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TELECOMMUNICATION
STANDARDIZATION SECTOR
OF ITU

K.46
(05/2012)

SERIES K: PROTECTION AGAINST INTERFERENCE

Protection of telecommunication lines using metallic symmetric conductors against lightning-induced surges

Recommendation ITU-T K.46

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Summary

Recommendation ITU-T K.46 gives a procedure to protect telecommunication lines using metallic symmetric conductors (i.e., twisted pair cables) against overvoltages and overcurrents imposed on the lines due to nearby lightning flashes.

The procedure is based on the representation of the line by a sequence of sections and nodes, and the evaluation of each node exposure to the lightning-induced surges. Based on the node exposure, the ground flash density and the earth resistivity, the annual number of surges above a given voltage level is calculated. If the voltage level considered is the impulse withstand voltage of the node, then the number of surges above this level corresponds to the annual number of damages to the node. This number shall be multiplied by the loss due to induced surges in order to obtain the risk of failure due to indirect lightning flashes. The highest risk of all nodes is the risk of the line.

The risk of failure due to indirect lightning flashes (R'_Z) can be used in the risk assessment of a larger system to which the telecommunication line is a part, according to IEC 62305-2. The calculated risk can also be used by the line owner (e.g., telecommunication operator) in order to evaluate the need of implementing additional protection measures on the line. In this case, the calculated risk (R'_Z) shall be compared with the tolerable risk due to indirect flashes (R_{Ti}), the latter calculated based on ITU-T K.72. If the calculated risk is lower than the tolerable limit, the line is adequately protected. Otherwise, it is necessary to implement additional protection measures until the risk of damage is lower than or equal to the tolerable limit.

The appendices are organized as follows: Appendix I provides data on the electrical characteristics of cable shields, Appendix II presents an algorithm to guide the elaboration of software based on this Recommendation, Appendix III presents the calculation of the collection area for flashes near the line and Appendix IV shows some examples of calculation.

History

Edition	Recommendation	Approval	Study Group
1.0	ITU-T K.46	2000-12-08	5
2.0	ITU-T K.46	2003-07-29	5
3.0	ITU-T K.46	2008-04-13	5
4.0	ITU-T K.46	2012-05-29	5

Keywords

Earthing resistance, lightning-induced surges, lightning protection, refraction factor, risk assessment, shielding factor, surge protective device, telecommunication lines.

FOREWORD

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The World Telecommunication Standardization Assembly (WTSA), which meets every four years, establishes the topics for study by the ITU-T study groups which, in turn, produce Recommendations on these topics.

The approval of ITU-T Recommendations is covered by the procedure laid down in WTSA Resolution 1.

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

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Protection of telecommunication lines using metallic symmetric conductors against lightning-induced surges

1 Scope

This Recommendation gives a procedure in order to protect telecommunication lines using metallic symmetric conductors (i.e., twisted pair cables) against overvoltages and overcurrents imposed on the lines due to nearby lightning flashes.

Its calculation procedure allows the assessment of the expected annual number of damages (N_Z) and the risk of damage due to indirect lightning flashes (R'_Z). The risk of damage due to indirect lightning flashes can be used in the risk assessment of a larger system to which the telecommunication line is a part, according to [IEC 62305-2]. The calculated risk can also be used by the line owner (e.g., telecommunication operator) in order to evaluate the need of implementing additional protection measures on the line. In this case, the calculated risk (R'_Z) shall be compared with the tolerable risk due to indirect flashes (R_{Ti}), the latter calculated based on [ITU-T K.72]. If the calculated risk is lower than the tolerable limit, the line is adequately protected. Otherwise, it is necessary to implement additional protection measures until the risk of damage is lower than or equal to the tolerable limit.

Depending on the user's desire, the resistibility of the external port of network terminal equipment (e.g., exchange line card, modem, POTS telephone set, etc.) may or may not be included in the calculation. This decision implies the selection of the appropriate impulse withstand voltage (U_W) of the relevant line node and the result shall be limited to the damage caused to the external port of the equipment. However, the protection of other equipment ports (e.g., power port) and of equipment that does not have a direct interface with the line is outside the scope of this Recommendation and should be evaluated using the risk assessment applied to the exchange or to the customer's structure.

The protection of persons using telecommunication equipment inside the exchange or the customer's structure from dangerous situations caused by touch voltages is outside the scope of this Recommendation and should be evaluated using the risk assessment applied to the exchange or to the customer's structure.

2 References

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

[ITU-T K.12]	Recommendation ITU-T K.12 (2010), *Characteristics of gas discharge tubes for the protection of telecommunications installations*.
[ITU-T K.27]	Recommendation ITU-T K.27 (1996), *Bonding configurations and earthing inside a telecommunication building*.
[ITU-T K.28]	Recommendation ITU-T K.28 (2012), *Parameters of thyristor-based surge protective devices for the protection of telecommunication installations*.
[ITU-T K.47]	Recommendation ITU-T K.47 (2012), *Protection of telecommunication lines against direct lightning flashes*.

[ITU-T K.66] Recommendation ITU-T K.66 (2011), *Protection of customer premises from overvoltages*.

[ITU-T K.67] Recommendation ITU-T K.67 (2006), *Expected surges on telecommunications and signalling networks due to lightning*.

[ITU-T K.72] Recommendation ITU-T K.72 (2011), *Protection of telecommunication lines using metallic conductors against lightning – Risk management*.

[IEC 62305-2] IEC 62305-2 (2010), *Protection against lightning – Part 2: Risk management*. <http://webstore.iec.ch/webstore/webstore.nsf/ArtNum_PK/45856?OpenDocument>

3 Definitions

3.1 Terms defined elsewhere

None.

3.2 Terms defined in this Recommendation

This Recommendation defines the following terms:

3.2.1 conversion factor: Ratio between the line-to-shield voltage and the line-to-earth voltage arriving at the transition from an unshielded section to a shielded section.

3.2.2 downstream direction: Direction from the first node to the last node of the line.

3.2.3 impulse withstand voltage (U_W): Peak value of the maximum common-mode impulsive voltage (10/700 µs waveform) that can be applied to an external equipment port or cable insulation without causing damage.

3.2.4 lightning flash near a line: Lightning flash striking close enough to a line so that it may induce dangerous overvoltages on the line.

3.2.5 loss (L): Annual mean amount of loss (humans and goods) consequent to a specified type of damage due to a dangerous event, relative to the total value (humans and goods) of the object to be protected.

3.2.6 loss due to lightning-induced surges (L_i): Annual mean amount of loss (to the public and economic value) consequent to damage in a telecommunication line due to lightning-induced surges, relative to the total value of the service (according to [IEC62305-2], $L_i = L_o$).

3.2.7 metallic symmetric conductors: Transmission media consisting of a pair of twisted wires balanced with respect to earth, usually assembled in groups in order to form a telecommunication cable.

3.2.8 node: Point between two sections of a telecommunication line.

3.2.9 node exposure: Value assigned to a line node (in km) that represents the exposure of this node to the effects of the lightning-induced voltages.

3.2.10 number of damages (N_Z): Expected annual number of damages in the telecommunication line due to lightning-induced surges.

3.2.11 protection factor of SPD (P_{SPD}): Factor taking into account the effect of surge protective device (SPD) installation at a given node.

3.2.12 protection measures: Measures to be adopted in a telecommunication line to reduce its risk of damage.

3.2.13 refraction factor: Ratio between the common-mode surge voltage travelling in the line after passing through a discontinuity in its surge impedance and the surge that would travel in the line if there were no discontinuity in its surge impedance.

3.2.14 risk (R): Value of probable average annual loss (humans and goods) due to lightning, relative to the total value (humans and goods) of the object to be protected.

3.2.15 risk of damage from indirect flashes (R'_Z): Risk component related to failure of lines and connected equipment caused by surges induced on the line by indirect lightning flashes.

3.2.16 rural environment: Area with a low density of buildings. "Countryside" is an example of rural environment.

3.2.17 section of a telecommunication line: Part of a telecommunication line with homogeneous characteristics where only one set of parameters is involved in the assessment of a risk component.

3.2.18 shielded node: Reference point of the telecommunication line where at least one cable is shielded. A node at the transition between a shielded and an unshielded cable is shielded.

3.2.19 shielded section: Section of the line where the cable is made of one or more pairs of twisted wires balanced with respect to earth, assembled together and covered by a metallic sheath.

3.2.20 shielding factor: Ratio between the voltage at a point of the line when the shield is present and the voltage at the same point when the shield is absent.

3.2.21 suburban environment: Area with a medium density of buildings. "Town outskirts" is an example of suburban environment.

3.2.22 surge: Temporary excessive voltage or current, or both, coupled on a telecommunication line from an external electrical source.

3.2.23 surge impedance (Z): Impedance presented by a line section to the surge propagation. It is generally given by the square root of the ratio between line-to-earth inductance and line-to-earth capacitance.

3.2.24 surge protective device (SPD): A device that is intended to mitigate surge overvoltages and overcurrents of limited durations. It may consist of a single component or have a more complex design, where several functions are integrated. It contains at least one non-linear component.

3.2.25 telecommunication line: Transmission medium intended for communication between equipment that may be located in separate structures, such as a phone line and a data line.

3.2.26 tolerable risk (R_T): Maximum value of the risk which can be tolerated for the object to be protected.

3.2.27 tolerable risk due to indirect flashes (R_{Ti}): Maximum value of risk that can be tolerated for the line due to lightning surges.

3.2.28 transition node (q): Node that corresponds to the transition between shielded and unshielded line sections.

3.2.29 unshielded node: Reference point of the telecommunication line where the cable(s) is (are) unshielded.

3.2.30 unshielded section: Section of the line where the cable is made of one or more pairs of twisted wires balanced with respect to earth and assembled together without a metallic sheath.

3.2.31 upstream direction: Direction from the last node to the first node of the line.

3.2.32 urban environment: Area with a high density of buildings or densely populated communities with high buildings. "Town centre" is an example of urban environment.

4 Abbreviations and acronyms

This Recommendation uses the following abbreviations and acronyms:

BB	Bonding Bar
CCP-AP	Colour Coded Polyethylene Aluminium laminated Polyethylene (sheath)
MDF	Main Distribution Frame
SPD	Surge Protective Device

5 Reference configuration

Figure 1 shows the reference configuration for a telecommunication line with metallic symmetric conductors, composed of m sections and m +1 nodes. A generic section or node along the line is designated by the symbol i. The direction from node 1 to node m +1 is designated as "downstream direction", while the direction from node $m + 1$ to node 1 is designated as "upstream direction", as shown in Figure 1.

Usually, the telecommunication line starts at the exchange (node 1) and ends at the subscriber premises (node m +1), but the following situations are possible:

a) If equipment installed in the line is protected by SPDs installed between line conductors (at both input and output ports) and the equipment earth connection, then this equipment shall be treated as an ending point for the line that comes from the exchange and a starting point for the line that goes to the subscriber premises. This is usually the case for access network equipment located in a remote electronic site.

b) If equipment installed in the line has no earth connection and its protection is given by the insulation to earth and by SPDs installed at both input and output ports against a common reference, then the presence of this equipment can be neglected, but the presence of SPDs shall be considered.

c) If telecommunication or signal lines are connecting equipment located in different buildings within the subscriber's premises (e.g., signal lines between computers), then this telecommunication line starts and ends within the subscriber premises.

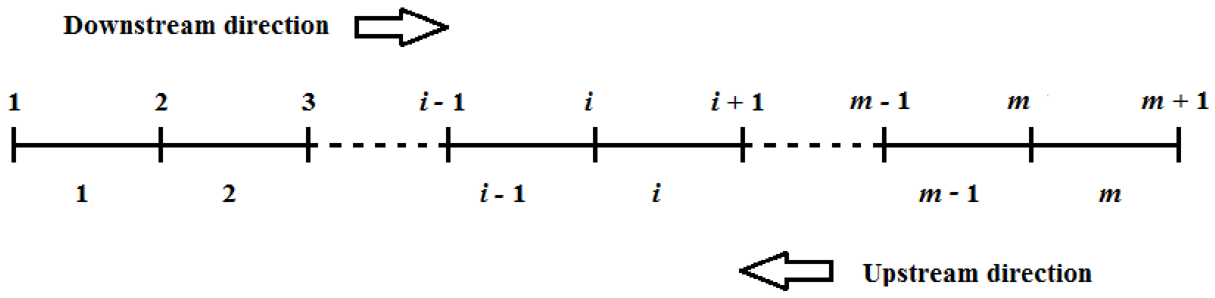


Figure 1 – Reference configuration of a line composed of *m* sections and *m* + 1 nodes

If there are shielded sections, the first section (section 1) must be shielded and all other shielded sections must be adjacent to each other, so that the shield is kept continuous. An unshielded section between two shielded sections is not allowed by the procedure of this Recommendation. The node containing a transition between shielded and unshielded sections is a shielded node and it is designated by the symbol q (e.g., node q), as shown in Figure 2.

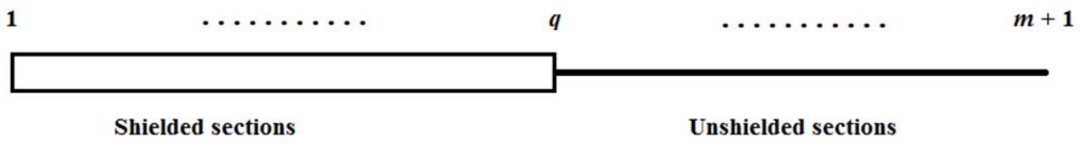


Figure 2 – Sequence of shielded and unshielded sections, with transition node *q*

The last node (node *m* +1) usually represents the subscriber premises and the first node (node 1) may represent:

– exchange building, where the main switching equipment is located;

– access network equipment, usually installed in the outside plant (remote electronic site);

– equipment within the subscriber premises.

The intermediate nodes shall be created in the presence of the following conditions:

– transition between paper-insulated and plastic-insulated cables;

– transition between buried and aerial cables;

– transition between shielded and unshielded cables;

– transition between types of cable (e.g., number of pairs);

– earthing system connected to the line;

– surge protective devices connected to the line;

– whenever the user wants it.

NOTE – The term "node" in [IEC 62305-2] has a different meaning.

Sometimes two or more transitions may occur at the same node, such as the transition in the line from paper to plastic insulation and from buried to aerial installation.

This Recommendation uses the concept of surge propagation along the line, which requires that a minimum distance of 200 m shall be observed between consecutive nodes (i.e., the minimum section length is 200 m). If two transitions occur at shorter distances, they have to be considered at the same node. For instance, if two earthing systems are very close (e.g., 50 m apart), they shall be considered as a single earthing with a resistance given by the parallel association.

6 General requirements

6.1 Impulse withstand voltage levels

For the purpose of this Recommendation, the following impulse withstand voltage levels (U_W) shall be considered, when tested with 10/700 µs waveform.

– Shielded cables with paper insulation: The insulation between any conductor and shield shall withstand an overvoltage of 1.5 kV peak.

– Shielded cables with plastic insulation: The insulation between any conductor and shield shall withstand an overvoltage of 5.0 kV peak.

– Unshielded cables with plastic insulation: The insulation between any conductor and earth shall withstand an overvoltage of 15.0 kV peak.

NOTE – The U_W level of equipment connected to the line (external port) is given by the resistibility level provided by the relevant ITU-T Recommendation.

6.2 Surge protective devices (SPDs)

The SPD shall comply with [ITU-T K.12] when using gas discharge technology or with [ITU-T K.28] when using semi-conductor technology. The latter are usually used in the exchange building only.

The minimum DC breakdown voltage of the SPD shall be greater than the maximum line voltage expected. It shall be observed that, in some equipment, ringing voltage may add to DC powering voltage. Due to the possibility of variations in the line voltage and/or the presence of power frequency voltage induced on the line, a safety margin shall be provided between the maximum line voltage and the minimum DC breakdown voltage of the SPD.

The maximum impulse breakdown voltage of the SPD shall be lower than the impulse withstand voltage (U_W) of the unit to be protected. A significant safety margin is recommended.

The line terminals of an SPD shall be connected to the conductors of the telecommunication line and their earth terminals shall be connected to the earthing bonding bar of an unshielded node or to the cable shield of a shielded node. Figure 3 shows the connections of SPDs at a shielded node (Figure 3a) and at an unshielded node (Figure 3b). If a local earthing system is available, the bonding bar or the cable shield shall be connected to it. However, if there is no earthing system available at an unshielded node, one has to be constructed in order to allow the proper installation of the SPD.

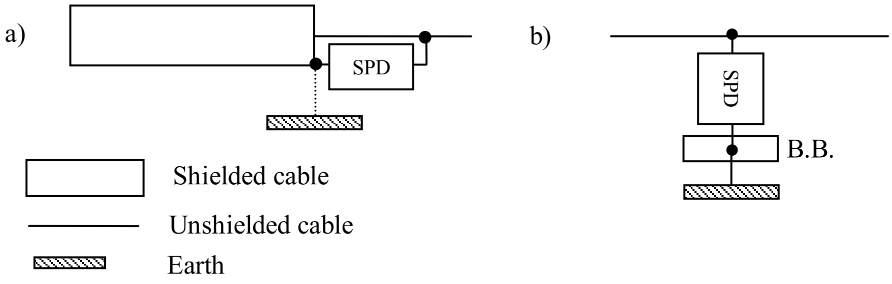


Figure 3 – Installation of surge protective devices (SPDs)

6.3 Earthing and bonding

6.3.1 Exchange

All shielded cables entering the exchange building shall have continuous metallic sheaths, which means that the sheath shall be bonded across all splices. At the entrance of the building (cable chamber), all metallic sheaths shall be bonded to the building's main earthing terminal located near this point, according to [ITU-T K.27]. This bonding shall be made using low-impedance conductors (short and wide).

NOTE – In some particular cases, where there is evidence of galvanic corrosion in the cable plant, it is acceptable to perform this bonding by means of SPD, provided that they are adequately dimensioned.

If the cable arriving at the main distribution frame (MDF) has a metallic sheath, it shall be bonded to the MDF bonding bar. The MDF bonding bar shall be connected to the main earthing terminal by means of a low impedance conductor.

6.3.2 Outside plant

At the transition between two shielded cables, the shield shall be bonded across the transition by an adequate bonding conductor. In the case of aluminium sheath, care shall be taken in order to assure good and permanent contact between the sheath and the bonding conductor, which can be accomplished by use of an adequate clamp. If the transition takes place at a cross-connect cabinet, it is recommended that a bonding bar is provided close to the cable entrance point and that all the metallic sheaths are bonded to this bar.

If the transition between a shielded and an unshielded cable is made by means of a distribution box, its bonding terminal shall be connected to the cable shield directly or through the metallic sheath of a stub cable.

If the cable connected to the access network equipment is shielded, its shield shall be bonded to the equipment bonding bar located at the entrance of the shelter.

6.3.3 Subscriber premises

If the cable that arrives at the subscriber premises is shielded, its shield shall be bonded to the subscriber's equipotential bonding bar, according to [ITU-T K.66]. The other metallic parts of the subscriber premises (such as metallic water and/or gas pipes, and metal framework of the building) shall be connected to the equipotential bonding bar, in order to reduce the overvoltages between accessible parts.

7 Indirect lightning performance of a telecommunication line

7.1 Number of damages and risk assessment

This Recommendation characterizes the performance of a telecommunication line due to indirect lightning flashes by evaluating the expected annual number of damages (N_Z) of a given line node and the risk of failure (R'_Z) of the line. The calculation procedure for these two quantities is given in this clause.

The expected number of damages (N_Z) per year of a given node is given by:

$$N_Z = 0.216\, N_G\, \rho^{1/2}\, \mathrm{X}\, U_W^{-1.8} \qquad (1)$$

where:

N_Z is the number of damages per year (i.e., number of surges with peak values above U_W);

N_G is the ground flash density in flashes per km^2 per year;

ρ is the average earth resistivity in Ωm;

X is the node exposure in km;

U_W is the impulse withstand level of the considered node, in kV.

NOTE – Equation 1 is supported by the experimental data available, as shown in Appendix IV. In this equation, the line physical characteristics and its protection measures are captured by the node exposure X.

The risk of failure of a given node i ($R'_Z(i)$) due to indirect flashes is given by:

$$R'_Z(i) = N_Z(i)\, L_i(i) \qquad (2)$$

where:

$L_i(i)$ is the loss due to lightning-induced surges referred to the node i and calculated according to [IEC62305-2], where $L_i = L_o$;

The risk of line damage (R'_Z) is the highest value among the risks of damage of its nodes ($R'_Z(i)$).

7.2 Tolerable risk

The protection measures applied to a telecommunication line are intended to reduce its exposure to lightning-induced surges and, consequently, to reduce its number of damages (N_Z) and its risk (R'_Z). The need of protection and the evaluation of its effectiveness shall be assessed by the procedure contained in this Recommendation.

According to [ITU-T K.72], the tolerable risk of damage due to flashes near a telecommunication line (R_{Ti}) is given by the difference between the total tolerable risk (R_T) and the risk of damage due to direct flashes (R_d):

$$R_{Ti} = R_T - R_d \qquad (3)$$

If the risk of damage due to indirect flashes is lower than or equal to the tolerable risk for indirect flashes ($R'_Z \leq R_{Ti}$), then no additional protection measure is needed. Otherwise, additional protection measures shall be applied until the tolerable condition is achieved ($R'_Z \leq R_{Ti}$). The detailed procedure for this risk assessment is described in [ITU-T K.72] and the procedure for the evaluation of R_d is given in [ITU-T K.47].

NOTE – When the determination of R_{Ti} is uncertain or difficult, this Recommendation suggests to adopt $R_{Ti} = 2 \times 10^{-4}$ as a reference value. Combined with the typical consequential loss value ($L_i = L_o = 10^{-3}$) suggested by [IEC 62305-2], it leads to an upper limit for N_Z equal to 0.2 (i.e., one line damage every five years). This suggested value shall be revised by the user based on service requirements and field experience.

8 Node exposure to lightning-induced surges

This clause gives a procedure for the evaluation of a node exposure to lightning-induced surges (X). The procedure is presented in the form of recursive equations in order to facilitate its implementation in a computer code. Its manual application is exemplified in Appendix IV.

8.1 Unshielded nodes

The exposure of an unshielded node (X_u) is a number (in km) that quantifies the node exposure to the lightning-induced surges. It is calculated considering that each line section is a lumped source of surges and that the surges are refracted as they travel towards the node considered.

The exposure of an unshielded node is calculated from the downstream (X_{ud}) and upstream (X_{uu}) directions (see Figure 1), according to:

$$\mathrm{X}_{ud}(i) = \frac{1}{2}\sum_{j=1}^{i-1}\left[C_e(j)K_i(j)L(j)\prod_{k=j+1}^{i}\delta_d(k)\right] \qquad (4)$$

$$\mathrm{X}_{uu}(i) = \frac{1}{2}\sum_{j=i}^{m}\left[C_e(j)K_i(j)L(j)\prod_{k=i}^{j}\delta_u(k)\right] \qquad (5)$$

where:

$\mathrm{X}_{ud}(i)$	is the exposure of the unshielded node i computed downstream the line;
$\mathrm{X}_{uu}(i)$	is the exposure of the unshielded node i computed upstream the line;
$C_e(j)$	is the environmental factor of section j (see Annex A);
$K_i(j)$	is the installation factor of section j (see Annex A);
$L(j)$	is the length of section j in km;
$\delta_d(k)$	is the refraction factor of node k computed in the downstream direction (see Annex B);

$\delta_u(k)$ is the refraction factor of node k computed in the upstream direction (see Annex B).

NOTE – In the use of Equations 4 and 5, whenever the initial value of an index is lower than its final value, the respective term shall be considered null. For example, if $i = 1$ in Equation 4, then the right-hand side is null and $X_{ud}(1) = 0$.

The exposure of the unshielded node i ($X_u(i)$) is the higher value between $X_{uu}(i)$ and $X_{ud}(i)$.

8.2 Shielded nodes

The exposure of a shielded node (X_s) takes into account the shielding factors (η) of the shielded sections. The exposure of a shielded node is calculated in the downstream (X_{sd}) and upstream (X_{su}) directions, according to:

$$X_{sd}(i) = \frac{1}{4}\sum_{j=1}^{i-1} \eta(j) L(j) K_i(j) C_e(j) + \frac{1}{2}\sum_{j=2}^{i-1} \eta(j) \sum_{k=1}^{j-1} L(k) K_i(k) C_e(k) \qquad (6)$$

$$X_{su}(i) = \frac{1}{4}\sum_{j=i}^{q-1} \eta(j) L(j) K_i(j) C_e(j) + \frac{1}{2}\sum_{j=i}^{q-2} \eta(j) \sum_{k=j+1}^{q-1} L(j) K_i(j) C_e(j) + \beta\, X_{uu}(q_m) \qquad (7)$$

where:

$\eta(j)$ is the shielding factor of section j (see Annex C);

$L(j)$ is the length of section j (in km);

β is the line-to-shield conversion factor (see Annex C);

$X_{uu}(q_m)$ is the unshielded upstream exposure computed at the transition node q, considering that the refraction factor at this node is equal to one ($\delta_{uu}(q) = 1$).

NOTE – In the use of Equations 6 and 7, whenever the initial value of an index is lower than its final value, the respective term shall be considered null. For example, if $i = q$ in Equation 7, then the two first terms are null and $X_{su}(q) = \beta\, X_{uu}(q_m)$.

The exposure of the shielded node i ($X_s(i)$) is the higher value between $X_{su}(i)$ and $X_{sd}(i)$.

8.3 Effect of surge protective devices

The installation of a surge protective device in a line reduces the exposure of the nodes as follows:

The earthing resistance of the SPD connected to an unshielded node reduces the surges crossing this node by means of its refraction factor. This effect is considered in Annex B, where the earthing resistance of the SPD shall be considered as if it was directly connected to the unshielded line.

The SPD installation at an unshielded node also reduces the exposure of this node by the protection factor P_{SPD}.

The SPD installation at a shielded node p (where $1 < p < q$) reduces the downstream exposure of this node and of the subsequent nodes according to:

$$\text{For } i = 1 \text{ to } p-1,\ X'_{sd}(i) = X_{sd}(i) \qquad (8)$$

$$\text{For } i = p \text{ to } q,\ X'_{sd}(i) = X_{sd}(i)\, P_{SPD} \qquad (9)$$

The SPD installation at a shielded node p (where $p < q$) reduces the upstream exposure of this node and of the subsequent nodes according to:

$$\text{For } i = p+1 \text{ to } q,\ X'_{su}(i) = X_{su}(i) \qquad (10)$$

$$\text{For } i = 1 \text{ to } p,\ X'_{su}(i) = X_{su}(i)\, P_{SPD} \qquad (11)$$

NOTE 1 – In Equations 8 to 11, $X'_{sd}(i)$ and $X'_{su}(i)$ are the downstream and upstream exposures of node i, respectively, after considering the SPD protection factor.

For the usual case where the SPD is installed at the transition between shielded and unshielded cables ($p = q$), then:

$$\text{For } i = 1 \text{ to } q,\ X'_{sd}(i) = X_{sd}(i) \qquad (12)$$

$$\text{For } i = 1 \text{ to } q,\ X'_{su}(i) = X_{su}(i)\ P_{\text{SPD}} \qquad (13)$$

In all cases, the protection factor $P_{\text{SPD}} = 0.001$.

NOTE 2 – The value $P_{\text{SPD}} = 0.001$ is obtained from [IEC 62305-2] considering the expected induced overcurrent given by [ITU-T K.67].

Annex A

Environmental factor and installation factor

(This annex forms an integral part of this Recommendation.)

The line exposure to the inducing electromagnetic fields produced by indirect lightning flashes is captured in a simplified way by two quantities: the environmental factor and the installation factor. The environmental factor (C_e) is intended to represent the shielding effect provided by the structures that may be surrounding the line, and its values are given in Table A.1 (according to [IEC62305-2]).

Table A.1 – Representative values of the environmental factor C_e

Occupation pattern of the area	Environment factor (C_e)
Rural	1
Suburban (height of buildings less than 10 m)	0.5
Urban (height of buildings ranging between 10 m and 20 m)	0.1
Urban (height of buildings greater than 20 m)	0.01

The installation factor (K_i) takes into account the reduction in the coupling between the lightning flash and the telecommunication line due to the installation of the line underground, when compared with an aerial installation. The values of K_i are given in Table A.2, alongside with the respective line surge impedance.

Table A.2 – Representative values of the installation factor K_i and surge impedance (Z)

Type of line installation	Surge impedance (Z)	Installation factor (K_i)
Aerial	400 Ω	1
Buried	100 Ω	0.5

Annex B

Refraction factor

(This annex forms an integral part of this Recommendation.)

The refraction factor (δ) is defined as the ratio of the surge voltage travelling in the line after passing through a discontinuity in its surge impedance, and the surge that would travel in the line if there was no discontinuity in its surge impedance. The discontinuities in the surge impedance of the line are due to the earthing connections of a cable shield, the installation of SPDs between the conductors of an unshielded cable and the earth or to the transition from buried to aerial installation (and vice versa). From its definition, the refraction factor is a number between 0 and 2 ($0 \leq \delta \leq 2$). The refraction factor of a node depends on the direction of surge propagation, so that the downstream refraction factor (δ_d) applies to the propagation from node 1 to node m+1 and the upstream refraction factor (δ_u) applies to the propagation in the opposite direction. These factors can be computed by:

$$\delta_d(i) = \frac{2\,R_t(i)\,Z(i)}{\left(R_t(i)\,Z(i-1) + R_t(i)\,Z(i) + Z(i-1)\,Z(i)\right)} \tag{B-1}$$

$$\delta_u(i) = \frac{2\,R_t(i)\,Z(i-1)}{\left(R_t(i)\,Z(i) + R_t(i)\,Z(i-1) + Z(i)\,Z(i-1)\right)} \tag{B-2}$$

where:

$\delta_d(i)$ is the downstream refraction factor at node i;

$\delta_u(i)$ is the upstream refraction factor at node i;

$R_t(i)$ is the resistance of the earthing connection at the node i;

$Z(i)$ is the surge impedance of the line section i;

$Z(i-1)$ is the surge impedance of the line section $i-1$.

In the application of Equations 3 and 4 the following rules apply.

- The refraction factors of the first node in the downstream direction ($\delta_d(1)$) and of the last node in the upstream direction ($\delta_u(m+1)$) are not defined.
- The line surge impedances are given in Table A.2.
- The line surge impedance beyond the last node in the downstream direction and beyond the first node in the upstream direction shall be considered as infinite. This leads to the following simplifications:

$$\delta_d(m+1) = \frac{2\,R_t(m+1)}{\left(R_t(m+1) + Z(m)\right)} \tag{B-3}$$

$$\delta_u(1) = \frac{2\,R_t(1)}{\left(R_t(1) + Z(1)\right)} \tag{B-4}$$

- If there is no earthing connection at a given node i, the value of $R_t(i)$ shall be considered as infinite, which leads to the following simplifications:

$$\delta_d(i) = \frac{2\,Z(i)}{\left(Z(i-1) + Z(i)\right)} \tag{B-5}$$

$$\delta_u(i) = \frac{2\,Z(i-1)}{\left(Z(i) + Z(i-1)\right)} \tag{B-6}$$

$$\delta_d(m+1) = 2 \tag{B-7}$$

$$\delta_u(1) = 2 \tag{B-8}$$

Annex C

Shielding factor

(This annex forms an integral part of this Recommendation.)

The use of properly earthed/bonded shielded-cables attenuates the lightning-induced surges on the telecommunication line and this attenuation can be expressed by the shielding factor (η). In order to obtain the shielding factor, the shielding must be continuous along the shielded section(s) of the line and connected to the bonding bar at both ends. The shielding factor of a shielded section is given by:

$$\eta(i) = \frac{R_S(i)\,L(i)}{Z(i)} \qquad \text{(C-1)}$$

where:

$R_S(i)$ is the shield resistance (in Ω/km) of section i (see Tables I.1 and I.2);

$Z(i)$ is the surge impedance (in Ω) of section i (see Table A.2);

$L(i)$ is the length (in km) of section i;

NOTE – Equation 2 assumes that $R_S(i)\ L(i) < Z(i)$, i.e., the shield resistance is much smaller than the line surge impedance, which is the usual case of telecommunication lines.

At the transition from an unshielded section to a shielded section (node q), part of the induced common mode voltage from the unshielded section is converted into the line-to-shield mode. The conversion factor is given by:

$$\beta = \frac{2Z_c}{\left[Z(q) + Z_c + Z_p\right]} \qquad \text{(C-2)}$$

$$Z_p = \frac{Z(q-1)\,R_t(q)}{\left[Z(q-1)\,R_t(q)\right]} \qquad \text{(C-3)}$$

where:

Z_c is the surge impedance between the conductor and the shield ($Z_c \approx 50$ Ω);

$R_t(q)$ is the resistance of the earthing connection at node q;

Z (q) is the surge impedance of line unshielded section q (see Table A.2);

Z (q–1) is the surge impedance of line shielded section q–1 (see Table A.2);

q is the number of the last shielded node ($q > 1$).

Appendix I

Shield resistance of cables with metallic symmetric conductors

(This appendix does not form an integral part of this Recommendation.)

Table I.1 – Shield resistance in Ω/km for lead sheath

Number of pairs	**Conductor diameter (mm)**			
	0.40	**0.50**	**0.65**	**0.90**
10	6.2	5.4	4.8	3.4
20	5.0	4.2	3.4	2.4
30	4.4	3.4	2.8	2.0
50	3.4	2.7	2.2	1.5
75	2.8	2.3	1.8	1.2
100	2.4	2.0	1.5	1.0
200	1.7	1.4	1.0	0.65
300	1.3	1.1	0.79	0.49
400	1.1	0.91	0.66	0.40
600	0.87	0.70	0.49	–
900	0.66	0.54	0.38	–
1200	0.54	0.43	–	–
1500	0.46	–	–	–
1800	0.40	–	–	–
2400	0.33	–	–	–
NOTE – Values for sheath thickness T = 2 mm. For other thickness T'(mm), multiply the table value by 2/T'.				

Table I.2 – Shield resistance in Ω/km for aluminium sheath

Number of pairs	**Conductor diameter (mm)**			
	0.40	**0.51**	**0.64**	**0.91**
10	5.2	4.9	4.2	3.1
20	4.0	3.6	3.1	2.3
30	3.5	3.1	2.6	1.9
50	2.9	2.6	2.1	1.6
75	2.4	2.2	1.8	1.3
100	2.0	1.9	1.6	1.1
200	1.5	1.4	1.1	0.80
300	1.2	1.1	0.92	0.64
400	1.1	1.0	0.80	0.56
600	0.89	0.80	0.64	–
NOTE – Values for sheath thickness T = 0.2 mm. For other thickness T'(mm), multiply the table value by 0.2/T'.				

Appendix II

Algorithm for computer code

(This appendix does not form an integral part of this Recommendation.)

The procedures of this Recommendation are suitable to be implemented in a computer code. This appendix presents an algorithm to guide the elaboration of such code.

1) Do you accept the tolerable risk and loss limits suggested in clause 7.2?
   a) YES: Go to Step (2);
   b) NO: Calculate the limits according to [ITU-T K.72] and go to Step (2);
2) Identify the sections and nodes of the line;
3) Assign an impulse withstand level (U_W) to each node according to clause 6.1;
4) Input the environmental data (ground flash density and earth resistivity);
5) Input data of each section (length, buried/aerial, rural/suburban/urban, shielded/unshielded, shield resistance) based on Annex A and Appendix I;
6) Input data of each node (earthing resistance, with/without SPD);
7) Compute the refraction factor for each node in both directions from Annex B;
8) Compute the shielding factor for each shielded section from Annex C;
9) Compute the exposure of the unshielded node(s) from clause 8.1;
10) Compute the exposure of the shielded node(s) from clause 8.2;
11) Compute the SPD protection factor for each node from clause 8.3;
12) Apply the SPD protection factors to the nodes;
13) Compute the expected annual number of damages for each node (N_Z) from clause 7.1;
14) Compute the risk of damage for each node ($R'_Z(i)$) and for the line (R'_Z) from clause 7.1;
15) Compare R'_Z with the limit R_{Ti} :
    15.1) If $R'_Z \leq R_{Ti}$, then the line is adequately protected against induced surges: END;
    15.2) If $R'_Z > R_{Ti}$, then the line needs additional protection: Continue;
16) Identify the node with higher risk and apply a protection measure to it;
17) Go back to Step (7).

Appendix III

Collection area for flashes near a telecommunication line

(This appendix does not form an integral part of this Recommendation.)

Equation 1 allows an interpretation that can be useful for a fast assessment of the number of dangerous lightning-induced surges in an unprotected line. This equation is reproduced below for convenience:

$$N_Z = 0.216\, N_G\, \rho^{1/2}\, \mathrm{X}\, U_W^{-1.8} \qquad \text{(III-1)}$$

where:

N_Z is the number of damages per year (i.e., number of surges with peak values above U_W);

N_G is the ground flash density in flashes per km^2 per year;

ρ is the average earth resistivity in Ωm;

X is the node exposure in km;

U_W is the impulse withstand level of the considered node, in kV.

Assuming that the line has length L, is aerial and has no protection, the refraction factor at its end is $\delta_u = 2$ (see Annex B) and its exposure is given by (see clause 8):

$$\mathrm{X} = 0.5 \times L \times 2 = L \qquad \text{(III-2)}$$

Equation III-1 can then be re-written as:

$$N_Z = 0.216\, N_G\, \rho^{1/2}\, L\, U_W^{-1.8} = A_i\, N_G \qquad \text{(III-3)}$$

where A_i is the collection area for flashes near a telecommunication line, which is given by:

$$A_i = 0.216\, \rho^{1/2}\, L\, U_W^{-1.8} \qquad \text{(III-4)}$$

As shown in Equation III-4, this collection area depends on the threshold voltage level considered (U_W) and on the earth resistivity (ρ). For reference values $U_W = 1$ kV and $\rho = 400$ Ωm, Equation III-4 simplifies into:

$$A_i = 4.32\, L \qquad \text{(III-5)}$$

In Equation III-5, A_i is in km^2 and L is in km. Expressing these quantities in m^2 and m, respectively, leads to:

$$A_i = 4320\, L \qquad \text{(III-6)}$$

The standard [IEC 62305-2] uses this approach in order to have a first assessment of the number of dangerous events due to lightning-induced surges in a service, where the multiplying factor has been rounded to:

$$A_i = 4000\, L \qquad \text{(III-6)}$$

For a buried line, the installation factor $K_i = 0.5$ is considered in the calculation of the line exposure, which leads to:

$$A_i = 2000\, L \qquad \text{(III-6)}$$

Appendix IV

Examples of calculation

(This appendix does not form an integral part of this Recommendation.)

The objective of this appendix is to exemplify the manual application of the calculation procedure contained in this Recommendation and to validate the referred procedure by comparing its results with experimental results obtained from field surveys, as reported in Chapter 10 of [b-ITU-T Handbook].

IV.1 Italian survey

The data of the Italian survey are reported in Appendix IV of Chapter 10 of [b-ITU-T Handbook]. According to these data, the equivalent line can be represented by three sections ($m = 3$), which means four nodes, as shown in Figure IV.1. The refraction factors are computed by Equations B-1 and B-2 and the obtained values are shown in Table IV.1. The environmental factor was considered as $C_e = 1$ for all sections.

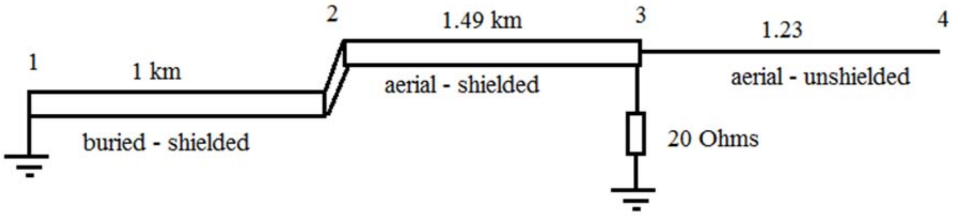


Figure IV.1 – Diagram of the equivalent line of the Italian survey

Table IV.1 – Refraction factors for the equivalent Italian line

Refraction factor	Node 1	Node 2	Node 3	Node 4
Downstream (δ_d)	–	1.6	0.0909	2
Upstream (δ_u)	0	0.4	0.0909	–

IV.1.1 Subscriber end

The subscriber end (node 4), which is unshielded, will be considered first, according to Equation 3, the contributions of the 3 sections are computed as follows:

- Aerial-unshielded: $X_{ud}(4; 3) = 0.5 \times 1.23 \times 2 = 1.23$
- Aerial-shielded: $X_{ud}(4; 2) = 0.5 \times 1.49 \times 0.0909 \times 2 = 0.135$
- Buried-shielded: $X_{ud}(4; 1) = 0.5 \times 0.5 \times 1.00 \times 1.6 \times 0.0909 \times 2 = 0.073$

which gives a total exposure $X_u(4) = 1.23 + 0.135 + 0.073 = 1.438$ km.

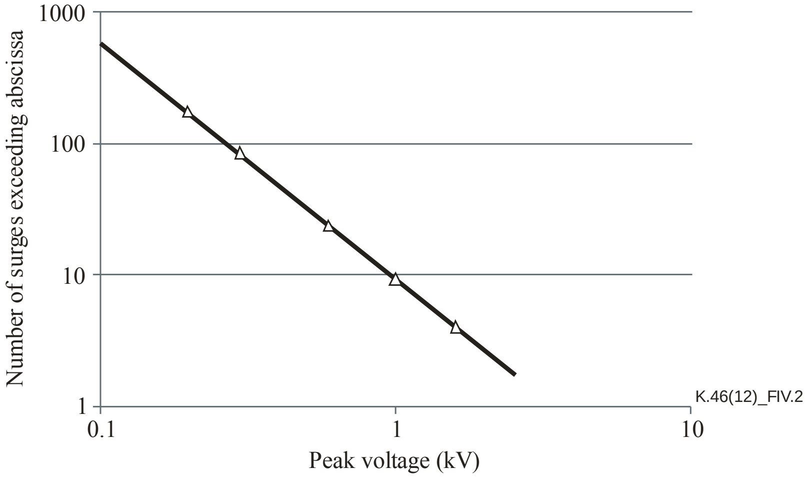
NOTE 1 – The nomenclature $X_{ud}(4; 3)$ means the exposure of the unshielded node 4 in the downstream direction due to the contribution of section 3 (see Figure IV.1).

Here, a physical meaning from this number can be grasped. This means that the actual 3.72 km line will apply lightning surges to the subscriber node as if it had 1.438 km and had no shield/protection. Considering that the average earth resistivity is ρ = 875 Ωm and the ground flash density is N_g = 3.6 flashes/km^2.year (i.e., using the relation $N_G = T_D/10$, where T_D is the keraunic level), then Equation 1 gives:

$$N_Z = 0.216 \times 3.6 \times 875^{1/2} \times 1.438 \times V_P^{-1.8} = 33\ V_P^{-1.8}$$

NOTE 2 – The ground flash density and the earth resistivity representative of the Italian survey was updated during the elaboration of this appendix, based on the information provided by a participant of the referred survey.

If 1 kV is chosen as reference, then 33 surges per year above this value at node 4 should be expected. The number of surges above a given voltage value is plotted in Figure IV.2, alongside the measured values. In this figure, the data were normalized to 10 thunderstorm days for convenience. The excellent correlation between the theoretical and experimental data in this figure is due to the use of this case as the ground-truth to obtain the constant and the exponent contained in Equation 1.



NOTE – solid line: calculated; dots: experimental.

Figure IV.2 – Number of surges exceeding abscissa per 10 thunderstorm days for the subscriber premises of the Italian survey

IV.1.2 Buried/aerial transition

The real proof of the methodology comes from its application to other nodes or lines. Consider the transition between the buried and aerial cables (node 2). Although the cables were shielded, the measurement at this point was carried out between line to earth, i.e., the results shall refer to an unshielded node.

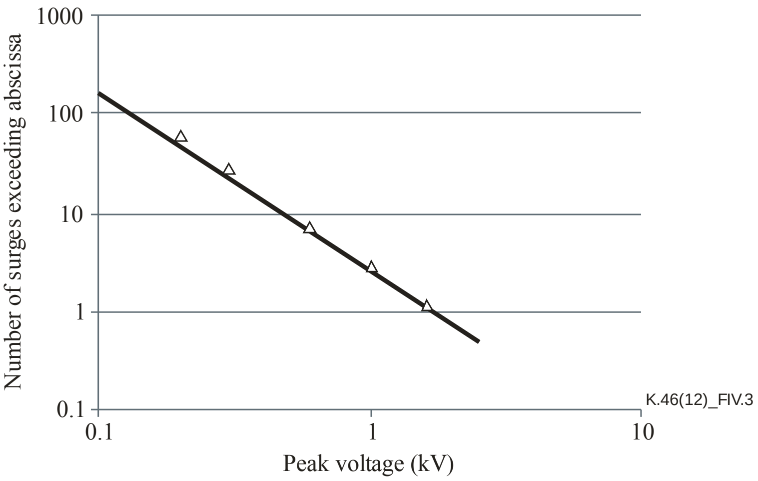
The downstream exposure at node 2 comes only from the buried section, which is:

– X_{ud} (2) = 0.5 × 0.5 × 1.00 × 1.6 = 0.400

The upstream exposure comes from the two aerial sections:

– X_{uu} (2) = 0.5 × 1.49 × 0.4 + 0.5 × 1.23 × 0.0909 × 0.4 = 0.320

The higher value is the downstream one, which gives N_Z = 9.2 surges above 1 kV. The measured value was 10 surges, which is a remarkable result. Figure IV.3 shows the calculated and measured number of surges above a given voltage level and normalized to 10 thunderstorm days. The very good correlation shown in this figure supports the calculation methodology, especially regarding to intermediate nodes.



NOTE – solid line: calculated; dots: experimental.

Figure IV.3 – Number of surges exceeding abscissa per 10 thunderstorm days for the buried/aerial transition of the Italian survey

IV.1.3 Exchange end

The next step is to consider the node 1, which is the line termination at the main distribution frame (MDF) of an exchange. This is a shielded node, so that in order to get realistic shield data it is assumed that the cables have the characteristics shown in Table IV.2, which also shows the shielding factors calculated according to Annex C.

Table IV.2 – Characteristics assumed for shielded cables for the Italian survey

Cable	Shield type	No. of pairs	Cond. diameter	Shield resistance[a)]	Shielding factor
Buried	Lead	400	0.50 mm	0.91 Ω/km	0.0091
Aerial	Aluminium	50	0.64 mm	2.1 Ω/km	0.0078
[a)] Appendix I gives values of shield resistance for different types of cables.					

According to Equation 7, the contributions of the three sections are considered as follows:

– buried section:

X_{su} (1; 1) = 0.5 × 0.5 × 0.5 × 0.0091 × 1 = 0.00114

– aerial shielded section:

X_{su} (1; 2) = 0.5 × 0.5 × 0.0078 × 1.49 + 0.5 × 0.0091 × 1.49 = 0.00969

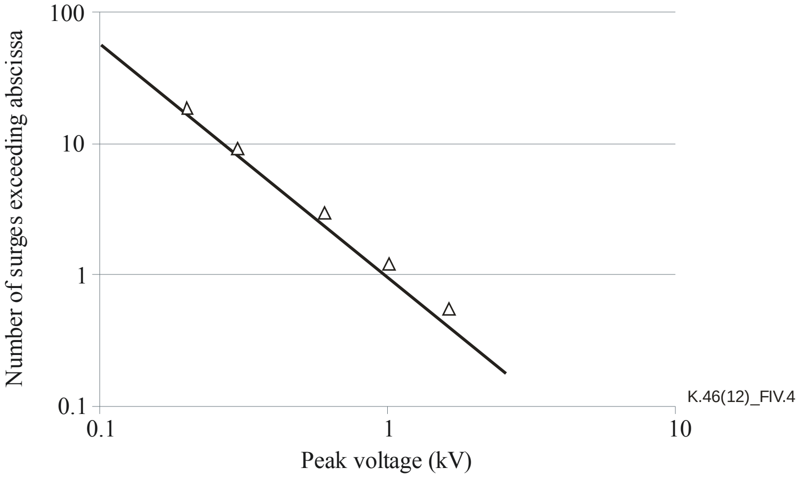
– aerial unshielded section: X_{su} (1; 3) = β X_{uu} (3_m) where:

  - X_{uu} (3_m) = 0.5 × 1.23 = 0.615 (unshielded exposure with line matched at node 3);
  - Z_P = 400 × 20/(400 + 20) = 19.0 (earthing resistance in parallel with cable impedance);
  - β = 2 × 50/(400 + 50 + 19) = 0.213
  - X_{su} (1; 3) = 0.213 × 0.615 = 0.131

The total exposure of node 1 is then: X_s (1) = 0.00114 + 0.00969 + 0.131 = 0.141. It is clear that the main contribution to the exposure of node 1 comes from the unshielded section, i.e., overvoltages that are coupled into the cable (wire/sheath mode) at the transition. The number of surges is:

$$N_Z = 0.216 \times 3.6 \times 875^{1/2} \times 0.141 \times V_P^{-1.8} = 3.24\ V_P^{-1.8}$$

The calculated number of surges is plotted in Figure IV.4, along with the results from the field survey. The good correlation between these two sets of results supports the voltage coupling at the shielded/unshielded transition as stated in Equation 8.



NOTE – solid line: calculated; dots: experimental.

Figure IV.4 – Number of surges exceeding abscissa per 10 thunderstorm days for the MDF of the Italian survey

IV.2 Japanese survey

The data of the Japanese survey are reported in Appendix V of Chapter 10 of [b-ITU-T Handbook] and it is complemented by [b-Koga]. The Japanese reference line is shown in Figure IV.5. The measurement at node 3 was made with respect to earth, so that the node shall be considered as unshielded. One problem with Koga and Motomitsu's data is that the earthing resistance of the shield is not given, but only the terminating resistance of the pair under measurement. Considering the low average earth resistivity in the survey area (ρ = 100 Ωm), it will be assumed that effective earthing resistance at node 3 is 20 Ω.

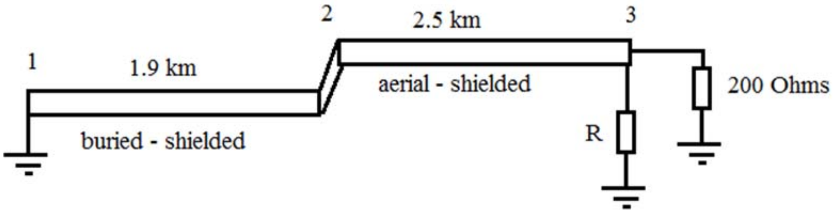


Figure IV.5 – Diagram of the equivalent line of the Japanese survey

The refraction factors are computed by Equations B-1 and B-2 and the obtained values are shown in Table IV.3.

Table IV.3 – Refraction factors for the Japanese line

Refraction factor	Node 1	Node 2	Node 3
Downstream (δ_u)	–	1.6	0.131
Upstream (δ_d)	0	0.4	–

IV.2.1 Subscriber end

Consider now the subscriber end (node 3). According to Equation 2, the contributions of the 2 sections are computed as follows:

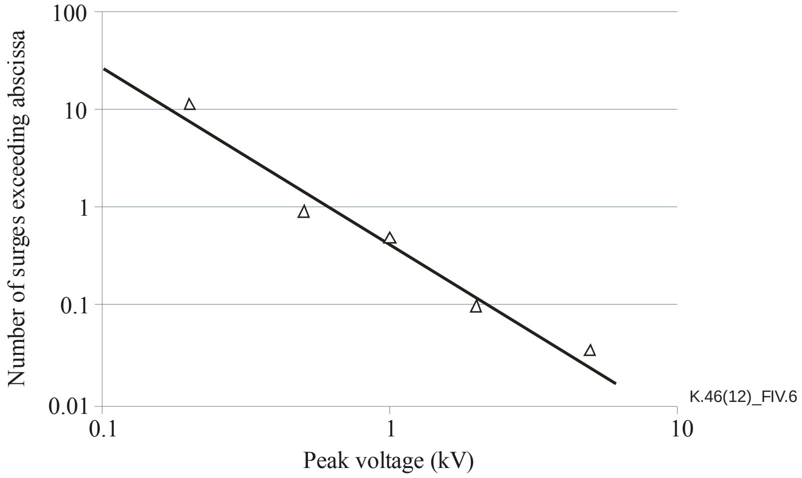
– Aerial: $X_{ud} = 0.5 \times 2.50 \times 0.131 = 0.164$

– Buried: $X_{ud} = 0.5 \times 0.5 \times 1.90 \times 1.6 \times 0.131 = 0.100$

which gives a total exposure X = 0.164 + 0.100 = 0.264 km. The average earth resistivity is 100 Ωm and the reference ground flash density is 1 flash/km^2.year ($T_D = 10$), which gives:

$$N_Z = 0.216 \times 1.0 \times 100^{1/2} \times 0.264 \times V_P^{-1.8} = 0.57\ V_P^{-1.8}$$

If 1 kV is used as reference, it is expected 0.57 surges per year above this value at node 2. The number of expected surges above 1 kV obtained from [b-Koga] is 0.5, which has a good correlation with the calculated value. Figure IV.6 shows a comparison between the experimental results and the calculated ones, which shows a very good correlation.



NOTE – solid line: calculated; dots: experimental.

Figure IV.6 – Number of surges exceeding abscissa per 10 thunderstorm days for the subscriber end of the Japanese survey

IV.2.2 Exchange end

The next step is to consider the shielded node 1, which is the line termination at the main distribution frame (MDF) of an exchange. The data assumed for the cables are shown in Table IV.4, which also shows the shielding factors calculated according to Annex C.

Table IV.4 – Characteristics assumed for shielded cables of the Japanese survey

Cable	Shield type	No. of pairs	Cond. diameter	Shield resistance	Shielding factor
Buried	Al + Fe (Stalpeth sheath)	600	0.51 mm	0.62 Ω/km	0.0118
Aerial	Al (CCP-AP)	100	0.64 mm	1.6 Ω/km	0.0100

According to Equation 7, the contributions of the two sections are considered as follows:

– buried section:

$X_{su}\ (1; 1) = 0.5 \times 0.5 \times 0.5 \times 0.0118 \times 1.9 = 0.0028$

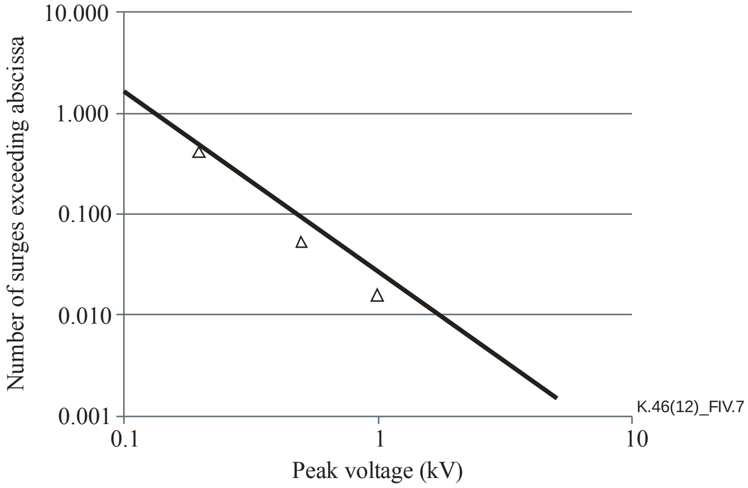
– aerial shielded section:

X_{su} (1; 2) = 0.5 × 0.5 × 0.01 × 2.5 + 0.5 × 0.0118 × 2.5 = 0.0210

The total exposure of node 1 is then: X_s (1) = 0.0028 + 0.0210 = 0.0238. The number of surges is:

$$N_Z = 0.216 \times 1.0 \times 100^{1/2} \times 0.0238 \times V_P^{-1.8} = 0.051\ V_P^{-1.8}$$

The comparison of this theoretical result with the experimental one has to take into account that the measurement was made across a 200 Ω resistor that reduces the measured voltage. Assuming that this is a matching condition means that the calculated result shall be divided by 2, which leads to the values shown in Figure IV.7. It can be seen that the experimental results agree relatively well with the theoretical ones.



NOTE – solid line: calculated; dots: experimental.

Figure IV.7 – Number of surges exceeding abscissa per 10 thunderstorm days for the MDF of the Japanese survey

IV.3 German survey

The data of the German survey are reported in Appendix III of Chapter 10 of [b-ITU-T Handbook]. All measurements are carried out at the exchange end, which is a shielded node. The data were classified according to the environment, i.e., rural, suburban and urban. As the number of surges recorded in the urban area is very small (only three), this environment is not considered in this appendix. The ground flash density is 2.4 flashes/km^2.year and the average earth resistivity is 45 Ω.

IV.3.1 Rural area

The German reference rural line is completely shielded and it is shown in Figure IV.8. The data assumed for the cables are shown in Table IV.5, which also shows the shielding factors calculated according to Annex C.

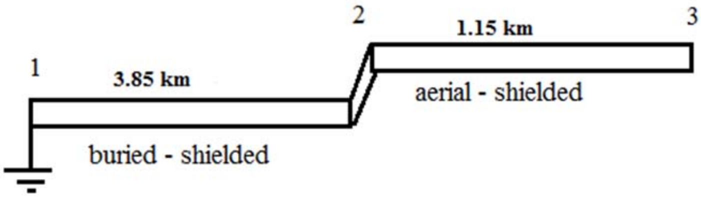


Figure IV.8 – Diagram of the equivalent rural line of the German survey

Table IV.5 – Characteristics assumed for rural cables of the German survey

Cable	Shield type	No. of pairs	Cond. diameter	Shield resistance	Shielding factor
Buried	Lead	100	0.50 mm	2.0 Ω/km	0.0770
Aerial	Aluminium	30	0.51 mm	3.1 Ω/km	0.0089

According to Equation 7, the contributions of the two sections are considered as follows:

– buried section:

X_{su} (1; 1) = 0.5 × 0.5 × 0.5 × 0.0770 × 3.85 = 0.037

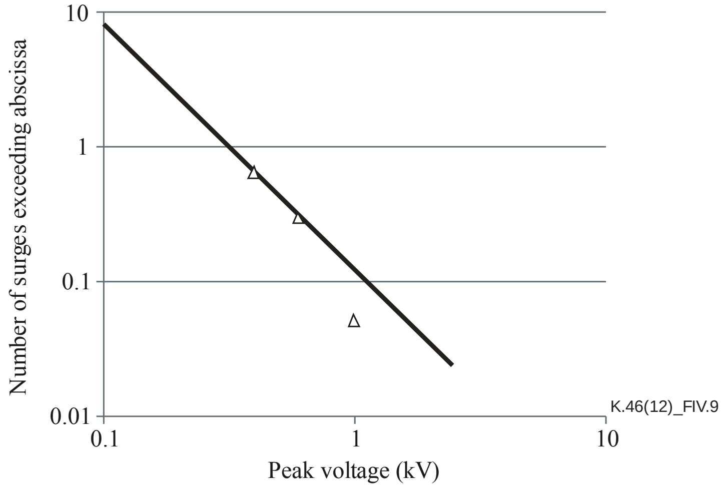
– aerial shielded section:

X_{su} (1; 2) = 0.5 × 0.5 × 0.0089 × 1.15 + 0.5 × 0.0770 × 1.15 = 0.0468

The total exposure of node 1 is then: X_s (1) = 0.0037 + 0.0468 = 0.0505. The number of surges is:

$$N_Z = 0.216 \times 2.4 \times 45^{1/2} \times 0.0505 \times V_P^{-1.8} = 0.176\ V_P^{-1.8}$$

The comparison with experimental results is shown in Figure IV.9, where the values are normalized to 10 thunderstorm days. A very good agreement of the first two data points can be seen, while the third one is somewhat lower than predicted. One possible explanation to the lower value of the measured surges above 1 kV is the reported existence of SPDs at the buried/overhead transition of long aerial sections.



NOTE – solid line: calculated; dots: experimental.

Figure IV.9 – Number of surges exceeding abscissa per 10 thunderstorm days for the MDF of the German survey

IV.3.2 Suburban area

The German reference suburban line is completely shielded and it is shown in Figure IV.10. The data assumed for the cables are shown in Table IV.6, which also shows the shielding factors calculated according to Annex C. The environmental factor is $C_e = 0.5$ (see Annex A).

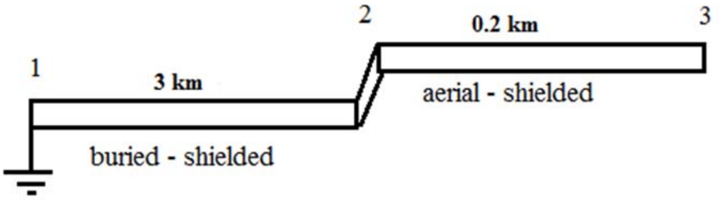


Figure IV.10 – Diagram of the equivalent suburban line of the German survey

Table IV.6 – Characteristics assumed for suburban cables of the German survey

Cable	Shield type	No. of pairs	Cond. diameter	Shield resistance	Shielding factor
Buried	Lead	200	0.51 mm	1.4 Ω/km	0.0420
Aerial	Aluminium	30	0.51 mm	3.1 Ω/km	0.0089

According to Equation 7, the contributions of the two sections are considered as follows, where an additional 0.5 factor accounts for the environmental factor:

– buried section:

$X_{su}(1; 1) = 0.5 \times 0.5 \times 0.5 \times 0.5 \times 0.0420 \times 3.00 = 0.0079$

– aerial shielded section:

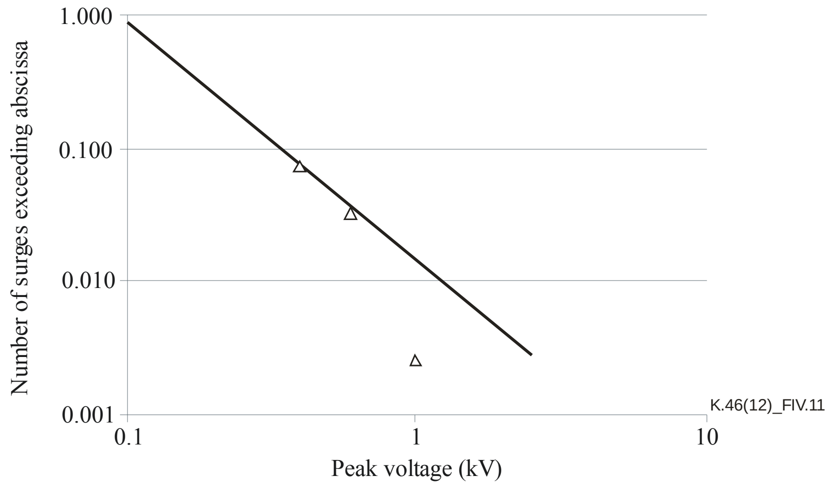
$X_{su}(1; 2) = 0.5 \times 0.5 \times 0.5 \times 0.0089 \times 0.2 + 0.5 \times 0.5 \times 0.0420 \times 0.2 = 0.0023$

The total exposure of node 1 is then: $X_s(1) = 0.0079 + 0.0023 = 0.0102$. The number of surges is:

$$N_Z = 0.216 \times 2.4 \times 45^{1/2} \times 0.0102 \times V_P^{-1.8} = 0.035\ V_P^{-1.8}$$

The comparison with experimental results is shown in Figure IV.11, where the values are normalized to 10 thunderstorm days. Similarly to the case of the rural area, there is a very good agreement of the first two data points, while the third one is somewhat lower than predicted. One possible explanation to the lower value of the measured surges above 1 kV is the reported existence of SPDs at the buried/overhead transition of long aerial sections.

One interesting result of this comparison is that it supports, to some extent, the assumption of an environmental factor $C_e = 0.5$ for suburban lines.



NOTE – solid line: calculated; dots: experimental.

Figure IV.11 – Number of surges exceeding abscissa per 10 thunderstorm days for the MDF of the German survey

IV.4 American survey

This survey relates to measurements in three different long lines in the United States of America, located in Kentwood, Washington, and Cleveland. The results are presented in Appendix VI of Chapter 10 of [b-ITU-T Handbook], and also in [b-Carrol 1] and [b-Carrol 2]. These are very long lines (7.7 to 16.6 km) that may have earthing connections, branch cables and surge protective devices along the route, but this information is not available. Therefore, the lines are assumed to be homogeneous, which is a pessimistic approach. In all lines, the measurements were made between line to earth at the subscriber end.

IV.4.1 Kentwood

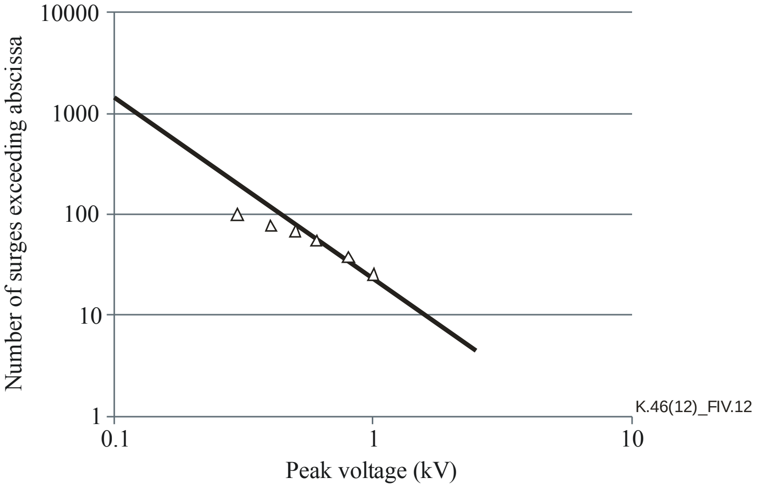
This line has 10.7 km buried and 0.1 km aerial. The aerial section is too short to characterize a transmission line, so that the entire line will be considered as buried and having 10.8 km. This gives the following exposure of the subscriber end:

$$X_{ud} = 0.5 \times 0.5 \times 10.8 \times 2 = 5.4 \text{ km}$$

The earth resistivity is from 100 to 700 Ωm, so that the average value is 400 Ωm. Normalizing the data to 10 thunderstorm days ($N_G = 1$) gives:

$$N_Z = 0.216 \times 1 \times 400^{1/2} \times 5.4 \times V_P^{-1.8} = 23\ V_P^{-1.8}$$

Figure IV.12 shows the theoretical results alongside the measured ones. Considering the crude line representation, the agreement between the two sets of data is surprisingly good, especially in the range of higher voltages.



NOTE – solid line: calculated; dots: experimental.

Figure IV.12 – Number of surges exceeding abscissa per 10 thunderstorm days for the subscriber end of the Kentwood (USA) survey

IV.4.2 Washington

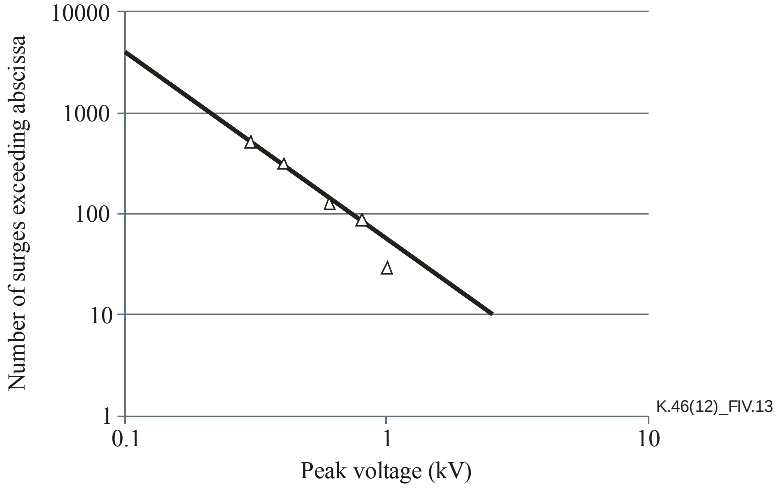
The line has a total 16.6 km, but no information is given regarding aerial/buried lengths, so that it is assumed 10 km buried and 6.6 km aerial. This gives the following exposure of the subscriber end:

$$X_{ud} = 0.5 \times 0.5 \times 1.6 \times 10 \times 2 + 0.5 \times 6.6 \times 2 = 14.6 \text{ km}$$

The average earth resistivity is 300 Ωm. Normalizing the data to 10 thunderstorm days ($N_G = 1$) gives:

$$N_Z = 0.216 \times 1 \times 300^{1/2} \times 14.6 \times V_P^{-1.8} = 55\ V_P^{-1.8}$$

Figure IV.13 shows the theoretical results alongside the measured ones. Considering the crude line representation, the agreement between the two sets of data is also surprisingly good. The small mismatch observed for surges above 1 kV may be explained by the operation of SPDs (6-mil carbon blocks) that were installed in a protected cable terminal at 60 m upstream of the measuring station.



NOTE – solid line: calculated; dots: experimental.

Figure IV.13 – Number of surges exceeding abscissa per 10 thunderstorm days for the subscriber end of the Washington (USA) survey

IV.4.3 Cleveland

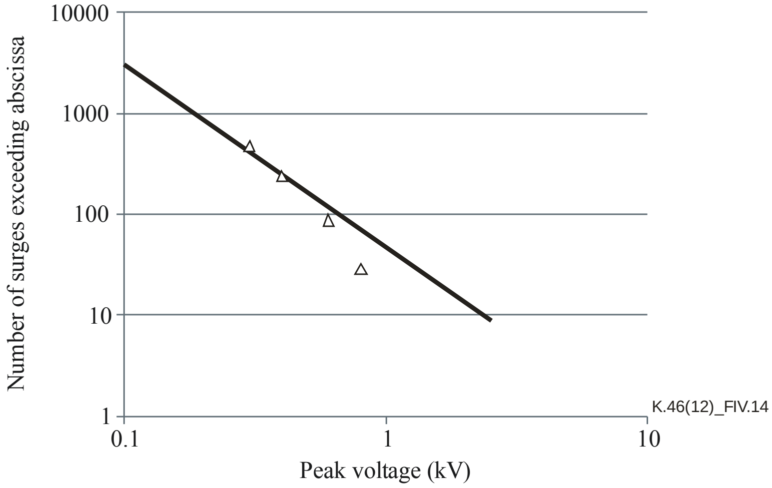
This line has 7.7 km, but the only information given is that the buried section is longer than the aerial section. Therefore, it is assumed that the line has 5 km buried and 2.7 km aerial. This gives the following exposure of the subscriber end:

$$X_{ud} = 0.5 \times 0.5 \times 1.6 \times 5 \times 2 + 0.5 \times 2.7 \times 2 = 6.7 \text{ km}$$

The earth resistivity ranges widely from 400 to 11000 Ωm, so that it will be considered 1000 Ωm. Normalizing the data to 10 thunderstorm days ($N_G = 1$) gives:

$$N_Z = 0.216 \times 1 \times 1000^{1/2} \times 6.7 \times V_P^{-1.8} = 46\ V_P^{-1.8}$$

Figure IV.14 shows the theoretical results alongside the measured ones. Considering the crude line representation, the agreement between the two sets of data is also very good. Similarly to the Washington survey, the small mismatch observed for surges above 1 kV may be explained by the operation of SPDs (6-mil carbon blocks) that were installed in a pedestal at 60 m upstream of the measuring station.



NOTE – solid line: calculated; dots: experimental.

Figure IV.14 – Number of surges exceeding abscissa per 10 thunderstorm days for the subscriber end of the Cleveland (USA) survey

IV.5 Final remarks

Considering the uncertainty of the input data, it can be concluded that the application of the calculation procedure contained in this Recommendation agrees very well with the existing experimental data regarding the peak value of lightning-induced overvoltages.

It is relevant to mention that the refraction factor formulas contained in Annex B are in line with the corresponding theoretical formulas presented in [b-Rusck]. The formulas of Annex B, as well as the shielding factor formulas contained in Annex C, were based on a theoretical and experimental study described in [b-Barbosa 1] and [b-Barbosa 2].

Although the calculation is straightforward, its manual execution is somewhat tedious. Therefore, it is important to implement the procedure in a computer code, so that it could be performed quickly and free of errors. The recursive form of the formulas lends itself to be programmed in a computer code.

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Printed in Switzerland
Geneva, 2012