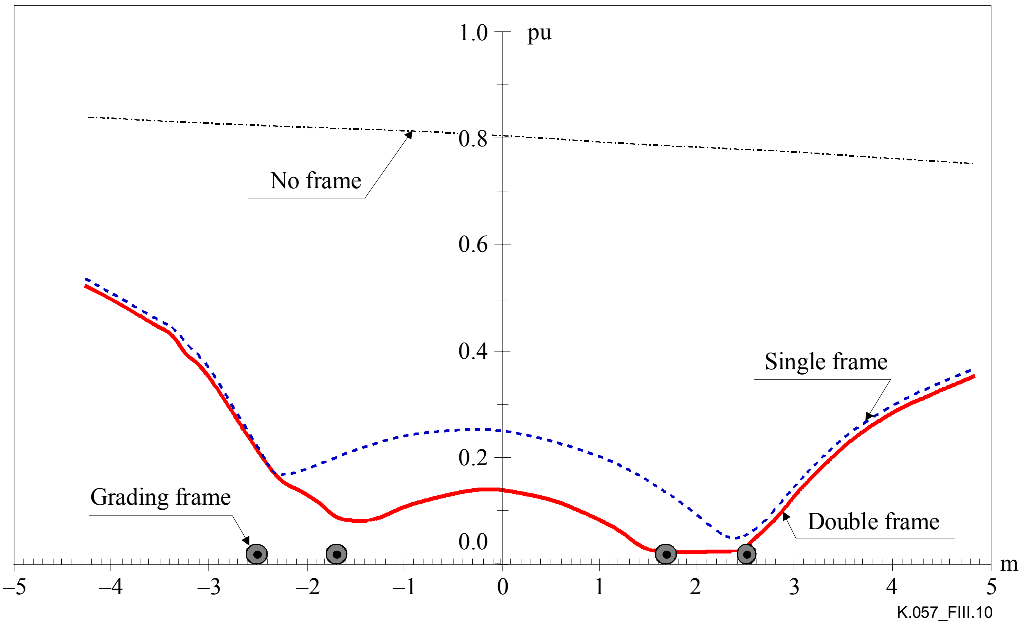



**Figure III.10/K.57 – Profile of touch voltage (pu, Base: T-EPR) for cabinet beside the tower. Profile: direction 45º through the centre point of the PGE frame**

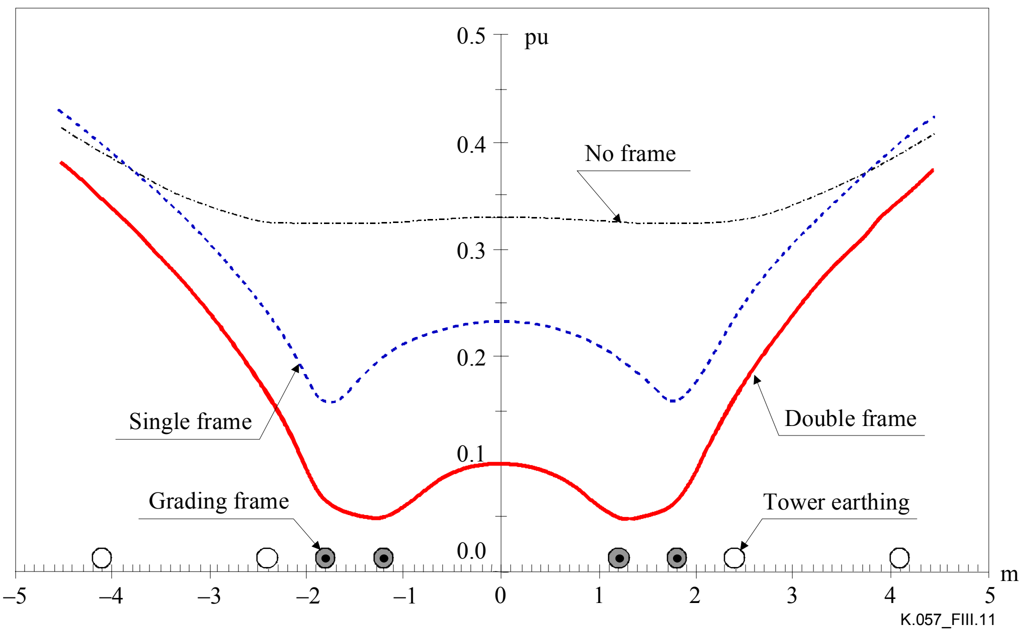



**Figure III.11/K.57 – Profile of touch voltage (pu, Base: T-EPR) for cabinet between the tower legs. Profile: X direction, in centre line of the PGE frame**

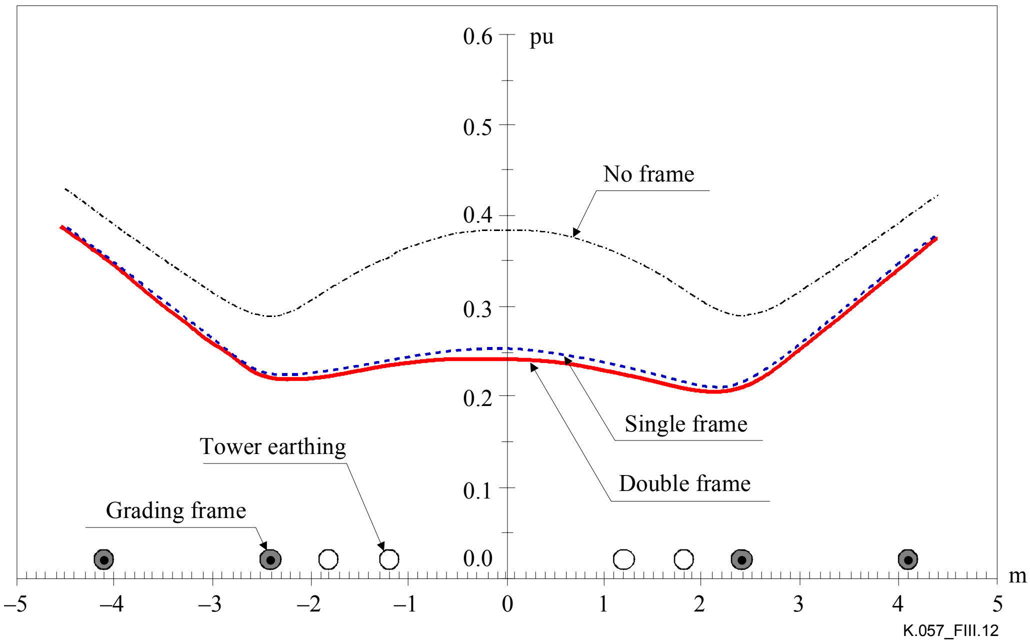



**Figure III.12/K.57 – Profile of touch voltage (pu, Base: T-EPR) for cabinet between the tower legs. Profile: X direction, in centre line of the tower-earthing electrodes**

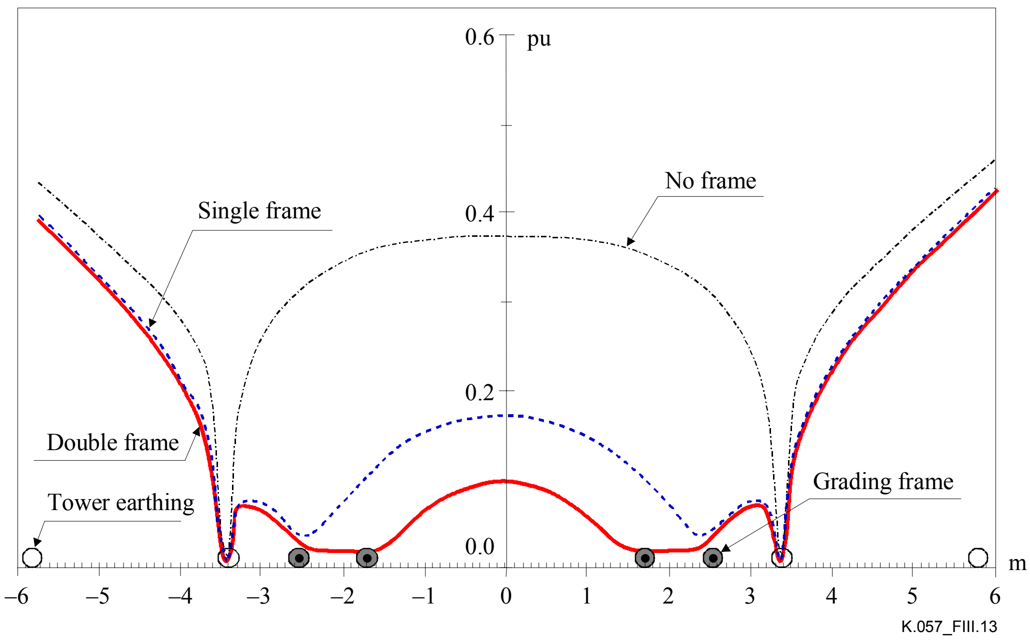



**Figure III.13/K.57 – Profile of touch voltage (pu, Base: T-EPR) for cabinet between the tower legs. Profile: direction 45° through the centre point of the grading electrode frame**

For the judgement of the effectiveness of the PGE frame, the profiles are given for the following investigated options:

- no PGE frame (solid brown profile);
- single PGE frame (dotted blue profile);
- double PGE frames (solid red profile).

The electrode potentials are the following for the basic conditions given in III.2.1 a).

| Cabinet location | Electrode potentials in V | | |
|---|---|---|---|
| | Applied PGE frame | | |
| | None | Single frame | Double frame |
| Between legs | 2746 | 2554 | 2530 |
| Beside the tower | 2746 | 1870 | 1844 |

It is worth mentioning that when dividing the above voltage values by 1000 A, the earthing resistance of the electrode system will be obtained.

Considering that the profiles are given as normalized values, neither the value of ρ nor the injected current magnitude affects the results.

The vertical scale of the plots is per unit (pu). The base is the electrode potential rise (T-EPR).

Small filled or empty circles placed above the length scale indicate the positions of the PGE frame or the tower-earthing frame mesh along the profile direction. These help in the qualitative analysis of the effectiveness of the applied grading electrodes.

The pu value can easily be recalculated to voltage relevant to an actual line condition on the basis of the information given in Appendix I, particularly in Table I.1.

***For example***, let be the touch voltage $u_t = 0.15$ pu. (Corresponds to Figure III.8, i.e., Cabinet beside the tower, use of single PGE frame, location side of the cabinet just above the PGE frame.)

The tower holding the RBS should belong to a line characterized by:

1) average tower-earthing resistance of 25 Ω;
2) two shield-wires;
3) mean span around 330 m (no span correction factor can be considered);
4) phase-to-earth fault current $I_{ef} = 15$ kA.

Taking into consideration conditions 1) and 2), the tower-earthing potential rise taken from Table I.1 is: $U_b = 5589$ V/10 kA.

The value of the touch voltage when considering condition 4) as well is obtained as follows:

$$U_t = u_t \times U_b \frac{I_{ef}}{10} = 0.15 \times 5589 \frac{15}{10} = 0.15 \times 8384 = 1258 \text{ V}$$

The touch voltages relevant to the three investigated PGE frame options are:

| Touch voltage | Applied PGE frame | | |
|---|---|---|---|
| | None | Single | Double |
| pu | 0.805 | 0.15 | 0.08 |
| For the actual condition, in V | 6751 | 1258 | 671 |

d) *Analysis of the results*

The presented profiles clearly show the effectiveness of the PGE frames in reducing the touch and step voltages. The PGE effect is shown at the side of the cabinet in the X direction profiles going through the centre line of the PGE frame (see Figures III.8 and III.11), while it is shown at the corner region of the cabinet in 45º profiles (see Figures III.10 and III.13). The Y direction profile for that arrangement, when the cabinet is beside the tower (see Figure III.9), provides values both for the surrounding area of the cabinet and for that of the tower legs.

1) *Touch voltage reduction effect of the grading*

The reduction effect of the grading frames can be characterized by the following touch voltage values:

| Application of the grading | Touch voltage range | Remarks |
|---|---|---|
| None | 0.33 to 0.4 to 0.8(*) | (*) For cabinet beside the tower |
| Single frame | 0.15 to 0.20 | Above the grading frame |
| Double frame | 0.05 to 0.10 | In the zone above the frames |

The reduction effect of the grading frames on the touch voltage can be summarized in the following statements:

- A single PGE frame reduces the touch voltage by a factor of about 0.5 in relation to that condition when no PGE frame is applied. This reduction level occurs in a narrow zone just above the PGE electrode. The reduction rate can be even below 0.25, when the cabinet is beside the tower.
- The application of a second grading frame provides an additional reduction rate of 0.33 to 0.50. This reduction level affects a wider zone above the double PGE frames.

2) *Effect on the step voltage of the PGE*

The step voltage is given by the gradient (steepness) of the earth potential profiles. The following statements can characterize the effect of the PGE electrode system on the step voltage:

- The application of the grading frames practically does not affect the step voltage outside the outer grading frame (see, e.g., Figures III.11 and III.12).
- The step voltage is significantly reduced in the zone above the double PGE electrode frames.
- The step voltage is practically identical for the single and double PGE frame systems outside the outer grading frame.

### III.2.2 Conclusions and proposals

a) *Conclusions*

The use of the PGE system effectively reduces the touch voltage to the cabinet body. This is a key issue for the safety of staff working beside the RBS cabinet. Therefore, the use of the PGE system is reasonable in any case and absolutely necessary in case of cabinets located beside the tower.

The PGE reduces the step voltage as well. However, in the case of a single PGE frame this reduction is limited to a narrow path just above the PGE electrode. The step voltage is more effectively reduced by double PGE frames, especially in the zone above the double PGE frames.

The PGE system does not reduce the step voltage in the area outside of the PGE system. It is worth mentioning that the reduction of the step voltage is not a key safety issue in the outside zone. Such kind of step voltage can occur in the surrounding area of any HV power line tower. No action is made to reduce this step voltage. According to long time experiences no injuries to people have been reported due to step voltages, which can occur in the surrounding area of power line towers.

b) *Proposals for the application of the PGE*

In order to avoid unsafe level of step and touch voltages, when approaching and entering the equipment cabinet, PGE electrode frames shall surround the cabinet. The electrode arrangements are shown in Figures III.14 and III.15 respectively for two typical cabinet locations, i.e., between the tower legs or beside the tower. Regarding the implementation of the PGE system, the following guidance can be stated:

- The laying depth of the earth electrodes should be 0.3 m.
- The minimum size of the electrode conductor should be 3.5 by 30 mm zinc-coated flat steel or cylindrical steel with a diameter of 20 mm.
- The PGE electrode shall be bonded both to the cabinet earth and to the legs of the tower at least at two corners diagonally, when the cabinet is located between the legs (see Figure III.14).
- If necessary, two vertical earth rods should also be installed and connected to the earthing system.
- When a single PGE frame is applied, it should be laid around the cabinet at a distance of 0.6 m from the periphery of the cabinet, including the metallic steps if any.
- When a double PGE frame earth is applied, the frames should be placed ±0.3 m from the centre line assumed at a distance of 0.6 m from the periphery of the cabinet; i.e., the inner and outer frame earths should be laid 0.3 m and 0.9 m distance from the periphery of the cabinet, respectively. The use of this kind of double frame earth is preferable in case of stringent conditions resulting in high potential rise especially for cabinets located beside the tower.

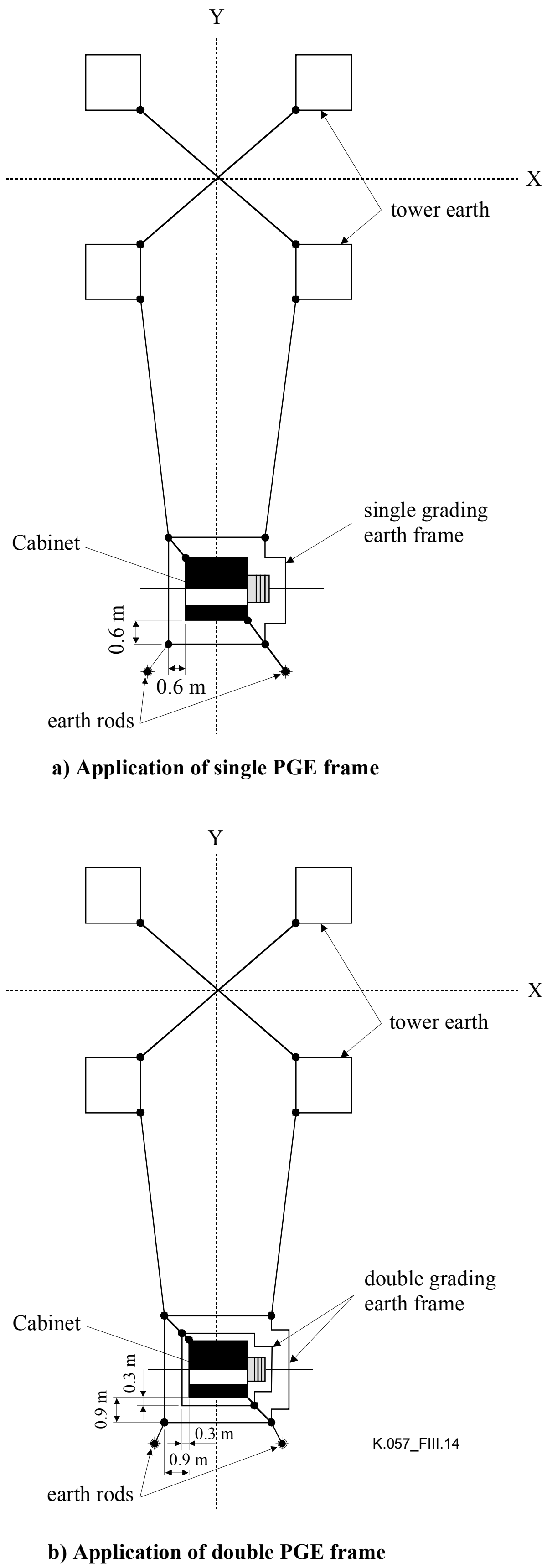
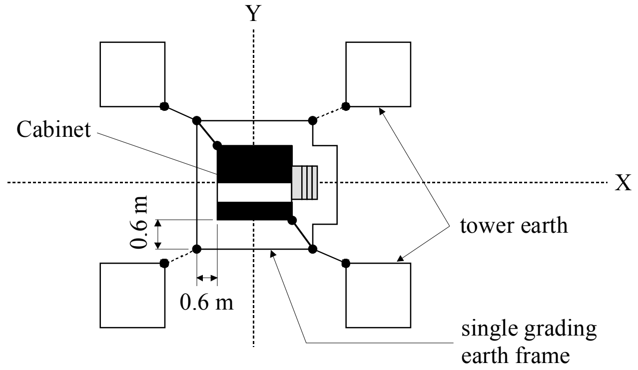
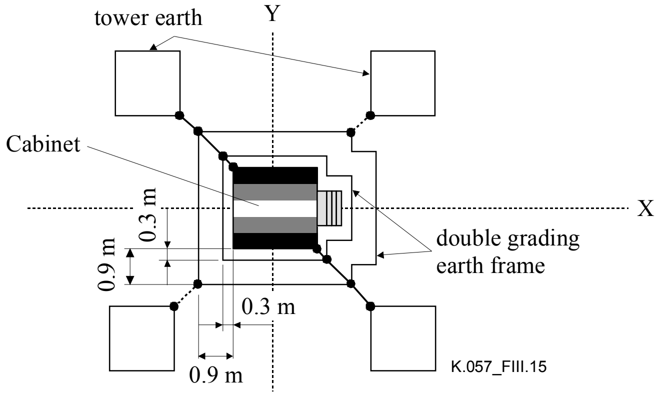



**Figure III.14/K.57 – Arrangement of the PGE system in case of cabinet located beside the tower**




**a) Application of single PGE frame**




**b) Application of double PGE frame**

**Figure III.15/K.57 – Arrangement of the PGE system in case of cabinet located between the tower legs**

## III.3 Estimation of minimum length values

For orientation purposes, estimated values are derived for the earthing electrode potentials equal to the isolation voltage levels considered in Appendix I.

The ρ/R value is needed for the estimation of the minimum length values by the expression III-4. The estimation is based on the representation of the tower-earthing resistance *R* by an equivalent hemisphere. The following relation applies between the equivalent radius $r_{eq}$ of the hemisphere and *R*:

$$R = \frac{\rho}{2\pi r_{eq}} \tag{III-5}$$

The following expression is obtained for the ρ/*R* ratio with the rearrangement of the above formula:

$$\frac{\rho}{R} = 2\pi\, r_{eq} \tag{III-6}$$

The formula III-6 clearly shows that the ρ/*R* value is linked with the $r_{eq}$ by the multiplier 2π.

The ρ/*R* ratios are identified by the following technique for practical purposes. The earthing system of the tower footing, as a whole, is simulated by the CDEGS code [III.2] for a series of actual arrangements (in fact for 21 different cases). In the calculations, 1000 A (arbitrary value) is injected to the electrode system. The CDEGS code solves the electromagnetic field problem of the inputted electrode system embedded in homogeneous earth with a given specific soil resistivity ρ. (The CDEGS code would allow the calculations for stratified earth structure as well.) The value of ρ has, arbitrarily, been selected to 50 Ωm in the simulation calculations. One of the results of the calculation is the potential rise of the electrode with respect to the remote earth. The earthing resistance, $R$, of the tower-earthing system is obtained, by definition, as the ratio of the calculated potential rise to the injected current considered in the calculation, i.e., 1000 A. Using the calculated $R$ value and the value of ρ assumed in the calculation, the $\rho/R$ ratio is calculated for each simulated earthing electrode structure. It is worth mentioning that the $\rho/R$ ratio depends neither on the value of ρ nor on the value of the injected current considered in the simulation calculations.

The structure and geometrical sizes of the earth electrode of each tower leg are demonstrated in Figure III.16.

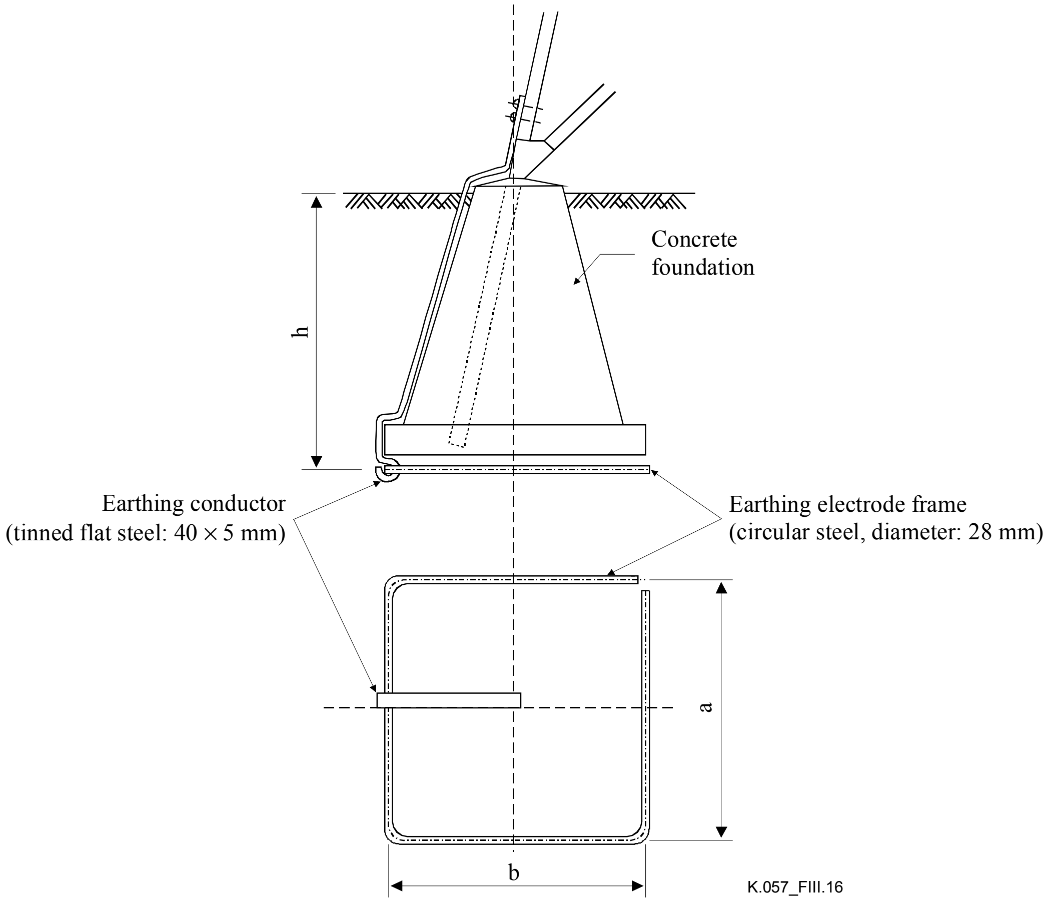



**Figure III.16/K.57 – Structure and geometrical sizes of the earth electrode of a tower leg**

The foundation of a tower is composed of either four legs (typical for a self-supporting tower foundation) or two legs (typical for an H-frame suspension tower). Correspondingly to these options, the calculations have been performed for earthing electrode arrangements containing four or two frame electrodes (see in the 1st column of Table III.1). The spacing between the legs ($f_1$ and $f_2$) of the foundation, the lateral sizes ($a$ and $b$) of the frame electrode, and the depth of the earthing electrode identify geometrical sizes of the electrode systems according to Table III.1.

The $\rho/R$ values calculated for 21 earthing system structures are plotted in the last column of Table III.1. Taking $\rho/R = 18$, which will cover about half of the values in the referred table, we get with formula III-4:

$$x_{\min} = \frac{1}{2\pi} 18 \frac{V_e}{V_x} = 2.9 \frac{V_e}{V_x} \qquad \text{(III-7)}$$

When considering:

– the earthing electrode potentials according to the isolating voltage levels used in Appendix I:

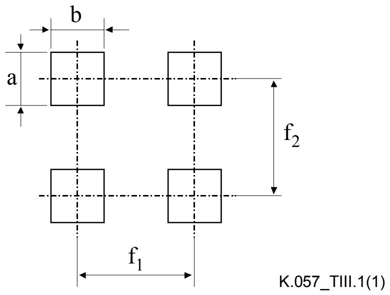
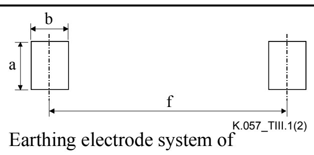
$$V = 10 \text{ kV, } 15 \text{ kV, } 20 \text{ kV and } 50 \text{ kV}$$

– the permissible stipulated no load earth potentials at the conversion cabinet for copper telecom cable or at the junction points:

$$V_x = 650 \text{ V or } 1 \text{ kV, } 1.5 \text{ kV and } 2 \text{ kV}$$

the minimum lengths of the junction section obtained from formula III-7 are given in Table III.2.

**Table III.1/K.57 – Examples of values for the parameter ρ/R for different tower-earthing arrangements**

| Tower earthing | | | | | | | | | ρ/*R* |
|---|---|---|---|---|---|---|---|---|---|
| Arrangement | | Typical voltage level [kV] | Case code | Sizes of the frame electrode [m] | | | | | |
| | | | | Legs spacing[a)] | | Lateral[b)] | | Depth | |
| | | | | $f_1$ | $f_2$ | a | b | | |
| Direction of the line route |  Self-supporting tower foundation | 120 | 1 | 3.6 | | 1.3 | | 1.8 | 13.3 |
| | | 120 | 2 | 3.7 | | 1.3 | | 1.8 | 13.5 |
| | | 220 | 3 | 4.5 | 4.0 | 1.4 | | 1.6 | 14.1 |
| | | 120 | 4 | 4.8 | | 1.6 | | 1.6 | 15.5 |
| | | 120 | 5 | 7.2 | 4.3 | 1.4 | | 1.8 | 15.8 |
| | | 120 | 6 | 4.5 | | 2.0 | | 1.9 | 17.1 |
| | | 220 | 7 | 6.0 | | 1.7 | | 1.8 | 17.4 |
| | | 400 | 8 | 6.8 | | 1.7 | | 1.6 | 17.6 |
| | | 220 | 9 | 6.5 | | 1.7 | | 2.0 | 18.2 |
| | | 120 | 10 | 6.0 | | 1.9 | | 2.4 | 19.3 |
| | | 400 | 11 | 7.5 | 5.5 | 2.0 | | 2.0 | 19.4 |
| | | 750 | 12 | 9.0 | | 2.2 | | 1.8 | 21.9 |
| | | 400 | 13 | 8.2 | | 2.3 | | 2.4 | 22.9 |
| | | 220 | 14 | 7.0 | | 2.8 | | 2.0 | 23.1 |
| | | 750 | 15 | 10.0 | | 2.4 | | 2.9 | 25.7 |
| | | 220 | 16 | 9.0 | | 3.0 | | 2.8 | 27.3 |
| | | 750 | 17 | 11.0 | | 3.0 | | 4.1 | 31.2 |
| |  Earthing electrode system of H-frame suspension tower | 400[c)] | 18 | 19.0 | | 1.2 | | 1.6 | 9.7 |
| | | 120 | 19 | 5.4 | | 4.2 | 1.8 | 2.5 | 15.5 |
| | | 220 | 20 | 18.0 | | 3.2 | 2.5 | 2.9 | 18.1 |
| | | 750[c)] | 21 | 26.4 | | 2.9 | 1.1 | 5.3 | 18.4 |

a) One value is only given when the spacing sizes between the legs of the tower foundation are identical, i.e., $f_1 = f_2 = f$, or the tower foundation consists only of two legs with spacing f (see the upper and lower schemes in the 1st column of the table, respectively).

b) One value is only given when the lateral sizes of the frame type earthing electrode are identical, i.e., a = b.

c) Earthing electrode system of guyed H-frame suspension tower.

**Table III.2/K.57 – Minimum required lengths of the junction section corresponding to the isolation voltage levels (Appendix I) and admissible Z-EPR at the junction point**

| Isolation voltage level, *V* [kV] | Minimum length [m] | | | |
|---|---|---|---|---|
| | to conversion cabinet for copper telecom cable[a)] | of the junction section | | |
| | Admissible EPR at the junction point, $V_x$ | | | |
| | **650 V** | **1 kV** | **1.5 kV** | **2 kV** |
| 10 | 44 | 29 | 19 | 14 |
| 15 | 67 | 43 | 29 | 22 |
| 20 | 28 | 58 | 39 | 29 |
| 50 | 221 | 144 | 96 | 72 |

[a)] See Figures 5 and 6.

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