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SERIES K: PROTECTION AGAINST INTERFERENCE

Shielding factors for lightning protection

Recommendation ITU-T K.101

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Summary

Recommendation ITU-T K.101 contains the calculation procedure for the shielding factors used in Recommendations ITU-T K.46, ITU-T K.47, ITU-T K.56 and ITU-T K.97, and it is intended to:

1) provide the rationale for the shielding factor approximate formulas or values contained in the aforementioned Recommendations;

2) allow a more precise calculation of the shielding factors, by using the equations provided in this Recommendation.

The shielding factors considered in this Recommendation refer to:

- that of the lightning current distribution in a telecommunication tower, i.e., that of the tower (α_T) as per Recommendations ITU-T K.56 and ITU-T K.97;
- that of the lightning current distribution among several conductors placed in a cable ladder, i.e., that of the feeder tray (α_F) as per Recommendations ITU-T K.56 and ITU-T K.97;
- that provided by the cable tray (β) as per Recommendation ITU-T K.56;
- that of parallel conductors (η) as per Recommendation ITU-T K.47;
- that of refraction (δ) due to the earthing connection of a telecommunication cable, as per Recommendation ITU-T K.46;
- that provided by a telecommunication cable having a metallic sheath (shield) (η) as per Recommendation ITU-T K.46.

History

Edition	Recommendation	Approval	Study Group	Unique ID*
1.0	ITU-T K.101	2014-12-07	5	11.1002/1000/12291

Keywords

Earthing, lightning, shielding, telecommunication lines, telecommunication towers.

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Shielding factors for lightning protection

1 Scope

This Recommendation provides the rationale and formulas for calculating the shielding factors used in series K Recommendations dealing with lightning protection of telecommunication lines and structures. The shielding factors considered are related to:

– the use of a metallic tower to hold telecommunication feeder cables and antennas;
– the placement of several feeder cables in a metallic cable ladder in the tower;
– the placement of telecommunication cables in a metallic cable tray;
– the use of a guard-wire above a buried telecommunication cable;
– the connection of a telecommunication cable to earth;
– the use of a telecommunication cable with a metallic sheath.

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.46] Recommendation ITU-T K.46 (2012), *Protection of telecommunication lines using metallic symmetric conductors against lightning-induced surges*.

[ITU-T K.47] Recommendation ITU-T K.47 (2012), *Protection of telecommunication lines against direct lightning flashes*.

[ITU-T K.56] Recommendation ITU-T K.56 (2010), *Protection of radio base stations against lightning discharges*.

[ITU-T K.97] Recommendation ITU-T K.97 (2014), *Lightning protection of distributed base stations*.

3 Definitions

3.1 Terms defined elsewhere

This Recommendation uses the following terms defined elsewhere:

3.1.1 cable tray [ITU-T K.56]: Rigid structural system used to securely fasten or support cables.

3.1.2 feeder cable [ITU-T K.56]: Wave-guide or coaxial cable that conducts signals to an antenna.

3.1.3 guard-wire [ITU-T K.47]: Metallic wire buried above a cable in order to reduce physical damage due to direct lightning flashes to the cable.

3.1.4 refraction factor [ITU-T K.46]: 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 was no discontinuity in its surge impedance.

3.1.5 shielding factor [ITU-T K.56]: Factor that represents the attenuation of the voltage or current in a conductor due to the presence of a nearby shielding conductor.

3.2 Terms defined in this Recommendation

This Recommendation defines the following terms:

3.2.1 shielded cable: Group of one or more pairs of twisted wires balanced with respect to earth, assembled together and covered by a continuous metallic sheath.

3.2.2 unshielded cable: Group of one or more pairs of twisted wires balanced with respect to earth and assembled together without a metallic sheath.

4 Abbreviations and acronyms

This Recommendation uses the following abbreviations and acronyms:

DC Direct Current

GDT Gas Discharge Tube

GMR Geometric Mean Radius

SPC Surge Protective Component

5 Conventions

None.

6 Shielding factor due to conductors in parallel

The shielding factor, considered in this clause, is relevant to the following Recommendations:

– [ITU-T K.56]:
  - tower shielding factor (αT);
  - feeder shielding factor (αF);
  - shielding factors of cable trays (β).

– [ITU-T K.47]:
  - guard-wire shielding factor (η).

6.1 Modelling the problem

In many practical situations, there is a transient current injected in a transmission system formed by multiple conductors in parallel. This is the case of a metallic tower struck by lightning, where the current is distributed among the tower structure and the available conductors. As the time-derivative of the lightning current is high, the initial current distribution is determined by the magnetic flux linkages within the conductors. Therefore, if the low time-derivative wave-tail is not of concern, it is permissible to neglect the resistance of the conductors when assessing the current distribution.

Under this assumption, a number of practical problems may be represented by the canonical structure shown in Figure 1, in which two perfectly conducting cylinders of radius r_1 and r_2 are placed in parallel and submitted to a time-varying current $I(t)$. The problem consists in determining the currents $I_1(t)$ and $I_2(t)$ of each conductor, based on their dimensions and separation b.

The boundary condition required to calculate the current distribution is that the flux linkage in the area between the two conductors shall be null. This condition comes from the application of Maxwell's equation:

$$\oint_L E\,\mathrm{d}l = -\mu \oint_A \frac{\mathrm{d}H}{\mathrm{d}t}\,\mathrm{d}A \qquad (1)$$

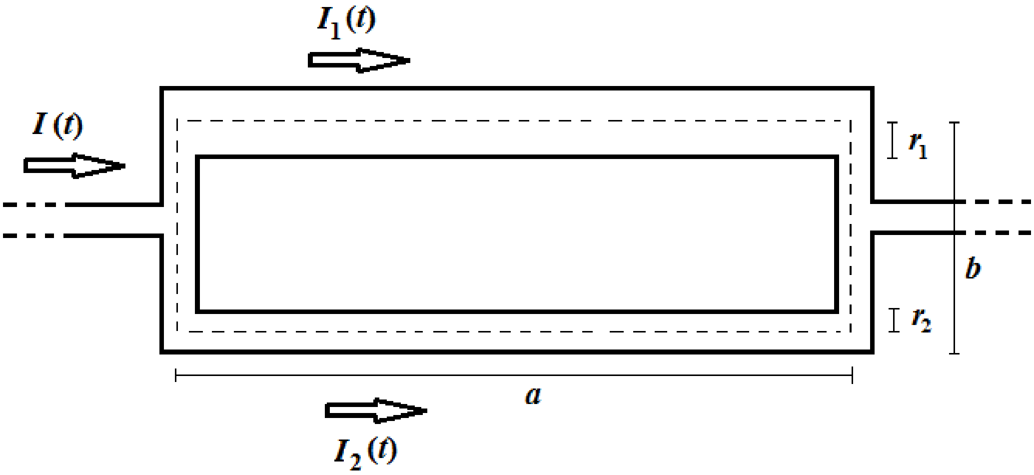

Figure 1 – Representation of a transient current being split into two parallel conductors

where the integration of the electric field E follows the path L along the dashed line in Figure 1 and the magnetic field H is integrated in the area $A = ab$ delineated by the dashed rectangle. As the electric field within a perfect conductor is null, the left-hand side of equation (1) is null. Therefore, the integral of the magnetic field time derivative within the loop area must be null.

Consider that the magnetic field has an harmonic time dependency given by:

$$H(t) = H_0 \exp\left(j\,\omega\,t\right) \qquad (2)$$

where ω is the angular frequency and $j = (-1)^{1/2}$ is the imaginary unit. This is not a limitation, as any impulsive signal can be broken down into a number of components of different frequencies. For each frequency, the integral of the magnetic field in the area between the conductors must be null. This means that the magnetic flux generated by the current I_1 in the dashed loop must be equal to the magnetic flux generated by the current I_2, as the corresponding magnetic fields have opposite directions. This condition is expressed by:

$$\int_{r_1}^{b-r_2} \frac{a\,I_1}{2\,\pi\,x}\,\mathrm{d}x = \int_{r_2}^{b-r_1} \frac{a\,I_2}{2\,\pi\,x}\,\mathrm{d}x \qquad (3)$$

Note that the integration limits are $b - r_2$ and $b - r_1$ because, due to the skin effect, the magnetic field within perfect conductors is null. A physical interpretation of equation (3) is that the smaller conductor 2 has a larger area to integrate the magnetic field, so that a lower current I_2 is necessary to generate the same field that is generated by the current I_1. Solving equation (3) gives:

$$I_1 \ln\left(\frac{b-r_2}{r_1}\right) = I_2 \ln\left(\frac{b-r_1}{r_2}\right) \qquad (4)$$

The total current is given by:

$$I = I_1 + I_2 \qquad (5)$$

Defining the shielding factor (η) as the fraction of the total current I that is left in conductor 1 after the placement of conductor 2, gives:

$$\eta = I_1 / I \qquad (6)$$

Inserting equation (5) into equation (4) and rearranging gives:

$$\eta = \ln\left(\frac{b - r_1}{r_2}\right) \bigg/ \ln\left[\frac{(b - r_1)(b - r_2)}{r_1 \; r_2}\right] \qquad (7)$$

In the situations where $b >> r_1$ and $b >> r_2$, equation (7) can be simplified as:

$$\eta = \ln\left(\frac{b}{r_2}\right) \bigg/ \ln\left(\frac{b^2}{r_1 \; r_2}\right) \qquad (8)$$

6.2 Guard-wire

A common protection of buried cables against lightning flashes is the installation of a guard-wire above the cable, as shown in Figure 2. Besides protecting the cable from being directly struck by lightning (see [ITU-T K.47]), a guard-wire regularly bonded to the cable metallic sheath also diverts to earth part of the lightning current of the cable screen.

The model described in clause 6.1 can be applied to this situation, as the two conductors are in parallel. Making reference to Figure 2, Equation (8) can be rewritten as:

$$\eta = \ln\left(\frac{d}{r_g}\right) \bigg/ \ln\left(\frac{d^2}{r_c \; r_g}\right) \qquad (9)$$

where r_g is the guard-wire radius, r_c is the telecommunication cable radius, and d is the distance between these conductors.

For example, consider a guard-wire with radius r_g = 3 mm placed in parallel with a buried cable with r_c = 10 mm metallic sheath and bonded to it at regular intervals. The distance between the two conductors is d = 300 mm. Equation (9) provides the shielding factor η = 0.58.

If the cable of Figure 2 is connected to a structure (e.g., a telecommunication tower) that is struck by lightning, the cable metallic sheath will carry 58 per cent of the total current, while the guard-wire will carry the remaining 42 per cent. The reduction of the lightning current in the cable may have a significant effect on the cable protection, as described in [ITU-T K.47].

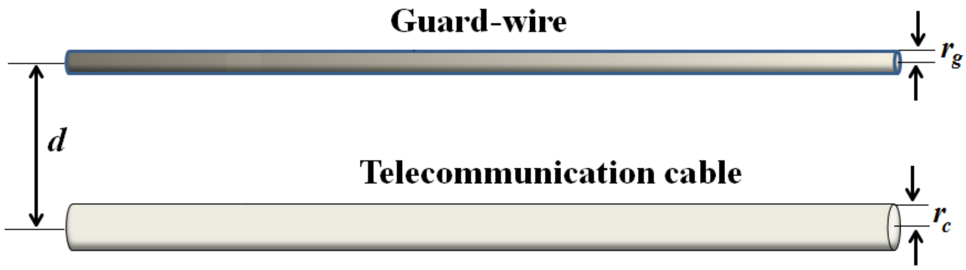

Figure 2 – Guard-wire above a telecommunication cable

6.3 Telecommunication towers

The model developed in clause 6.2 may be used to assess the current distribution on towers struck by lightning. In this case, the relevant shielding factor is related to the fraction of the total lightning current that flows through the cable feeders. This clause shows some examples that are good approximations to common tower structures, where the shielding factor provided by the tower is designated α_T to be in line with [ITU-T K.56] and [ITU-T K.97].

6.3.1 Tubular tower

If telecom cables are placed inside a tubular tower, the total lightning current flows through the tower and no current flows through the cable, so that $\alpha_T = 0$. Of course, this is an approximation that neglects the tower resistance. Otherwise, a more detailed calculation is needed, which takes into account the tower resistance. In this case, the cables are affected by the electric field developed along the internal surface of the tower. This electric field is given by the product of the internal surface impedance of the tower and the current in the tower.

If telecom cables are placed outside the tower, the distribution of current is determined by equations (7) or (8), which are rewritten here as equations (10) and (11), with the tower radius as r_t, the conductor radius as r_c, and the distance between the two axes as d.

$$\alpha_T = \ln\left(\frac{d - r_c}{r_t}\right) \bigg/ \ln\left[\frac{(d - r_c)(b - r_t)}{r_c \ r_t}\right] \tag{10}$$

$$\alpha_T = \ln\left(\frac{d}{r_t}\right) \bigg/ \ln\left(\frac{d^2}{r_t \ r_c}\right) \tag{11}$$

Usually, there are several conductors in parallel, such as coaxial feeders and power cables. In this case, r_c is the geometric mean radius (GMR) of a bundle of conductors. Annex A describes the calculation of the GMR. Figure 3 shows a cross-sectional view of the situation considered for a tubular tower.

It is important to highlight that, when the distance d between the two axes is not much larger than the tower radius r_t, some proximities effects arise. The result is that the current in the tower is no longer radially uniform, with the tower side opposite to the conductors carrying a higher current density and more current in the tower is required to fulfill the boundary condition described by equation (1). Therefore, neglecting the proximity effects in this calculation is a safe-side approach, as it leads to a shielding factor somewhat higher than the one obtained when the proximity effects are considered.

As an example of calculation, consider a tower radius $r_t = 150$ mm, a bundle of conductors with GMR $r_c = 50$ mm, and a distance between the two axes $d = 260$ mm. As in this case d is not much greater that r_t, equation (10) should be used, which provides $\alpha_T = 0.30$.

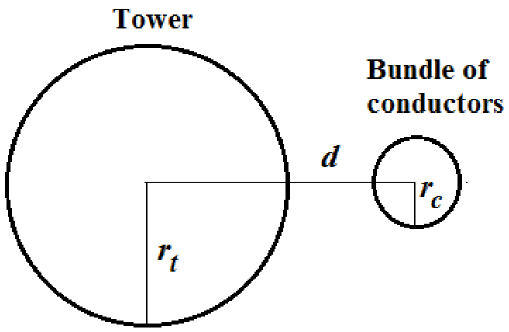

Figure 3 – Distances for tubular tower

6.3.2 Three-legged tower

Applying the same rationale to a three-legged tower, the following typical situations can be found, where the distance d is the distance from a leg to the axis of the tower. For towers in a pyramidal configuration, d shall be averaged along the tower.

– Bundle of cables at an arbitrary distance *s* from one leg. See Figure 4 (a).

$$\alpha_T = \left\{1 + \frac{3\ln(s/r_c)}{\ln\left[s\left(3d^2 + s^2 - 3d\,s\right)/3r_t\,d^2\right]}\right\}^{-1} \tag{12}$$

– Bundle of cables in the centre of the tower (*s* = *d*). See Figure 4 (b).

$$\alpha_T = \left[1 + \frac{3\ln(d/r_c)}{\ln(d/3r_t)}\right]^{-1} \tag{13}$$

– Cable in one side of the tower (*s* = 3*d*/2). See Figure 4 (c).

$$\alpha_T = \left[1 + \frac{3\ln(3d/2r_c)}{\ln(3d/8r_t)}\right]^{-1} \tag{14}$$

– Cable near one leg (*s* << *d*). See Figure 4 (d).

$$\alpha_T = \left[1 + \frac{3\ln(s/r_c)}{\ln(s/r_t)}\right]^{-1} \tag{15}$$

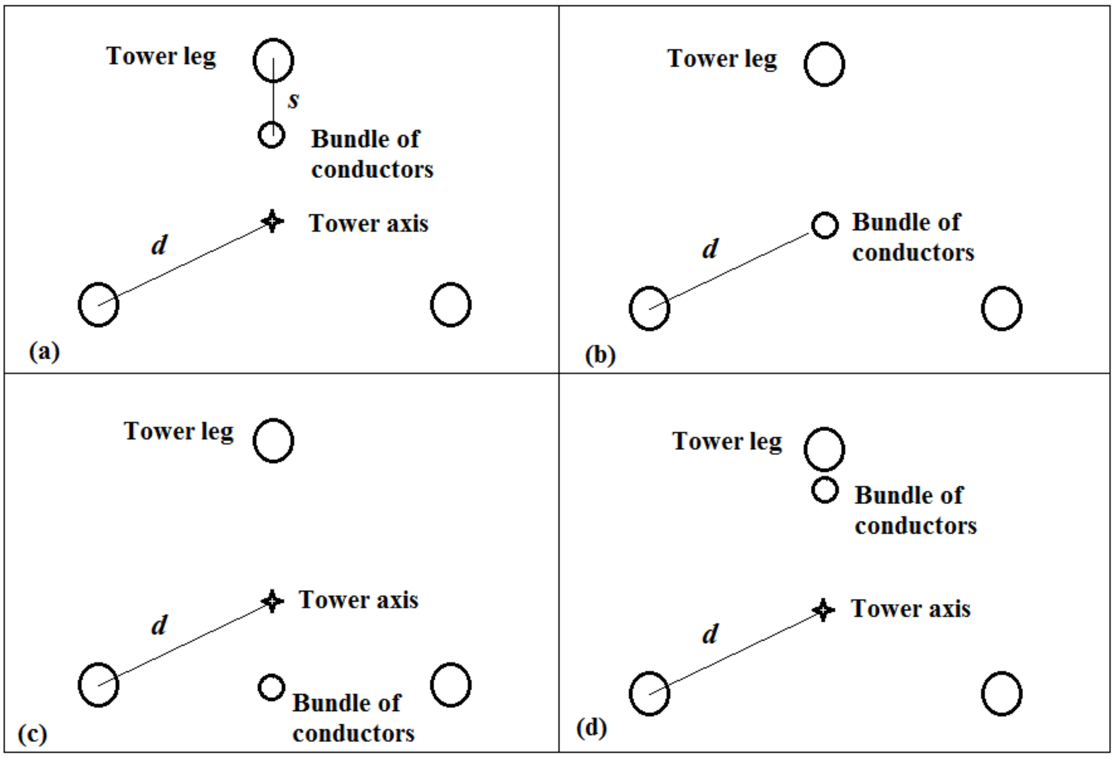

Figure 4 – Distances for three-legged tower

6.3.3 Four-legged tower

For a four-legged tower, the following typical situations can be found:

– Cable at an arbitrary distance *s* from one leg. See Figure 5 (a).

$$\alpha_T = \left\{1 + \frac{4\ln(s/r_c)}{\ln\left[s(2d - s)/2r_t\,d\right]}\right\}^{-1} \tag{16}$$

– Cable in the centre of the tower ($s = d$). See Figure 5 (b).

$$\alpha_T = \left[1 + \frac{4\ln(d/r_c)}{\ln(d/2r_t)}\right]^{-1} \tag{17}$$

– Cable near one leg ($s << d$). See Figure 5 (c).

$$\alpha_T = \left[1 + \frac{4\ln(s/r_c)}{\ln(s/2r_t)}\right]^{-1} \tag{18}$$

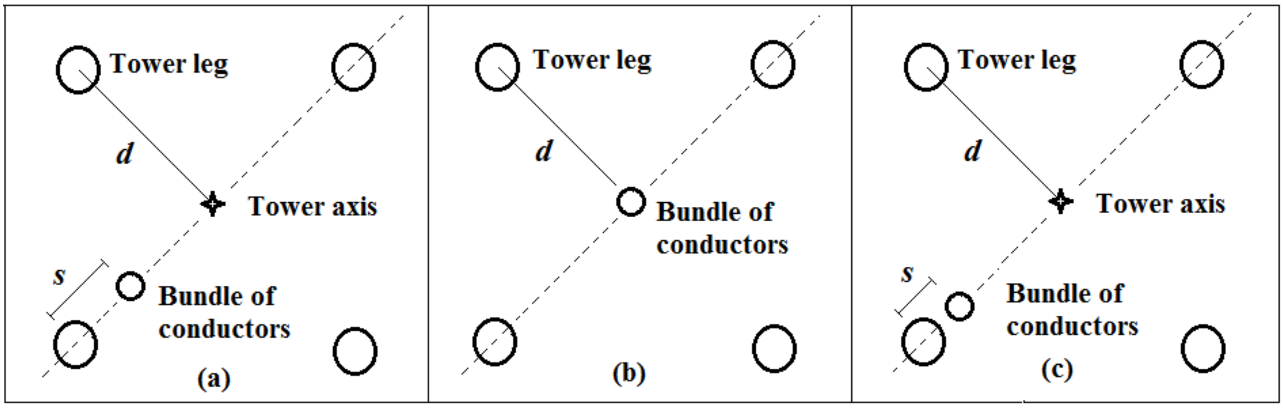

Figure 5 – Distances for four-legged tower

6.4 Cable trays and bundle of cables

Although the same rationale described in clause 6.1 applies to the case of having several cables in parallel, as in the bundle of cables and cables placed in a metallic tray, the lack of symmetry in the cable distribution prevents the development of generic formulas. Indeed, the shielding factor calculation for these complex cases often requires a dedicated numeric routine. In these routines, conductors of arbitrary cross-sectional profile may be represented by a number of cylindrical conductors disposed in the way as to form the desired profile.

For specific cases and using some approximations, it is possible to derive analytical expressions for the shielding factors. An example is shown in Figure 6 (a), where a feeder cable is placed in the middle of a ladder cable tray that runs along the tower. This situation is shown in Figure 6 (b), where the two lateral bars of the cable tray are replaced by equivalent cylindrical conductors. The radius of the equivalent conductor (r_b) is calculated with the procedure described in Annex A.

For the situation shown in Figure 6 (b), and considering that the cable is placed in the middle of the tray ($s = a/2$), the shielding factor can be easily calculated as:

$$\alpha_F = \frac{\ln(s/2r_b)}{\ln(s^3/2r_c^2 r_b)} \tag{19}$$

For instance, considering that the lateral bars in Figure 6 have a height $b = 50$ mm and a width that is negligible, Annex A gives $r_b = 16$ mm. For $r_c = 4$ mm and $s = 100$ mm, equation (19) gives $\alpha_F = 0.15$. If the cable tray is smaller ($s = 50$ mm), its shielding factor drops to $\alpha_F = 0.08$.

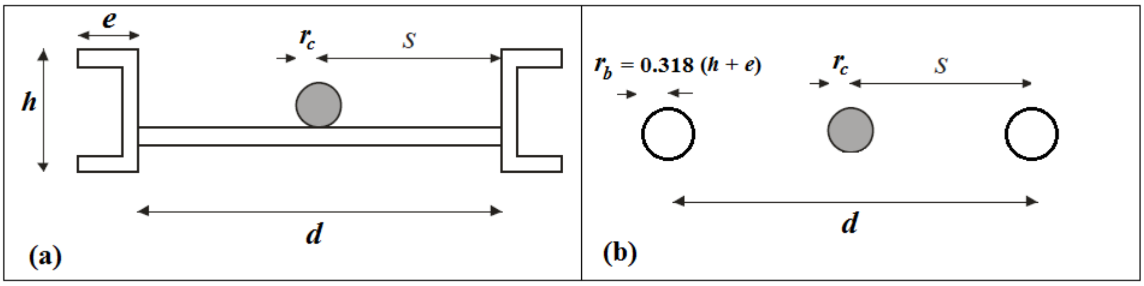

Figure 6 – Representation of a ladder tray by cylindrical conductors

7 Earthing connection of cables

This clause presents the rationale for the refraction factor δ considered in [ITU-T K.46].

Lightning flashes produce electromagnetic fields that induce impulsive voltages on aerial and buried telecommunication lines. These voltages are primarily induced in common-mode, i.e., the voltage is developed between the cable conductors and earth. The connection of the cable to earth reduces significantly the voltage (and current) that propagates along the line. This earthing connection may be done in two ways, depending on the type of cable:

1) Unshielded cables: the connection of the telecommunication conductors to earth is carried out by using surge protective components (SPCs), e.g., a gas discharge tube (GDT).
2) Shielded cables: the shield is usually connected direct to the earthing electrode.

This clause presents the rationale for the evaluation of the shielding effect provided by this earthing connection. For unshielded cables, the voltage developed across the SPC (e.g., arc voltage of a GDT) is neglected, so that the same model applies to shielded and unshielded cables.

This shielding effect is referred to here as the refraction factor (δ), in order to be in line with [ITU-T K.46]. 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 earthing connections of the line and the transition from buried to aerial installation (and vice versa) are examples of discontinuity in the line surge impedance.

Figure 7 (a) represents the refraction factor calculation, where the incident voltage wave $V_1(t)$ that propagates along a line with surge impedance Z_1 towards a discontinuity represented by an earthing connection and a change in the line surge impedance. As the incident wave reaches the discontinuity, it produces the refracted voltage $V_2(t)$ that is developed across the earthing connection R_g and propagates downline with surge impedance Z_2, as shown in Figure 7 (b). A reflected voltage $V_R(t)$ is also produced at the discontinuity, which travels back upline.

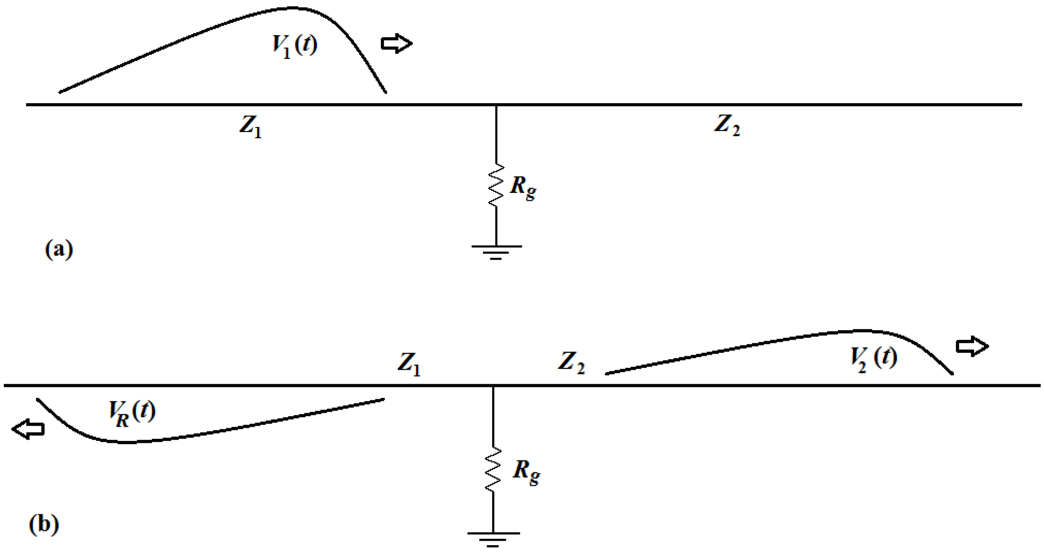

Figure 7 – Incident voltage $V_1(t)$ arriving at a line discontinuity (a) and the resulting reflected $V_R(t)$ and refracted $V_2(t)$ voltages (b)

It is clear that the voltage at the discontinuity is given by:

$$V_2(t) = V_1(t) + V_R(t) \tag{20}$$

Due to the energy conservation, the instantaneous power delivered by the incident voltage $V_1(t)$ must be equal to the power carried by the refracted voltage $V_2(t)$, carried by the reflected voltage $V_R(t)$, and dissipated in the earthing resistance R_g, which gives:

$$\frac{V_1^2(t)}{Z_1} = \frac{V_2^2(t)}{Z_2} + \frac{V_R^2(t)}{Z_1} + \frac{V_2^2(t)}{R_g} \tag{21}$$

Inserting $V_R(t)$ from equation (20) into equation (21) and rearranging yields the refraction factor:

$$\delta = \frac{V_2(t)}{V_1(t)} = \frac{2\,Z_2\,R_g}{Z_1\,R_g + Z_2\,R_g + Z_1\,Z_2} \tag{22}$$

An example of the application of equation (22) is a lightning surge induced in an aerial line (Z_1 = 400 Ω) being propagated towards a buried line (Z_2 = 100 Ω). At the transition between the aerial and buried cables, there is an earthing connection with 30 Ω resistance. Inserting these values into equation (22) gives the refraction factor δ = 0.11. Considering that the incident common mode surge has a 40 kV peak value, the common mode voltage in the buried cable is 40 × 0.11 = 4.4 kV.

Some specific situations may be derived from equation (22). For instance, if the line stops at the earthing connection, then $Z_2 = \infty$. This condition gives:

$$\delta = \frac{2\,R_g}{R_g + Z_1} \tag{23}$$

Similarly, if there is no earthing connection, but just a transition in the line surge impedance (e.g., from aerial to underground), then $R_g = \infty$ and the refraction factor becomes:

$$\delta = \frac{2\,Z_2}{Z_2 + Z_1} \tag{24}$$

If there is no earthing connection and the line stops at that point, then $Z_2 = \infty$ and $R_g = \infty$, which leads to δ = 2, i.e., the incoming voltage doubles at the open line end. On the other hand, if there is an earthing connection at the end of the line ($Z_2 = \infty$) and its value is equal to the incoming line impedance ($R_g = Z_1$), then $\delta = 1$ and the line is said to be matched to earth at this point.

8 Shielding factor of telecommunication cables

This clause presents the rationale for the shielding factor η of cables considered in [ITU-T K.46].

Figure 8 shows a tubular shielded telecommunication cable with its shield connected to earth at both ends through earthing resistances (R_g) equal to the cable surge impedance (Z), so that there is no reflection of the common mode voltages. A more general case with reflections from the cable ends can be derived from the model shown in Figure 8 by applying the superposition theorem on the voltages generated by each reflection.

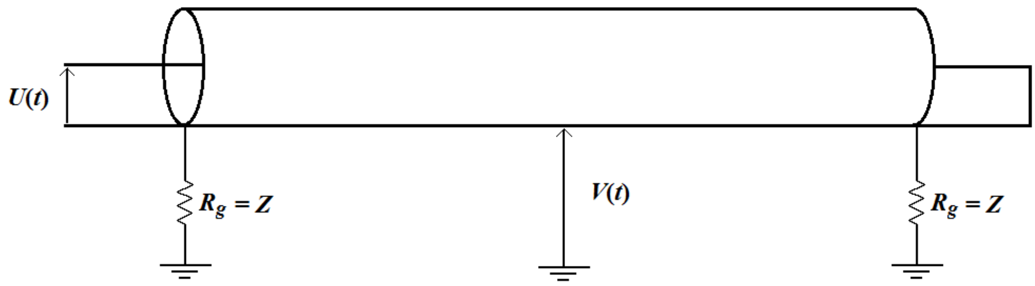

Figure 8 – Equivalent circuit for shielded telecommunication cable

Consider that the common mode voltage $V(t)$ is propagating in the line. The current associated with this voltage is:

$$I(t) = \frac{V(t)}{Z} \tag{25}$$

where Z is the common mode surge impedance of the line. Equation (25) assumes that the shield resistance R_S is much smaller than the cable common mode surge impedance Z, which is a reasonable assumption for regular shielded telecommunication cables.

The voltage $U(t)$ developed between the pairs and the shield is given by the voltage drop in the cable shield:

$$U(t) = I(t)R_S \tag{26}$$

where R_S is the internal surface impedance with external current return. For the low frequency, the internal surface impedance can be approximated by the direct current (DC) resistance of the shield.

Note that there are some conditions behind equation (25):

– the shield is tubular, so that no magnetic field leaks to the interior of the shield;

– for frequency bandwidth considered, the skin depth is significantly larger than the shield thickness, which is reasonable for lightning surges and shielded telecommunication cables;

– the pairs are terminated to the shield at one cable end and they are open at the other end (see Figure 8), which is a conservative approximation for telecommunication lines.

Substituting $I(t)$ from equation (24) into equation (25) yields:

$$\eta = \frac{U(t)}{V(t)} = \frac{R_S}{Z} \tag{27}$$

The shielding factor as per equation (27) shall be used only when the simplifying conditions considered in its development apply.

Annex A

Geometric mean radius of conductors

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

Table A.1 gives the GMR for typical conductor arrangements.

Table A.1 – Geometric mean radius of conductors

Conductor(s)	Illustration	Geometric mean radius
Solid circular conductor	Figure A.1 (a)	r
Solid rectangular conductor	Figure A.1 (b)	$0.318\,(a+b)$
Seven strand conductor	Figure A.1 (c)	r
Two parallel conductors	Figure A.1 (d)	$\left(d^2 r_1 r_2\right)^{1/4}$
Three parallel conductors	Figure A.1 (e)	$\left(d_{12}^2 d_{13}^2 d_{23}^2 r_1 r_2 r_3\right)^{1/9}$
n Parallel conductors	–	$\left(d_{12}^2 d_{13}^2 \ldots d_{1n}^2 d_{23}^2 \ldots d_{(n-1)n}^2 r_1 r_2 r_3 \ldots r_n\right)^{1/n^2}$
NOTE – Considering the inductive effects of lightning currents (high di/dt), the conductor internal magnetic flux has been neglected (perfect skin effect). For groups of conductors, symmetric current density at each conductor's periphery has been taken into account (the proximity effect has been neglected).		

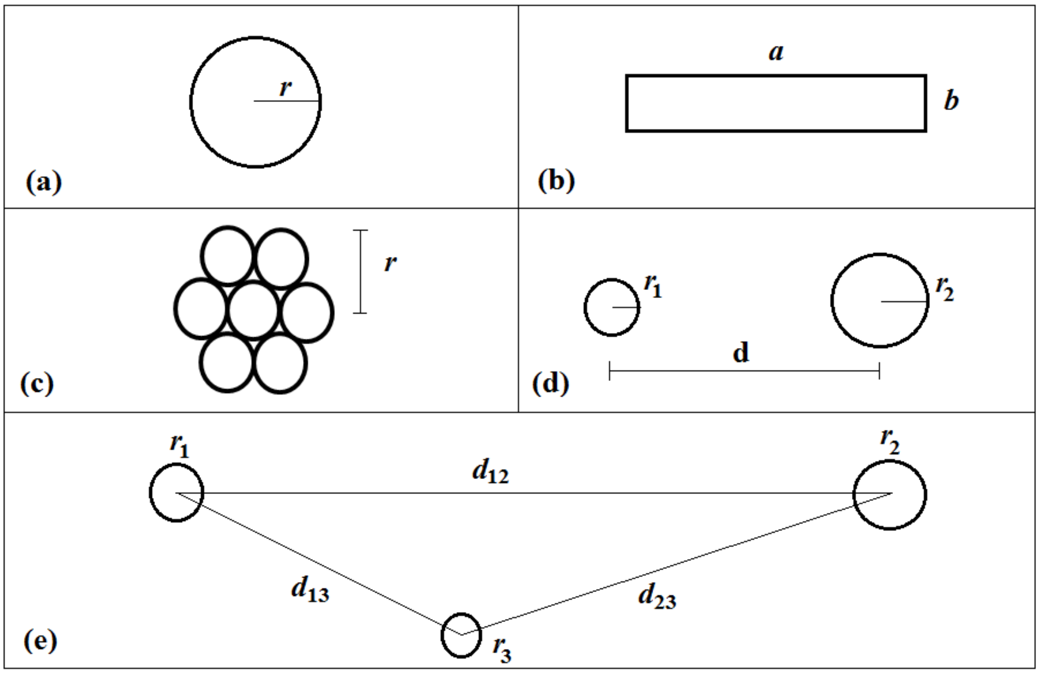

Figure A.1 – Geometric mean radius of typical conductors

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