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ITU-T

TELECOMMUNICATION
STANDARDIZATION SECTOR
OF ITU

K.67

(02/2006)

SERIES K: PROTECTION AGAINST INTERFERENCE

Expected surges on telecommunications and signalling networks due to lightning

ITU-T Recommendation K.67

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Summary

This Recommendation gives the characteristics (waveshapes and peak values) of the expected surges (overvoltages and overcurrents) due to lightning on telecommunication lines of the access network and on signalling lines at customers' premises using metallic conductors. These values of the expected surges are presented as a function of a set of lightning current parameters which define lightning as the source of damage by any type of electromagnetic coupling on a telecommunication or signalling line.

This Recommendation allows evaluation of the effectiveness of the protective measures (e.g., surge protective devices) that are intended to withstand the expected surge current at the installation point.

Source

ITU-T Recommendation K.67 was approved on 13 February 2006 by ITU-T Study Group 5 (2005-2008) under the ITU-T Recommendation A.8 procedure.

Keywords

Lightning, overcurrent, overvoltage, surge, transition point.

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.

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CONTENTS

Introduction

The origin of dangerous overvoltages and overcurrents on telecommunication and signalling networks is lightning (direct and indirect lightning strikes), induction from fault currents in power lines (including traction systems), contact with power lines, and the rise of earth potential.

Methods of protection, called "protective measures", are relevant to "lines" (e.g., use of shielded instead of unshielded cable) or to specific parts of the system. The latter fall broadly into 3 classes:

- the use of installation practices such as bonding, earthing, and shielding in the facility and on external lines to reduce the coupling of the lightning energy to the line;
- the use of protective devices which prevent excessive energy from reaching vulnerable parts either by diverting it (for example, spark gaps) or by disconnecting the line (for example, fuses); these protective devices are defined as "*primary protection*";
- the use of equipment with suitable dielectric strength, current carrying capacity and impedance so that it can withstand the conditions applied to it; this characteristic is defined as "*inherent protection*".

Protective devices (primary protection) are used against overvoltages (surge protective devices, (SPDs), e.g., air-gap protectors with carbon or metallic electrodes; gas discharge tubes (GDTs), semi-conductor protective devices) and against overcurrents (e.g., fuses, heat coils, self-restoring overcurrent protectors, fusible links).

For the specification of protective components and apparatus, the threat due to surges at their particular installation points need to be determined. The threat due to these surges must be lower than the withstand level of the affected protective components and equipment. This withstand level is determined by suitable tests.

This Recommendation deals with the expected surges due to lightning at different installation points of these protective components and equipment on telecommunication and signalling networks.

Certain formulas or assumptions for expected surges evaluation are severe approximations, and further refinement could improve them.

ITU-T Recommendation K.67

Expected surges on telecommunications and signalling networks due to lightning

1 Scope

The scope of this Recommendation is to define the expected surges (overvoltages and overcurrents) due to lightning at different transition points of the telecommunication access network and signalling lines, both outside and inside structures, i.e., exchanges customers' buildings and remote sites.

The objects of this Recommendation are the effects of overvoltages and overcurrents on telecommunication and signalling networks that use metallic conductors due to lightning current as a source of damage, which depend on the position of the point of strike with respect to the line under consideration (see 3.6).

The expected surges are defined by their peak values and waveshapes as a function of the surge protection level (SPL, see 3.7) for each type (S_1, S_2, S_3 and S_4) of source of damage (see 3.6). The waveshape of the expected surges is assumed to be a double exponential described by its front time, (T_1), and time to half value, (T_2).

This Recommendation allows evaluation of the effectiveness of the protective measures (e.g., surge protective devices) that are intended to withstand the expected surge current in the installation point.

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.

[1] ITU-T Lightning Handbooks, Chapter 10 (1995), *Overvoltages and overcurrents measured on telecommunication subscriber lines*.

[2] ITU-T Recommendation K.46 (2003), *Protection of telecommunication lines using metallic symmetric conductors against lightning-induced surges*.

[3] ITU-T Recommendation K.47 (2000), *Protection of telecommunication lines using metallic conductors against direct lightning discharges*.

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

[5] IEC 62305-1:2006, *Protection against lightning – Part 1: General principles*.

[6] IEC 62305-2:2006, *Protection against lightning – Part 2: Risk management*.

[7] IEC 62305-4:2006, *Protection against lightning – Part 4: Electric and electronic systems within structures*.

3 Definitions

This Recommendation defines the following terms:

3.1 dangerous surge voltage due to lightning: A surge voltage whose peak value U_p is greater than or equal to the surge voltage withstand level of the equipment or of the conductor insulation of the telecommunication line.

3.2 equivalent decay time to half value (T_2) [1]: The time to half value (T_2) of an impulse voltage or current is the time interval between the virtual origin and the first instant at which the voltage or current has decreased to half the peak value. (The virtual origin of an impulse voltage or current is the instant preceding that at which the voltage or current is 30% or 10% of the peak value by a time 0.3 or $0.1 \cdot T_1$ respectively.)

3.3 front time or rise time (T_1) [1]: The front time or rise time T_{1v} of an impulse voltage is defined as 1.67 times the time interval between the instants when the impulse is 30% and 90% of the peak value.

The front time T_{1i} of an impulse current is defined as 1.25 times the interval between the instants when the impulse is 10% and 90% of the peak value.

3.4 lightning protection level (LPL): A set of parameters that define protection levels against sources of damage represented by lightning current [4].

NOTE – Lightning protection level is used to design lightning protection components (e.g., cross section of conductors, thickness of metal sheets, current capability of SPD, separation distance against dangerous sparking) and to define test parameters simulating the effects of lightning on such components, according to the relevant set of lightning current parameters. Four lightning protection levels (I to IV) are introduced in the IEC 62305 standards. For each LPL, a set of maximum lightning current parameters is fixed (Table 1).

3.5 peak value (x_p) [1]: The peak value (x_p) of a surge voltage/current is defined as the maximum value observed during the surge.

3.6 source of damage: The source of damage depends on the position of the point of strike relative to the line being considered:

– Source of damage S_1: flashes to the structure (the exchange or the customer's building or remote site) where the telecommunication or the signalling line enters;

– Source of damage S_2: flashes near the structure (the exchange or the customer's building or remote site) where the telecommunication or the signalling line enters;

– Source of damage S_3: flashes to the telecommunications line entering the structure (the exchange or the customer's building or remote site);

– Source of damage S_4: flashes near the telecommunication line entering the structure (the exchange or the customer's building or remote site).

3.7 surge protection level (SPL): Peak values and waveshape of the expected dangerous surge voltages or currents which could appear in different points of the telecommunication networks due to the lightning current as source of damage.

NOTE – Three Surge Protection Levels (I to III) are introduced in this Recommendation. For each SPL, the peak values and the waveshape of the expected dangerous surge voltages and currents are estimated.

3.8 steepness of the front, or rate of rise (S) [1]: The steepness of the front, or the rate of rise, (S) is the average rate of change of the voltage or current. It can be determined by the ratio between the peak value x_p and the front time T_1:

$$S = \frac{x_p}{T_1} \quad (1)$$

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

NOTE 1 – Typical electrical sources are lightning and AC/DC power systems.

NOTE 2 – Electrical source coupling can be one or more of the following: electric field (capacitive), magnetic field (inductive), conductive (resistive), electromagnetic field.

3.10 **surge due to lightning**: A surge which is caused by lightning through any type of electromagnetic (conductive, inductive and capacitive) coupling.

NOTE – It is characterized by the following five parameters: peak value, front time (T_1), time to half value, T_2, (or time parameters T_1/T_2), steepness, and specific energy.

3.11 **surge protective device (SPD)**: Device that restricts the voltage of a designated port or ports, caused by a surge, when it exceeds a predetermined level.

NOTE 1 – An SPD is a combination of a protection circuit and a holder.

NOTE 2 – Secondary functions may be incorporated, such as current limiting to restrict a terminal current.

NOTE 3 – Typically, the protection circuit has at least one non-linear voltage-limiting surge protective component.

4 Abbreviations

This Recommendation uses the following abbreviations:

BN Bonding Network

CBN Common Bonding Network

E Exchange

LPL Lightning Protection Level

MDF Main Distribution Frame

MET Main Earthing Terminal

NT Network Termination

S Subscriber

SPD Surge Protective Device

SPL Surge Protection Level

5 Reference configuration

Figure 1 shows the reference configurations for the telecommunication lines with metallic symmetric conductors, where the reference nodes and the cable sections between them can be seen.

The Transition Points of Figure 1 have the following descriptions [2]:

- Transition point L: Transition between equipment interface inside the exchange building and the external cabling;
- Transition point E: Entrance of the exchange building, e.g., the main distribution frame (MDF);
- Transition point P: Transition between paper-insulated and plastic-insulated buried cables;
- Transition point C: Transition between buried and aerial cables;
- Transition point D: Transition between shielded and unshielded aerial cables;
- Transition point S: Entrance of the customer's building;

- Transition point A: Transition between equipment interface inside the customer's building and the external cabling;
- Transition point M: Transition between equipment interface inside the exchange's building and the internal cabling;
- Transition point I: Transition between equipment interface inside the customer's building and the internal cabling.

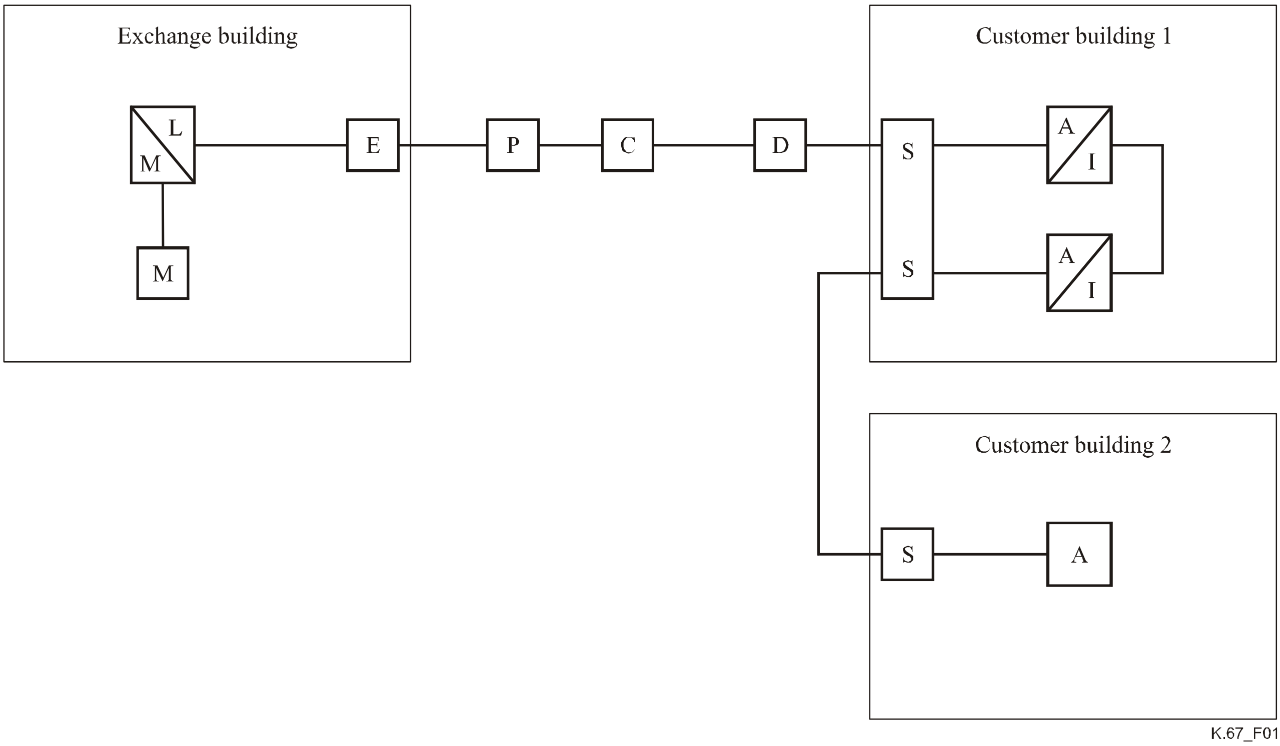


Figure 1/K.67 – Reference configuration

6 Protective measures

6.1 Inherent protection

The use of equipment with suitable dielectric strength, current carrying capacity and impedance so that it can withstand the conditions applied to it (i.e., the inherent resistibility characteristics of equipment), is necessary in order to achieve equipment protection and limit its risk of damage.

The resistibility requirements of telecommunication equipment used at different points of telecommunication networks have been defined in ITU-T Recs K.20, K.45 and K.21 for equipment installed in the exchange building, in the access network and in the customer's building respectively.

From the lightning protection point of view, this resistibility allows the equipment to withstand the majority of the induced surges caused by lightning near the line (see 7.4). Because these surges are the most frequent, the use of additional protective measures (primary protection) is limited to the "exposed" installations, evaluated by the risk assessment [2, 3, 6].

6.2 Primary protection

The use of primary protection prevents excessive energy from reaching vulnerable parts of the telecommunication and signalling installations (e.g., equipment and conductor insulations). To this end, adequate primary protection shall be installed and its characteristics shall be suitably selected.

The effectiveness of the primary protection depends on its capability of conducting the surge currents (for voltage-limiting devices, GDTs) or withstanding the surge voltages (for current limiting-devices, fuses). The lightning parameters that determine the maximum values of surge voltages and currents are given in Table 1, as a function of the lightning protection level (LPL). These maximum values of surge voltages and currents are associated to the following surge protection level (SPL): SPL I = 0.01, SPL II = 0.02 and SPL III = 0.05 which gives the probability value of the dangerous surge voltage or current to be greater than, or equal to, the associated peak value.

Table 1/K.67 – Maximum values of lightning parameters according to LPL

Current parameters		**Symbol**	**Unit**	**LPL**			
				I (99%)	**II (98%)**	**III (95%)**	**IV**
First short stroke	Peak current	I_p	kA	200	150	100	
	Short stroke charge	Qshort	C	100	75	50	
	Specific energy	W/R	kJ/Ω	10 000	5 625	2 500	
	Time parameters	T_1/T_2	µs/µs	10/350			
Subsequent short stroke	Peak current	I_p	kA	50	37.5	25	
	Average steepness	di/dt	kA/µs	200	150	100	
	Time parameters	T_1/T_2	µs/µs	0.25/100			
Long stroke	Long stroke charge	Qlong	C	200	150	100	
	Time parameter	Tlong	s	0.5			
Flash	Flash charge	Qflash	C	300	225	150	

6.3 Bonding, earthing and shielding

The use of installation techniques that provide bonding, earthing and shielding reduce the coupling between the lightning and the communication line. In case of direct lightning strikes or near strikes to the line, the CBN of the structure and equipment BNs disperse the lightning current providing shielding for the internal lines. A fully encircling shield or conduit can be effective in reducing the voltage and current coupled onto the communication conductors. The critical parameter for the shielding effectiveness of the cable is its transfer impedance, which for solid shields at lightning frequencies is approximately equal to the shield d.c. resistance.

The primary protection in combination with the bonding and earthing measures form an electromagnetic barrier of the facilities that reduces the penetration of electromagnetic disturbances into the facility from the outside.

7 Expected surges due to lightning

7.1 Direct lightning flashes to a structure (source of damage S1): Lightning current flowing through telecommunication or signalling lines entering the structure (exchange or customer's building or remote site)

The lightning current of a direct stroke to a structure flows into the earthing system of the structure as well as into the services that enter the structure. Therefore, a part of the lightning current enters the cable sheath or the cable conductors of the telecommunication or signalling line directly or via surge protective devices (SPDs) connected to them, as the cable is one of the services entering the structure.

The lightning current parameters are those given in Table 1 for the first short stroke as a function of the selected LPL. Therefore, the lightning current entering the telecommunication or signalling line is described by 10/350 μs waveshape and by the peak value I_f.

As a first approximation, it can be assumed that 50% of the lightning current (I), flows in the earth termination system and the remaining 50% of the current is shared between the n services entering the structure.

If the entering telecommunication or signalling line is unscreened or is not routed in metal conduit, each of the *m* conductors of the line carries an equal part (I_f), of the peak lightning current which may be evaluated by:

$$I_f = \frac{0.5 \times I_p}{n \times m} \qquad \text{for an unshielded line} \qquad (2)$$

For shielded entering lines (or for those routed in metal conduit) bonded at the entrance of the structure, the peak values (I_f), of current entering each of the m conductors, is given by:

$$I_f = \frac{0.5 \times I_p \times R_s}{n \times (m \times R_s + R_c)} \qquad \text{for a shielded line} \qquad (3)$$

where:

R_s = ohmic resistance for unit length of the shield or the metal conduit;

R_c = ohmic resistance for unit length of the conductor.

The open circuit voltage between a conductor and the main earthing terminal (MET) is approximately proportional to the product of the earthing resistance and the portion of the lightning current that flows to the earthing network if the cable is unshielded. If the cable is shielded, the open circuit voltage between the conductor and the MET that is bonded to the cable shield is approximately proportional to the product of the shield resistance and the portion of the lightning current that flows through the shield, limited by the breakdown voltage of the core conductors to the shield (e.g., 5 kV). Where the shield is periodically earthed, the shield current attenuates as it propagates away from the strike point. Propagation of the surge along the cable leads to dispersion and increase of the decay time.

Even considering possible ionization of the earth near the electrodes, the magnitude of the resulting voltage is likely to be sufficiently high to operate primary protection or to cause breakdown of the conductor insulation, if there is no protection. Therefore, detailed procedures for calculating the peak voltage are not considered. This applies to unshielded and shielded telecommunication lines.

7.2 Lightning flashes near, or to, a structure (source of damage S1 or S2): Induced surges in telecommunication or signalling lines inside the structure (exchange or customer's building or remote site)

A lightning flash near, or to, a structure induces common mode surge voltages into the telecommunication or signalling line inside the structure (exchange or customer's building or remote site) due to the time derivative of the lightning current (di/dt). The peak value V_{io} of the induced open circuit voltage is given by the following equation:

$$V_{io} = L_M \times \frac{di}{dt} = L_M \times \frac{I_p}{T_1} \tag{4}$$

where:

L_M = the mutual inductance between the induced loop and the lightning current;

I_p = peak value of the lightning current;

T_1 = front time of the lightning current.

The lightning current parameter is the average steepness (di/dt), given by the ratio between the peak value (I_p), and the front time (T_1) (see 3.8) of the subsequent strokes (worst case) given in Table 1 as a function of the selected LPL.

The waveshape of the induced open circuit voltages is expected to have a very short duration (in order of few µs, e.g., 2 µs to 10 µs) and a front time similar to that of the subsequent stroke (i.e., 0.25 µs), as shown by measurements of induced voltages into a loop carried out with triggered lightning, reported in Appendix I.

The peak value of the short circuit current (I_{sc}), if the ohmic resistance of the loop wires is neglected (worst case), is estimated as follows:

$$I_{sc} = \frac{V_{oi} \times T_1}{L_S} \tag{5}$$

or

$$I_{sc} = \frac{L_M}{L_S} \times I_p \tag{6}$$

where:

L_S = is the self-inductance of the induced loop.

For the short circuit current (I_{sc}), the lightning current parameter is the peak value (I_p), of the first strokes (worst case) given in Table 1 as a function of the selected LPL. Its waveshape is the waveshape of the lightning current (see Appendix I), therefore in the worst case it is described by the 10/350 µs wave shape.

The peak values of the open circuit voltage (V_{oi}), due to the subsequent strokes, and short circuit current (I_{si}), due to the first strokes, are reported in Table 2, for different SPL values. These values have been estimated, as shown in Annex A (A.2 and A.3), for an unshielded loop having a loop area of 50 m^2 (h = 5 m; e = 10 m) inside an unshielded structure or building.

Table 2/K.67 – Expected open circuit voltages and short circuit currents per conductor at different nodes of a telecommunication or signalling line due to lightning flashes direct to the structure (S_1) and to the telecommunication line (S_3) and near to the structure (S_2)

<table>
<tr><th rowspan="3">SPL</th><th colspan="3">Direct flashes to the structure source of damage S_1</th><th colspan="2">Near the structure source of damage S_2</th><th colspan="2">Direct flashes to the telecommunication line source of damage S_3</th></tr>
<tr><td>Nodes E and S</td><td colspan="2">Nodes L, A, M and I (Note 1) (1 down conductor only) (see Table A.2)</td><td colspan="2">Nodes L, A, M and I (Note 1) (see Table A.1)</td><td>Nodes L, E, P</td><td>Nodes C, D, S, A</td></tr>
<tr><td>(part of direct lightning current) waveshape: 10/350 µs [kA]</td><td>(induced voltage by subsequent strokes) waveshape: 0.25/2 µs [kV]</td><td>(induced current by first stroke) waveshape: 10/350 µs [kA]</td><td>(induced voltage by subsequent strokes) waveshape: 0.25/2 µs [kV]</td><td>(induced current by first stroke) waveshape: 10/350 µs [kA]</td><td>(part of direct lightning current) waveshape: 10/350 µs [kA]</td><td>(part of direct lightning current) waveshape: 10/350 µs [kA]</td></tr>
<tr><td>I</td><td>Equation (2) or (3)</td><td>250</td><td>6</td><td>5</td><td>0.1</td><td>0.50 (Note 2)</td><td>Equation (12) or (14)</td></tr>
<tr><td>II</td><td>Equation (2) or (3)</td><td>190</td><td>4.5</td><td>3.5</td><td>0.07</td><td>0.50 (Note 2)</td><td>Equation (12) or (14)</td></tr>
<tr><td>III</td><td>Equation (2) or (3)</td><td>125</td><td>3</td><td>2.2</td><td>0.05</td><td>0.50 (Note 2)</td><td>Equation (12) or (14)</td></tr>
<tr><td colspan="8">NOTE 1 – Calculation conditions: unshielded structure; unshielded induced line; loop dimensions: 50 m^2 (h = 5 m; e = 10 m); loop conductor radius: 0.5 mm.
NOTE 2 – In particular cases, Equation (12) or (14) can be used. Line-to-earth breakdown voltage is considered as equal to 100 kV and the line is short circuited to earth at the point of interest.</td></tr>
</table>

For an induced line with a different loop but area with the same loop length (e), the values of the surge voltages given in Table 2 must be multiplied by the following factor (K_r):

$$K_r = A/50 \qquad \text{(A is loop area in m}^2\text{)} \tag{7}$$

Then Equation (5) allows the evaluation of the short circuit current (I_{sc}), calculating the value of the self-inductance (L_S) of the new loop.

For shielded lines the values of surge voltages given in Table 2 can be reduced by factor K_{s3} given by the following equation:

$$K_{s3} = K_r \times K_{ss} \tag{8}$$

where:

$$K_{ss} = \frac{V_{cs}}{V_{io}} \tag{9}$$

V_{cs} = the voltage between conductor and shield given by the following equation:

$$V_{cs} = R \times I_{sc} \tag{10}$$

Using Equations (4) and (5) for V_{io} and I_{sc} respectively, Equation (8) becomes:

$$K_{ss} = \frac{R \times T_1}{L_S} \quad \text{valid for } (L_S/R) >> T_1 \tag{11}$$

where:

K_{ss} = the value of the shielding factor related to the shield (R is the shield resistance in Ω).

NOTE – Equation (10) is valid for tubular sheaths. For braided sheaths, this is an approximation.

The values of the surge currents for a different loop area can be evaluated considering that both the induced surge voltage and the loop inductance have different values (see A.2 and A.3).

7.3 Direct lightning to the telecommunication or signalling lines

There are two possible situations:

a) the striking point is far away from the structure;

b) the striking point is close to the structure.

In both situations, the lightning current entering the telecommunication or signalling line is described by the 10/350 µs waveshape and by the peak value I_f. Neglecting the propagation effects, the same 10/350 µs waveshape is assumed for the current expected in different sites of the network (exchange or customer's building or remote sites).

In situation a, the total peak current in the line will be given, in the worst case, by twice the line to earth breakdown voltage divided by the line surge impedance (e.g., 2 × 100 kV/400 Ω = 500 A); this worst case is independent from LPL I to IV. However, if the line is shielded and the shield is earthed periodically, the analysis for situation b applies.

In situation b, partitioning of the lightning current in both directions of the telecommunication network, and breakdown of insulation to earth, must be taken into account. As a first approximation, it can be assumed that 50% of the lightning current (I_p), breaks down to earth and half of the remaining 50% of the current is propagated in both directions, between the n services close to each other.

If the telecommunication or signalling line is unscreened or is not routed in metal conduit, each of the *m* conductors of the line carries an equal part (I_f) of the peak lightning current which may be evaluated by:

$$I_f = \frac{0.25 \times I_p}{n \times m} \quad \text{for an unshielded line} \qquad (12)$$

where n = 1 or 2; the latter case applies for example, where telecommunication and power lines are close to each other, e.g., they share the same poles.

The value given by Equation (12) shall be equal to or lower than the following value:

$$I_f \leq 8 \times A \qquad \text{[kA]} \qquad (13)$$

where A is the cross-sectional area of the telecommunication or signalling conductor [mm^2].

For shielded (or routed in metal conduit) entering lines bonded at the entrance of the structure, the peak values (I_f), of current entering each m conductor, is given by:

$$I_f = \frac{0.25 \times I_p \times R_s}{n \times (m \times R_s + R_c)} \qquad \text{for a shielded line} \qquad (14)$$

where:

R_s = ohmic resistance for unit length of the shield or the metal conduit;

R_c = ohmic resistance for unit length of the conductor.

The open circuit voltage between conductor and shield is approximately proportional to the product of the shield resistance and the portion of the lightning current that flows through the shield, limited by the breakdown voltage of the core conductors to the shield (e.g., 5 kV). Where the shield is periodically earthed, the shield current attenuates as it propagates away from the strike point. Propagation of the surge along the cable leads to dispersion and an increase of the decay time.

For exchange buildings, in general the lightning strikes the aerial line (few pairs) far away from the structure. For this situation, values reported in Table 2 can be used. For particular situations, Equations (12), (13) and (14) above can be used.

For the customer's building, the worst case occurs, in general, when the striking point is close to the structure. For this situation, values estimated with Equations (12), (13) and (14) above can be used.

NOTE – Little information is available on surge currents due to direct lightning to telecommunication lines. In Chapter 10 of the Lightning Handbook [1], the Canada survey reports that "*the 300 A, 300 µs half decay event was the result of a direct lightning strike to a pole which was approximately 200 m from a carbon monitor site. This site was also equipped with a level counter and digital waveform monitor. The cable and pole were severely damaged*". No information is available on the peak value of the lightning current striking the line. If it is assumed that this 300 A surge current has been caused by a lightning current of about 30 kA, corresponding to a 50% probability, then it is possible to estimate the values of 2 or 1 kA associated with LPL I or III respectively. Similar results can be obtained using Equation (6) with n = 1 and m = 20 when the lightning current is 200 kA (LPL I) or 100 kA (LPL III).

7.4 Lightning flashes near telecommunication lines

7.4.1 General

The peak values of the lightning surge voltages and currents expected in some transition points of the telecommunication network have been investigated by several surveys carried out in different countries. The results of these surveys have been reported in Chapter 10 of the Lightning Handbook [1].

The inherent resistibility requirements of telecommunication equipment, as defined in ITU-T Recs K.20, K.21 and K.45, are based on the survey results as shown in the Lightning Handbook [1].

The use of additional protective measures (primary protection) is limited to the "exposed" installations and is evaluated by the risk assessment [2, 3, 6].

The worst induction case, assumed by this Recommendation, is shown in Figure 2 where the lightning flash location is equidistant from the line terminations and at a distance "x" from the telecommunication line, which is a 6 m high (h = 6) aerial line.

The expected dangerous surge voltages and currents are evaluated in the middle point and at the line terminations.

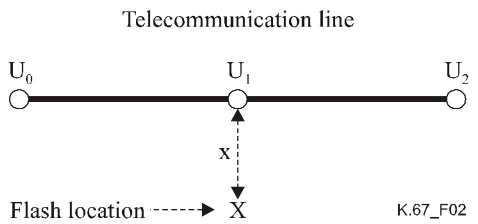


Figure 2/K.67 – Reference configuration for surge evaluation induced by a lightning near the line (worst case)

By the definition of SPL:

$$SPL = \frac{N_T(U_{SPL})}{N_T(U_R)} \tag{15}$$

where:

U_{SPL} = the voltage corresponding to the selected SPL;

U_R = a reference voltage (lower than U_{SPL}) that defines the minimum resistibility voltage level of the equipment connected to the line or of the line conductor insulation;

$N_T(U)$ = the total number of strikes that will induce a voltage equal to or greater than U.

The calculation of N_T and U_{SPL} is reported in Annex B for an aerial line, both unshielded and shielded, above perfectly conducting soil.

Annex B also suggests how to evaluate the short circuit currents associated with the dangerous surge voltages.

7.4.2 Calculated values (perfectly conducting soil)

The peak values of the dangerous surge open circuit voltages and short circuit currents expected in the transition points P, C and D (close to the middle point) of the unshielded aerial line are reported in Table 5, for the different SPL. The waveshape of the surge voltage and current varies widely with the characteristics of the lightning current (waveshape, peak value and velocity), with the distance between the stroke and the line and with the line characteristics (earthing connections, shielding, etc.). Considering a fixed lightning current and an unshielded line, the increase in the distance between the stroke and the line leads to lower induced voltage and current and longer waveshapes. Moreover, shielding a line also leads to lower induced voltage and current and longer waveshapes.

For the lightning currents considered in Table 1, the velocity of the return stroke is equal to 130 m/μs and the induced voltages corresponding to the selected range of SPL (i.e., 0.01 to 0.05), the waveshape of the induced voltages and currents on an unshielded line can be represented by a 8/20 μs double exponential wave. For a shielded line, the peak value is lower and the waveshape is longer, so that a 10/700 μs double exponential wave is more representative.

NOTE – The 8/20 μs waveshape for an unshielded aerial line has been calculated using reference [5], assuming velocity of the return stroke is equal to 130 m/μs. For the shielded line, the waveshape has been assumed in agreement with measurements.

7.4.3 Measured values (imperfectly conducting soil)

The surge voltages and currents which can appear in the access network have been measured in several countries and the measurement data are reported in Chapter 10 of the Lightning Handbook [1]. These data are summarized in Table 3.

These data have been collected in the field on lines composed of a mixture of buried and aerial shielded sections and often a short unshielded section near the customer (the *drop wire*). The majority of the data was measured at the exchange and at the subscriber ends. In Table 3, the voltage U_e is the voltage between the pair and the shield measured at the exchange end and i_{sce} is the associated short circuit current, whereas U_s is the open circuit voltage between the pair (or one conductor of the pair) and the earth at the customer end and i_{scs} is the associated short circuit current.

Table 3/K.67 – Measured open circuit surge voltages and short circuit surge currents at the exchange and customer ends

Probability	Exchange end		Customer end	
	U_e [V]	i_{sce} [A]	U_s [V]	i_{scs} [A]
0.01	860	17	2300	23
0.02	680	13	1640	16
0.05	480	8	1020	10

Assuming the shield resistance R_s = 5 Ω, the earth resistance of the shield connection to earth near the customer R_t = 40 Ω and the surge impedance Z = 100 Ω for buried section and Z = 400 Ω for aerial section, the following values of η_{ss} = 0.05 and η_{se} = 0.1 can be estimated.

Considering these shielding factor values, from measurement data it is possible to estimate the truncated distribution (U_R = 50 V) at the exchange end and (U_R = 150 V) at the customer end. Dangerous peak values of the surge voltages and currents are reported in Table 4 as a function of the SPL.

Table 4/K.67 – Measured open circuit dangerous surge voltages and short circuit surge currents at the exchange and customer ends

SPL	Exchange end		Customer end	
	U_e [V]	i_{sce} [A]	U_s [V]	I_{scs} [A]
I	1000	20	3500	35
II	750	15	2500	25
III	500	10	1500	15

These values are also reported in Table 5.

Table 5/K.67 – Expected open circuit voltages and short circuit currents per conductor at different nodes of a telecommunication or signalling line due to lightning flashes near to the telecommunication line (S_4)

SPL	Lightning flashes near the telecommunication or signalling line (worst case) source of damage S_4									
	Nodes L, E, P and C		Nodes D, S and A		Nodes L, E, P and C (calculated η_s = 0.05)	Nodes L, E, P and C (measured)		Nodes D, S and A (calculated η_e = 0.1)	Nodes D, S and A (measured)	
	Unshielded line (Note)				Line composed by: buried shielded (E-C nodes), aerial shielded (C-D nodes), and aerial unshielded (C-S nodes) sections					
	Induced voltage: 8/20 μs [kV]	Induced current: 8/20 μs [A]	Induced voltage: 8/20 μs [kV]	Induced current: 8/20 μs [A]	Induced voltage: 10/700 μs [kV]	Induced voltage: 10/700 μs [kV]	Induced current: 10/350 μs [A]	Induced voltage: 10/700 μs [kV]	Induced voltage: 10/700 μs [kV]	Induced current: 10/350 μs [A]
I	44	110	64	160	1	1	20	6.4	3.5	35
II	23	60	34	85	0.75	0.8	15	3.4	2.5	25
III	10	25	14	35	0.5	0.6	10	1.4	1.5	15
NOTE – Calculation conditions: Aerial line and perfectly conducting soil.										

Annex A

Induced surges inside the structure due to lightning near, or to, the structure

A.1 General

Lightning induced surges into loops formed by the wiring in an installation is an important issue for many ITU-T K-series Recommendations. Lightning surges are characterized by their waveshape and peak value.

Appendix I shows the waveshapes of these induced surge voltages based on the results of measurements carried out in an experimental installation.

The peak value of the open circuit voltage (V_{io}) and short circuit current (I_{io}) induced in the loop are estimated in A.2 and A.3 for lightning flashes near, or to, the structure respectively.

A.2 Lightning near the structure

The peak value of the open circuit voltage (V_{io}) induced in the loop inside the structure by lightning near the structure can be calculated with Equation (4) where the mutual inductance (L_M) is given by the following approximated equation (assuming the incident magnetic field to be a plane wave) [3, 6]:

$$L_M = 0.2 \times \eta \times K_s \times h \times \ln\left(\frac{f+d+e}{f+d}\right) \quad [\mu\text{H}] \qquad (A.1)$$

where (see Figure A.1):

h = width or height of the loop [m];

e = length of the loop [m];

f = distance from the lightning channel to the wall of the structure [m];

d = distance of the loop from the wall of the structure;

$\eta = 0.12 \times w$ = shielding factor of the structure shield (shield of LPZ 1), where $w \leq 5$ m is the mesh width of the grid-like spatial shield [5, 6];

K_s = shielding factor, taking into account the effect of the cable shield;

and:

I_{ps} = peak value of the subsequent strokes (Table 1) [kA];

$T_1 = 0.25$ = front time of the subsequent strokes (Table 1) [µs].

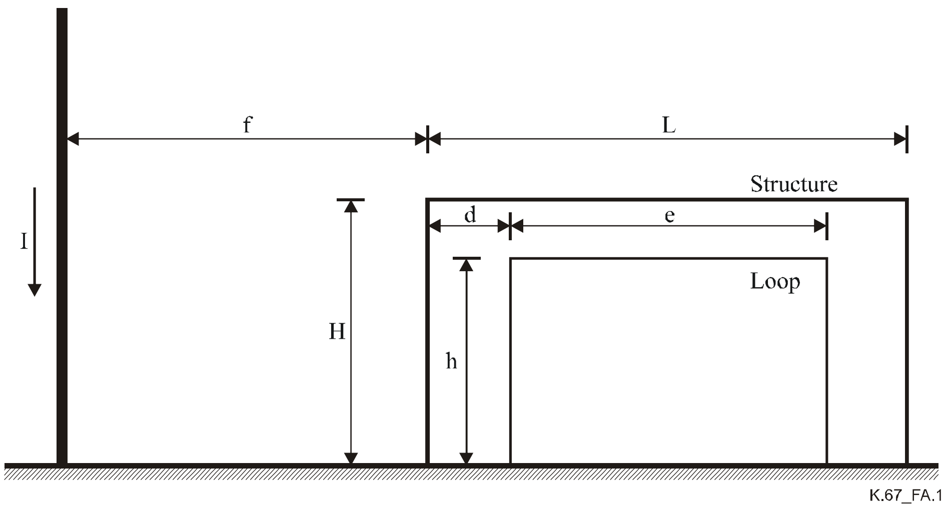


Figure A.1/K.67 – Lightning strokes near the structure

The short circuit current (I_{sc}), if the ohmic resistance of the wires is neglected (worst case), is estimated with Equation (5) or (6), where the self-inductance (L_S), in µH, of the loop is calculated with the following equation:

$$L_S = 0.8 \times \sqrt{e^2 + h^2} - 0.8 \times (e+h) + 0.4 \times e \times \ln\left[\frac{\frac{2 \times h}{r}}{e + \sqrt{e + \left(\frac{h}{e}\right)^2}}\right] + 0.4 \times h \times \ln\left[\frac{\frac{2 \times e}{r}}{e + \sqrt{e + \left(\frac{e}{h}\right)^2}}\right] \qquad \text{(A.2)}$$

where:

r = the radius of the loop wire [m].

The expected dangerous surge voltages induced into the internal loop are evaluated by Equation (4).

By the definition of SPL:

$$SPL = \frac{N_T(U_{SPL})}{N_T(U_R)} \qquad \text{(A.3)}$$

where:

U_{SPL} = the voltage corresponding to the selected SPL;

U_R = a reference voltage (lower than U_{SPL}) that defines the minimum resistibility voltage level of the equipment connected to the line or of the line conductor insulation;

$N_T(U)$ = the total number of strikes that will induce a voltage equal to or greater than U.

The total number of strikes N_T (U) is given by (see Figure A.2):

$$N_T = 4.N_g \int_R^{\infty} \int_o^{\pi/2} \int_I^{\infty} p(i).di.\cos\theta.d\theta.x.dx \qquad \text{(A.4)}$$

where:

N_g = the ground flash density (strikes/km^2 . year);

R = the minimum distance from the loop at which the lightning will not directly strike the structure (R ≅ 3H + L/2) (see Figure A.1);

$p(i)$ = the probability function of the strike current.

NOTE 1 – As shown in ITU-T Rec. K.47, $p(i) = 10^{-2}\ e^{(a-bi)}$ for $i \geq 0$, where "i" is lightning peak current [kA], a = 4.605 and b = 0.0117 for i ≤ 20 kA and a = 5.063 and b = 0.0346 for i > 20 kA.

θ = the angle between the loop and a straight line linking the strike and the loop;

x = the distance between the strike and the centre of the loop;

I_p = the peak strike current that will induce the voltage U at the loop given by Equation (4).

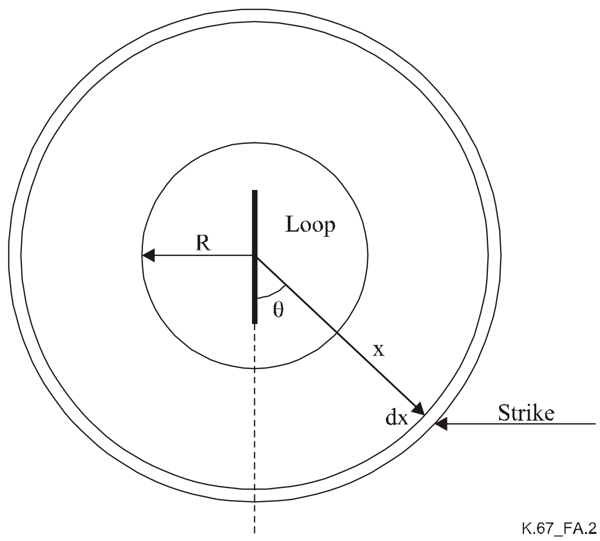


Figure A.2/K.67 – Reference configuration for evaluation of the surge induced into a loop by lightning near a structure

Considering that most of the strikes will be at some distance from the structure so that f+d >> e and, therefore, ln [(f+d+e)/(f+d)] ≅ e / (f+d), Equation (A.1) can be written as:

$$L_M = 0.2 \times \eta \times K_s \times h \times \frac{e}{(f+d)} \cong \frac{W}{x} \qquad \text{(A.5)}$$

Where x ≅ f+d and W is a constant given by:

$$W = 0.2 \times \eta \times K_s \times h \times e \qquad \text{(A.6)}$$

Solving the integrals of Equation (A.4), inserting the results into Equation (A.3) and making some algebraic manipulations lead to the following equations:

$$SPL = \left(\frac{U_R}{U_{SPL}}\right)^2 \frac{[(C_1.U_{SPL}+1)\exp(a_1 - C_1.U_{SPL}) - D]}{[(C_1.U_R+1)\exp(a_1 - C_1.U_R) - D]} \quad \text{for } U_R \text{ and } U_{SPL} \leq U_{LIM} \qquad \text{(A.7)}$$

$$SPL = \left(\frac{b_1.U_R}{b_2.U_{SPL}}\right)^2 \frac{[(C_2.U_{SPL}+1)\exp(a_2 - C_2.U_{SPL})]}{[(C_1.U_R+1)\exp(a_1 - C_1.U_R) - D]} \quad \text{for } U_R \leq U_{LIM} \text{ and } U_{SPL} > U_{LIM} \qquad \text{(A.8)}$$

$$SPL = \left(\frac{U_R}{U_{SPL}}\right)^2 \frac{[(C_2.U_{SPL}+1)\exp(a_2 - C_2.U_{SPL})]}{[(C_2.U_R+1)\exp(a_2 - C_2.U_R)]} \quad \text{for } U_R \text{ and } U_{SPL} > U_{LIM} \qquad (A.9)$$

NOTE 2 – These three Equations (A.7), (A.8) and (A.9), instead of only one, are due to the break in the function p(i) at i = 20 kA (see NOTE 1);

where:

$$U_{LIM} = \frac{20.W}{R.T_1} \qquad (A.10)$$

$$C_1 = \frac{b_1.R.T_1}{W} \qquad (A.11)$$

$$C_2 = \frac{b_2.R.T_1}{W} \qquad (A.12)$$

$$D = \left(1 + 20b_1 - 20\frac{b_1^2}{b_2} - \frac{b_1^2}{b_2^2}\right)\exp(a_1 - 20b_1) = 82.33 \qquad (A.13)$$

$a_1 = 4.605$; $b_1 = 0.0117$; $a_2 = 5.063$; and $b_2 = 0.0346$ are the parameters of p(i).

In the equations from (A.7) to (A.9), U_{SPL} and U_R are in kV.

A limit condition for the SPL is achieved for $R \to 0$. In this case, Equations (A.7) to (A.9) are reduced to the simple form shown in Equation (A.14), where U_{SPL} is independent of the loop dimensions and of the p(i) parameters.

$$SPL = \left(\frac{U_R}{U_{SPL}}\right)^2 \qquad (A.14)$$

Tables A.1 and A.2 show the values of U_{SPL} for different values of SPL, U_R, loop and structure dimensions, based on Equations (A.7) to (A.9).

The same rationale can be applied in order to induce the short circuit currents in the loop. The resulting equations are similar to Equations (A.7) to (A.9) where the voltages U_R, U_{SPL} and U_{LIM} shall be replaced by the currents I_R, I_{SPL} and I_{LIM}. Equations (A.10) to (A.12) shall be modified as follows:

$$I_{LIM} = \frac{20 \times W}{R \times L_S} \qquad (A.15)$$

$$C_1 = \frac{b_1 \times R \times L_S}{W} \qquad (A.16)$$

$$C_2 = \frac{b_2 \times R \times L_S}{W} \qquad (A.17)$$

In the calculation of the values for Tables A.1 and A.2 it has been considered that the function p(i) applies to the first stroke. As stated in Table 1, the subsequent stroke has the same distribution as the first stroke, but with the currents divided by a factor 4 (i.e., 200 kA for the first stroke corresponds to 50 kA for the subsequent stroke, and so on). Therefore, as the function p(i) has been used for the calculation of Equations (A.7) to (A.9), the front time of the subsequent stroke used in the calculation of U_{SPL} has been multiplied by a factor 4, i.e., $T_1 = 1$ μs, in order to compensate for the difference in the magnitude of the currents. The values of U_{SPL} and I_{SPL} were calculated for the subsequent and first strokes, respectively.

Table A.1/K.67 – Peak values of induced surge voltages and surge currents, in a 25 m² loop inside a structure, due to lightning near the structure

SPL	Structure dimensions (m)					
	L = 25 – H = 50 (large building)		L = 15 – H = 5 (small building)		L = 0 – H = 0 (no building)	
	U_{SPL} (V)	I_{SPL} (A)	U_{SPL} (V)	I_{SPL} (A)	U_{SPL} (V)	I_{SPL} (A)
I	2520	61	4630	112	5000	121
II	2100	51	3390	82	3540	86
III/IV	1610	39	2200	53	2240	54
NOTE – Calculation conditions: h = 2.5 m; e = 10 m; r = 0.5 mm (L_s = 41.2 μH); η = 1; K_s = 1.						

Table A.2/K.67 – Peak values of induced surge voltages and surge currents, in a 50 m² loop inside a structure due to lightning near the structure

SPL	Structure dimensions (m)					
	L = 25 – H = 50 (large building)		L = 15 – H = 5 (small building)		L = 0 – H = 0 (no building)	
	U_{SPL} (V)	I_{SPL} (A)	U_{SPL} (V)	I_{SPL} (A)	U_{SPL} (V)	I_{SPL} (A)
I	3370	64	4890	93	5000	95
II	2690	51	3500	67	3540	68
III/IV	1920	37	2230	43	2240	43
NOTE – Calculation conditions: h = 5 m; e = 10 m; r = 0.5 mm (L_s = 52.4 μH); η = 1; K_s = 1.						

The values of the inductance L_S for different loop dimensions can be calculated with Equation (A.2). Table A.3 shows some results of Equation (A.2) for different loop dimensions.

Table A.3/K.67 – Inductance values (L_s) in μH for different loop dimensions

h (m)	e = 20 m		e = 10 m	
	r = 0.5 mm	r = 5 mm	r = 0.5 mm	r = 5 mm
2.5	75.3	54.6	41.2	29.7
0.5	56.4	37.5	28.7	19.1
0.05	36.9	18.4	18.5	9.2
0.025	31.3	12.9	15.7	6.4

A.3 Lightning to the structure

In case of lightning to the structure, the following three cases can be considered:

1) structure protected by an LPS built of one separate rod (e.g., antenna tower which protects the nearby Radio Base Station (RBS));
2) structure protected by a meshed LPS with down-conductors spaced along the perimeter;
3) structure protected by a grid-like spatial shield (LPS) with mesh width w ≤ 5 m.

In the first two cases, the open circuit voltage (V_{io}) induced in the loop inside the structure can be evaluated with Equation (4), where the mutual inductance L_M is given by the following equation [4, 6]:

$$L_M = 0.2 \times K_c \times K_s \times h \times \ln\left(\frac{d+e}{d}\right) [\mu H] \quad (A.18)$$

where (see Figure A.3):

h = high of the loop [m];

e = length of the loop [m];

d = distance between the down conductors and the circuit loop [m];

K_c = factor taking into account the current-sharing among the down conductors;

K_s = shielding factor taking into account the shielding effect of the cable shield;

and:

I_{ps} = peak value of the subsequent strokes (Table 1) [kA];

$T_1 = 0.25$ = front time of the subsequent strokes (Table 1) [µs].

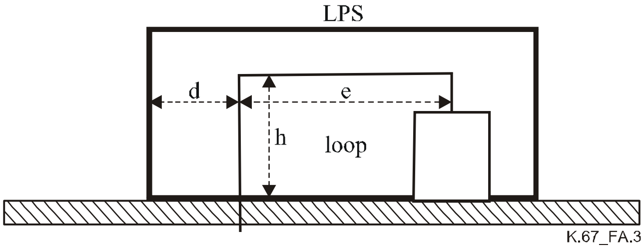


Figure A.3/K.67 – Lightning strokes to the structure: LPS with one or more down conductors

In the case of an LPS with one down conductor, $K_c = 1$ is assumed; in the case of LPS with multiple down conductors [6]:

$$K_c = \frac{1}{2 \times n} + 0.3 \quad (A.19)$$

where:

n = the number of down conductors equally spaced around the perimeter.

In the third case of a structure protected by a grid-like spatial shield LPS, the peak value of the open circuit induced voltage in the loop may be calculated with Equation (4) where the mutual inductance L_M is given by the following Equation [6]:

$$L_M = 0.4 \times \pi \times K_s \times h \times \ln\left(\frac{d_w + e}{d_w}\right) \times K_h \times \frac{w}{\sqrt{d_r}} \ [\mu H] \quad (A.20)$$

where (see Figure A.4):

d_w = distance of the loop from the wall [m];

d_r = distance of the loop from the roof [m];

K_h = configuration factor equal to $0.01[1/m^{0.5}]$;

K_s = shielding factor taking into account the shielding effect of the cable shield;

and:

I_{ps} = peak value of the subsequent strokes (Table 1) [kA];

$T_1 = 0.25$ = front time of the subsequent strokes (Table 1) [μs].

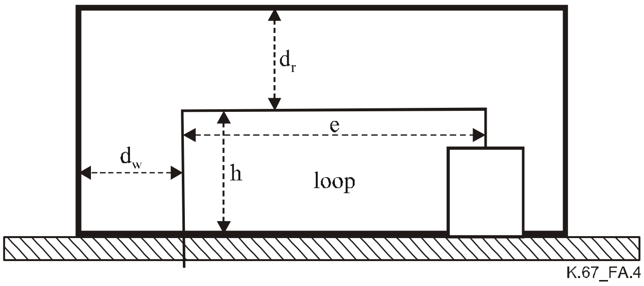


Figure A.4/K.67 – Lightning strokes to the structure: Grid-like spatial shield LPS

The short circuit current (I_{sc}), if the ohmic resistance of the wires is neglected (worst case), is estimated with Equation (5) or (6), where the self-inductance (L_S), in Henry, of the loop is calculated with Equation (A.2).

The values of V_{oi} and I_{sc}, due to the first and the subsequent strokes, are reported in Table A.4, as a function of the LPL, assuming that the structure is protected by an LPS built of one separate rod (K_c =1, worst case) and the internal cabling is unshielded and the induced loop dimension is 50 m^2 (h = 5 m; e = 10 m).

Table A.4/K.67 – Peak values of induced surges, in a 50 m² loop inside a structure, due to direct lightning to the structure

LPL	First strokes		Subsequent strokes	
	V_{oi} [kV]	I_{sc} [kA]	V_{oi} [kV]	I_{sc} [kA]
I	25	6	250	1.5
II	19	4.5	190	1.2
III/IV	12.5	3	125	0.8
Calculation conditions: L_S = 42 μH; L_M = 0.792 μH; Loop dimensions 50 m^2 (h = 5 m; e = 10 m); K_c = 1; K_s =1; d = 4 m; r = 0.5 m.				

Annex B

Induced surges on telecommunication lines due to lightning near the line: Perfectly conducting soil

The number of lightning strokes in the elementary section "$L_r \times dx$", inducing on the telecommunication line a voltage equal to or above U, is given by:

$$N = 2 \times L_r \times N_g \times dx \int_I^{\infty} p(i) \times di \qquad \text{(B.1)}$$

where N_g is the ground flash density, L_r is the line length, p(i) is the probability function of the strike current as given by ITU-T Recs K.25, K.47 and IEC 61663-1, and I is the peak strike current that will induce the voltage U at a given point on the line.

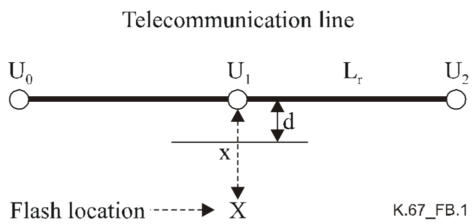


Figure B.1/K.67 – Reference configuration for surge evaluation induced by lightning near the line

The total number of strikes that will induce a voltage equal to or greater than U is given by:

$$N_T = 2 \times L_r \times N_g \int_d^{\infty} \int_I^{\infty} p(i).di.dx \qquad \text{(B.2)}$$

Where d is the minimum distance from the line that will not lead to a direct strike to it. The approximated relation d = 3 h is assumed (Figure B.1).

The peak value of the voltage U_1, in the middle point of the line, and U_0 or U_2, at the line terminations, can be estimated by the following equations when a perfectly conducting soil is assumed:

$$U_1 = \frac{30 \times I_p \times h}{d} \left(1 + \frac{v}{\sqrt{2 - v^2}} \right) \qquad \text{(B.3)}$$

$$U_0 = U_2 = \frac{30 \times I_p \times h}{d} \qquad \text{(B.4)}$$

where:

I_p = the peak value (in kA) of lightning current;

v = the ratio between the return-stroke velocity (v = 1.3×10^8 m/s is assumed) and the velocity of the light (c = 3×10^8 m/s):

$v = 0.43$ and $\left(1 + \frac{v}{\sqrt{2 - v^2}} \right) = 1.3$.

Inserting I_p from Equation (B.4) into Equation (B.2), solving the integrals, inserting the results into Equation (15) and making some algebraic manipulations lead to the following equations:

$$SPL = \frac{U_R\left[\exp(a_1 - A_1 U_0) - B\right]}{U_{SPL}\left[\exp(a_1 - A_1 U_R) - B\right]} \quad \text{where } U_R \text{ and } U_0 \le U_{LIM} \tag{B.5}$$

$$SPL = \frac{b_1 U_R\left[\exp(a_2 - A_2 U_0)\right]}{b_2 U_{SPL}\left[\exp(a_1 - A_1 U_R) - B\right]} \quad \text{where } U_0 > U_{LIM} \text{ and } U_R \le U_{LIM} \tag{B.6}$$

$$SPL = \frac{U_R\left[\exp(a_2 - A_2 U_0)\right]}{U_{SPL}\left[\exp(a_2 - A_2 U_R)\right]} \quad \text{where } U_0 > U_{LIM} \text{ and } U_R > U_{LIM} \tag{B.7}$$

NOTE 1 – These three Equations (B.5), (B.6) and (B.7), instead of only one, are due to the break in the function p(i) at i = 20 kA.

where:

η = is the shielding factor of the line (η = 1 when the line is unshielded)

$$U_{LIM} = 600\, h\, \eta / d \tag{B.8}$$

$$A_1 = \frac{b_1}{10\eta} = \frac{0.00117}{\eta} \tag{B.9}$$

$$A_2 = \frac{b_2}{10\eta} = \frac{0.00346}{\eta} \tag{B.10}$$

$$B = \left(1 - \frac{b_1}{b_2}\right)\exp(a_1 - 20 b_1) = 52.37 \tag{B.11}$$

a_1 = 4.605; b_1 = 0.0117; a_2 = 5.063; and b_2 = 0.0346 are the parameters of p(i).

In the equations from (B.5) to (B.7), U_{SPL} and U_R are in kV.

A limit condition for the SPL is achieved for d → 0. In this case, Equations (B.5) to (B.7) are reduced to the simple form shown in Equation (B.12), where U_{SPL} is independent of the line characteristics and of the p(i) parameters.

$$SPL = \left(\frac{U_R}{U_{SPL}}\right) \tag{B.12}$$

Table B.1 shows the values of U_{SPL} for different values of SPL and U_R based on Equation (B.5) for an aerial unshielded line (η = 1).

Table B.1/K.67 – Open circuit values of the dangerous surge voltage (U_{SPL}) at the ends of an aerial unshielded line as a function of the SPL for different values of reference voltage U_R

U_R (kV)	Dangerous surge voltage, U_{SPL} [kV]		
	SPL		
	0.01	0.02	0.05
1.5	111	64	28
1.0	81	44	19
0.75	64	34	14
0.5	44	23	10
0.25	23	12	5

In Table B.1, twice the referenced voltage value ($2 \times U_R$) is the lower limit of the open circuit for the "dangerous" voltages, in order to take into account the reflection in the line termination. For example, considering $U_R = 0.75$ kV and SPL = 0.01 means that 1% of the induced open circuit voltages above 1.5 kV will be equal to or greater than 64 kV.

The peak value of the short circuit current (I_{sc}) is estimated as follows:

$$I_{sc} = \frac{U_{SPL}}{Z} \tag{B.13}$$

where:

$Z = 400\ \Omega$ is the surge impedance of the aerial line.

For a shielded aerial line, the U_{SPL} values can be calculated following the same procedure reported above when the shielding factor value related to shield has been evaluated and used into Equations (B.9) and (B.10). However, the resulting U_{SPL} will have an absolute probability of occurrence (number of surges per year) much lower than the corresponding U_{SPL} for the unshielded line. Therefore, it is more representative to multiply the U_{SPL} of the unshielded line by the shielding factor in order to get the U_{SPL} of the shielded line.

NOTE 2 – Considering SPL II, for example, means that among all the voltages above 0.75 kV observed on an unshielded line during a certain period of time, 2% are equal to or greater than 34 kV and that this 2% corresponds to N_T surges. Therefore, for a shielded line ($\eta_e = 0.1$) and the same SPL II, in the same period of time N_T surges will be equal to or greater than 3.4 kV. However, it shall be noted that among all the voltages above 0.75 kV observed on this shielded line during this period of time, more than 2% are equal to or greater than 3.4 kV.

The resulting values for specific shielding factors, were inserted into Table 5, in particular, the shielding factor related to the shield ($\eta_s = 0.05$) for Nodes L, E, P and C and the shielding factor related to the earth ($\eta_e = 0.1$) for Nodes D, S and I.

NOTE 3 – The shielding factor related to shield has been evaluated assuming the shield resistance (R_s) is equal to 5 Ω, then $\eta_s = R_s/Z = 5/100 = 0.05$. The shielding factor related to earth has been evaluated assuming the earth resistance of the shield R_e equal to about 40 Ω, then $\eta_e = (R_s + R_e)/(Z + R_e) = 45/440 = 0.1$.

Table B.2 shows the values of U_{SPL} for different values of SPL and U_R for an aerial shielded line ($\eta = 0.1$) and the rationale described before.

Table B.2/K.67 – Open circuit values of the dangerous surge voltage (U_{SPL}) at the ends of an aerial shielded line as a function of the SPL for different values of reference voltage U_R

U_R (kV)	**Dangerous surge voltage, U_{SPL} [kV]**		
	SPL		
	0.01	**0.02**	**0.05**
1.5	11	6.4	2.8
1.0	8.1	4.4	1.9
0.75	6.4	3.4	1.4
0.5	4.4	2.3	1.0
0.25	2.3	1.2	0.5

The peak value of the short circuit current (I_{sc}) could be estimated by Equation (B.13) where Z equal to 50 Ω or to 100 Ω is the surge impedance of the conductor-shield circuit or of the conductor-earth circuit respectively, both empirically taken from the measurements.

Appendix I

Induced surges inside the structure due to lightning near, or to, the structure: Experimental setup and results

I.1 Introduction

The aim of this appendix is to support the assumption that the waveform of lightning induced voltage into an open loop has a very short front time and duration and that the waveform of lightning induced current into a closed loop is identical to the waveform of the lightning current itself. This is done with the aid of experimental data from a triggered lightning test site of Cachoeira Paulista – Brazil.

I.2 Theoretical model

The following assumptions are considered:

- The loop is relatively close to the lightning channel, so that the current can be considered as uniform along the lightning channel (this assumption neglects the propagation effects of the lightning current along the lightning channel).
- The earth is considered as a perfect conductor, so that image theory can be applied to the lightning channel below the surface of the earth.
- The effect of metallic conductors (for instance, power lines) that may carry part of the lightning current is neglected. This means to assume a symmetric current distribution on the surface of the earth, which allows the use of image theory.
- The loop is considered as having low resistance in comparison with its inductive reactance at the frequencies associated with lightning currents (this applies to most practical cases).
- Any shield effect around the loop is neglected.
- Any bending of the lightning channel from the vertical is neglected.
- The loop and the lightning channel are in the same plane (this is a conservative assumption for the current magnitude, but does not affect the wave shape).

Therefore, the inducing lightning current (I_a) flows uniformly along a vertical straight line (see Figure I.1). The magnetic induction field (B) produced by this current is:

$$B = \frac{\mu_0 \times I_a}{2 \times \pi \times x} \qquad \text{(I.1)}$$

where:

x is the distance from the lightning channel.

The magnetic flux into the loop is easily found by integrating the magnetic field across the loop.

$$\phi_B = \frac{I_a \times h \times \mu_0}{2 \times \pi} \int_f^{f+e} \frac{dx}{x} \qquad \text{(I.2)}$$

which leads to:

$$\phi_B = \frac{I_a \times h \times \mu_0 \times \ln\left(\frac{f+e}{f}\right)}{2 \times \pi} \qquad \text{(I.3)}$$

The driving voltage induced (V) into the loop is given by the time derivative of the magnetic flux:

$$V = \frac{\left(\frac{dI_a}{dt}\right) \times h \times \mu_0 \times \ln\left(\frac{f+e}{f}\right)}{2 \times \pi} \tag{I.4}$$

Equation (I.4) can be written as:

$$V = L_M \times \left({dI_a}/{dt} \right) \tag{I.5}$$

where:

L_M is the mutual inductance between the lightning channel and the loop, i.e.,:

$$L_M = \frac{h \times \mu_0 \times \ln\left(\frac{f+e}{f}\right)}{2 \times \pi} = 0.2 \times h \times \ln\left(\frac{f+e}{f}\right) \quad \text{in } \mu\text{H} \tag{I.6}$$

The induced current I_{loop} is given by:

$$I_{loop} = \left({1}/{L_S} \right) \int V dt = \left({L_M}/{L_S} \right) \times I_a \tag{I.7}$$

where:

L_S is the loop's self-inductance.

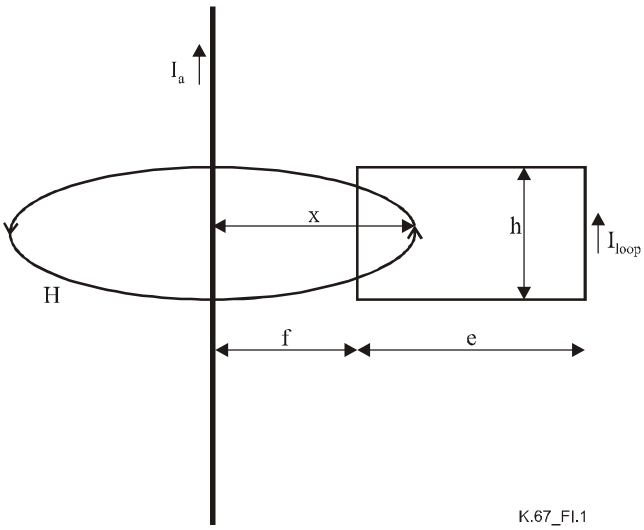


Figure I.1/K.67 – Induction into a loop

I.3 Experimental test site and test set-up

I.3.1 Experimental test site

The RBS of the test site is shown in Figure I.2a, where, at the tower's top there is a rocket pad used to trigger lightning discharges. Figure I.2b shows a closer view of the tower top. The pad is supported by insulators and connected to the structure by one single conductor which passes through a Pearson current monitor (type 1330) that feeds an oscilloscope housed in the metallic box nearby. The oscilloscope is remotely controlled by RS232 interface over fibre-optics. This provides a direct measurement of the lightning current.

a) RBS of the test site b) tower top

Figure I.2/K.67 – RBS of the test site

I.3.2 Test set-up for induced voltage into an open loop

The experimental setup is shown in Figure I.3, where lightning is triggered and recorded at the top of a telecommunication tower and the induced voltage is measured in a loop placed at a distance f from the tower. The set-up data are:

– Loop dimensions: e = 1.5 m and h = 2.0 m (loop area = 3 m^2);

– Distance between the loop and the lightning, f = 100 m.

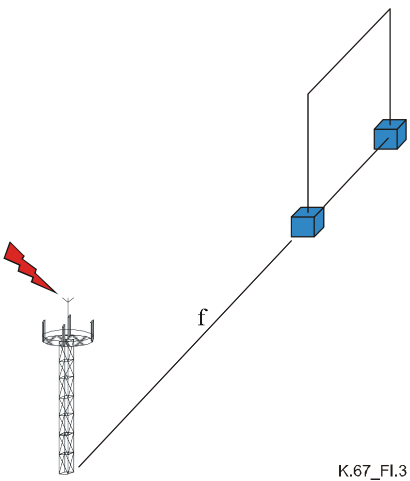


Figure I.3/K.67 – Test set-up for induced voltage into an open loop

The measured lightning current is shown in Figure I.4, and its main parameters are summarized below:

– current: front time (T) = 0.375 ms;
– peak value (I_s) = 9.8 kA.

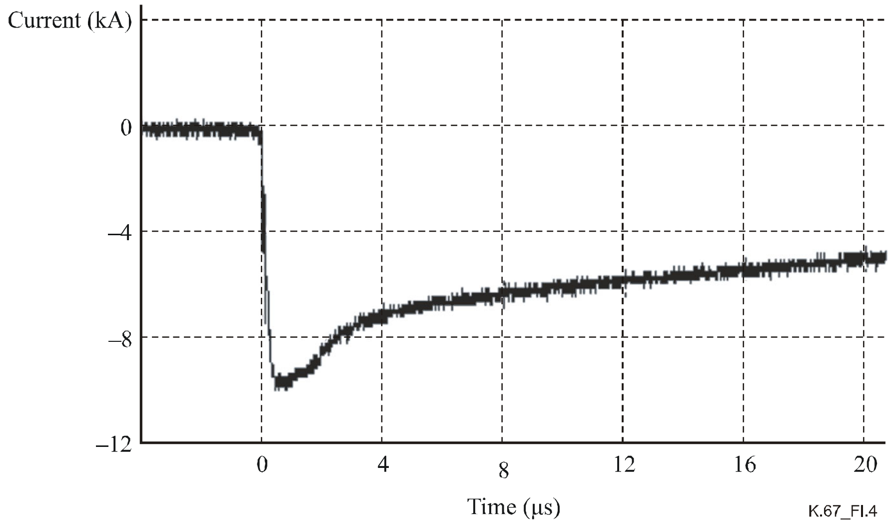
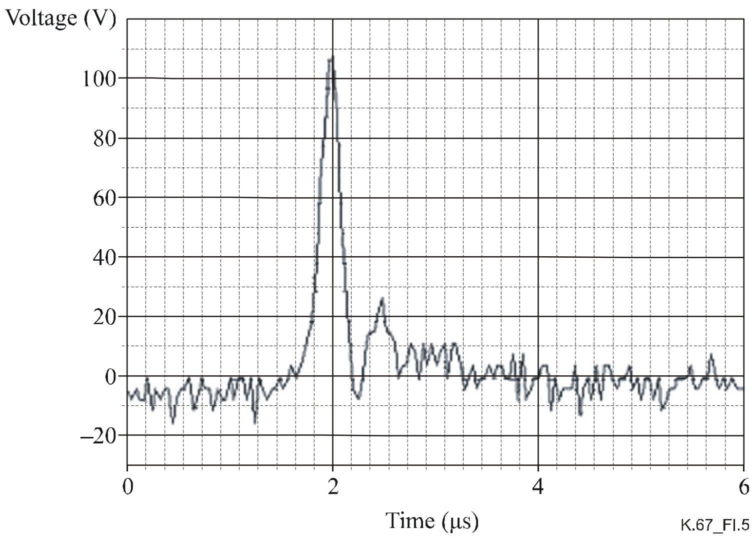


Figure I.4/K.67 – Triggered lightning current

The measured induced voltage into the loop is shown in Figure I.5, where it can be seen that the front time of the induced open circuit voltage is similar to that of the inducing current (i.e., 0.35 µs) and that its waveshape has a very short duration, in the order of a few µs.



(time-scale is not synchronized with Figure I.4)

Figure I.5/K.67 – Measured induced voltage into a loop

Inserting the numerical values into Equation (I.4) and considering the current waveform as trapezoid we get a rectangular wave with 0.375 µs of duration and 157 V peak. This value shall be compared with Figure I.5, where it can be seen that it is somewhat higher than the measured value (110 V).

A more elaborated method can be used, based on Rusck's work [I.1]. This model takes into account the current propagation along the lightning channel. Considering Rusck's equations for the magnetic induction field (B) at some distance from the lightning and computing its time derivatives we get:

$$\frac{dB}{dt} = 0 \quad \text{for } t \le r_0/v_0 \tag{I.8}$$

$$\frac{dB}{dt} = \frac{60 I_0 v}{r_0^2 T v_0} \left\{ \left[1 + \left(\frac{v}{v_0} \right)^2 \left[\left(\frac{v_0 t}{r_0} \right)^2 - 1 \right] \right]^{-1/2} t \right\} \quad \text{for} \quad r_0/v_0 \le t \le r_0/v_0 + T \tag{I.9}$$

$$\frac{dB}{dt} = \frac{60 I_0 v}{r_0^2 T v_0} \left\{ \left[1 + \left(\frac{v}{v_0} \right)^2 \left[\left(\frac{v_0 t}{r_0} \right)^2 - 1 \right] \right]^{-1/2} t - \left[1 + \left(\frac{v}{v_0} \right)^2 \left[\left(\frac{v_0 (t-T)}{r_0} \right)^2 - 1 \right] \right]^{-1/2} (t-T) \right\} \tag{I.10}$$

$$\text{for } t \ge r_0/v_0 + T$$

In Equations (I.9) and (I.10) ν_0 is the velocity of light in free space (3×10^8 m/s) and ν is the lightning current propagation velocity, assumed as equal to 1.3×10^8 m/s. Inserting the numerical values into these equations gives the waveform shown in Figure A.6. This wave shape has 112 V peak and agrees excellently with the measured voltage.

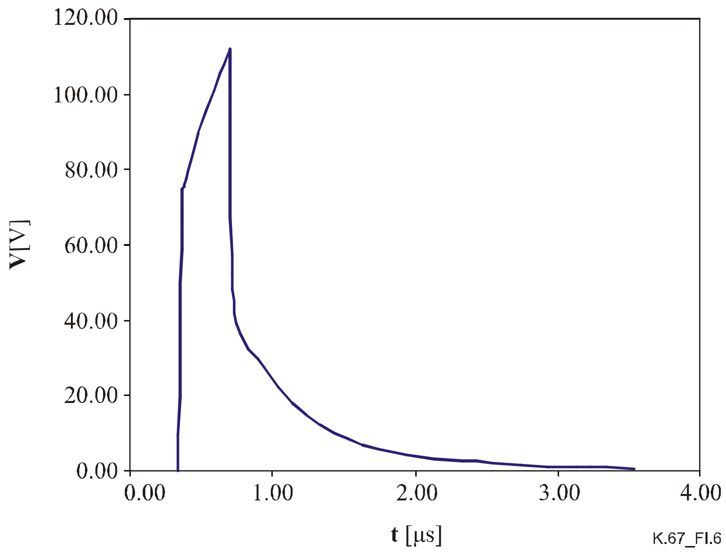
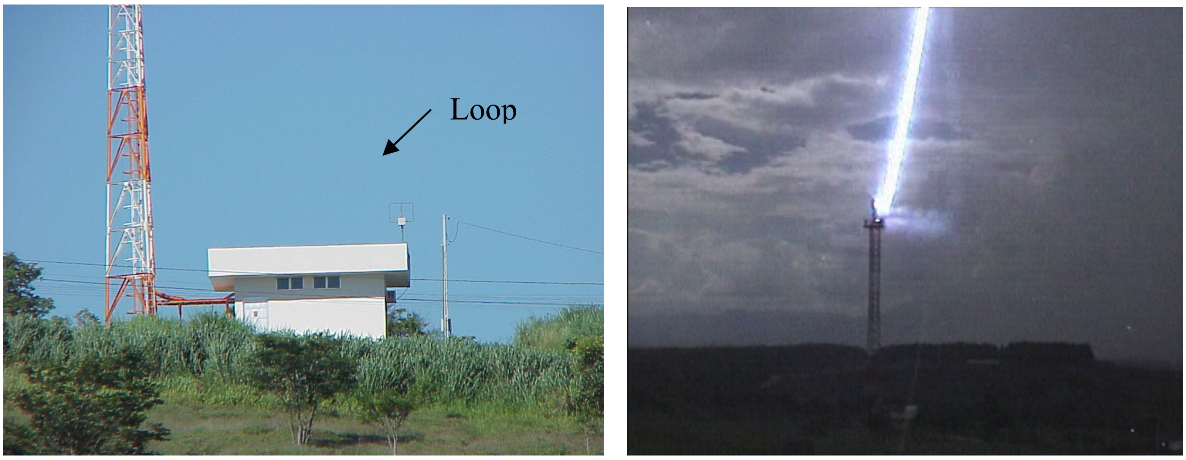


Figure I.6/K.67 – Voltage wave calculated with from Rusck's model

From Equations (I.9) and (I.10) it can be concluded that, for loops relatively close to the striking point ($f < T\ v_0$), the induced voltage peak value can be reasonably approximated by considering the lightning current as being uniform along the channel, as given by Equation (I.4). However, as the loop is moved away from the striking point, the induced voltage is progressively lower than the value calculated by Equation (I.4), because the current velocity of propagation becomes a relevant parameter. In this case, Equations (I.8) to (I.10) should be used.

I.3.3 Test set-up for induced current into a closed loop

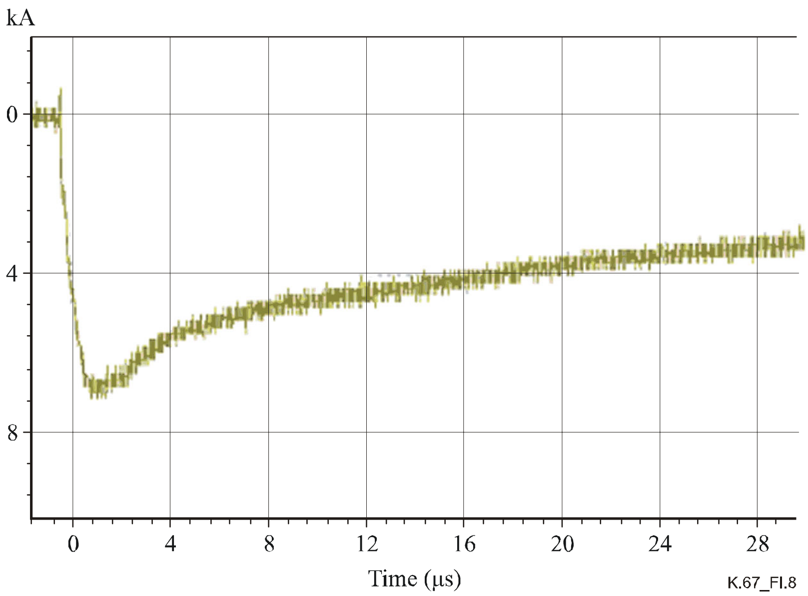
Figure I.7a shows a closer view of the RBS, where can be seen a loop at the top of the housing. This loop is made of a short circuited copper tube and its current is measured by means of a Pearson current monitor (type 110) which feeds an oscilloscope inside the RBS housing. Figure I.7b shows a triggered lightning to the tower top, as seen from the control shelter.



a) RBS housing with loop b) Triggered lightning

Figure I.7/K.67 – Test set-up for induced current into a closed loop

Waves, recorded simultaneously at the tower top (Figure I.8) and at the loop (Figure I.9), are described by the peak value, the time to half value (T_h) and the front time (T_f) defined as 1.25 ($T_{90\%} - T_{10\%}$).



Current 19/02/2005 – Block 1 – Tower top
Peak = 7.4 kA – T_h = 24 μs – T_f = 1.2 μs

Figure I.8/K.67 – Lightning current

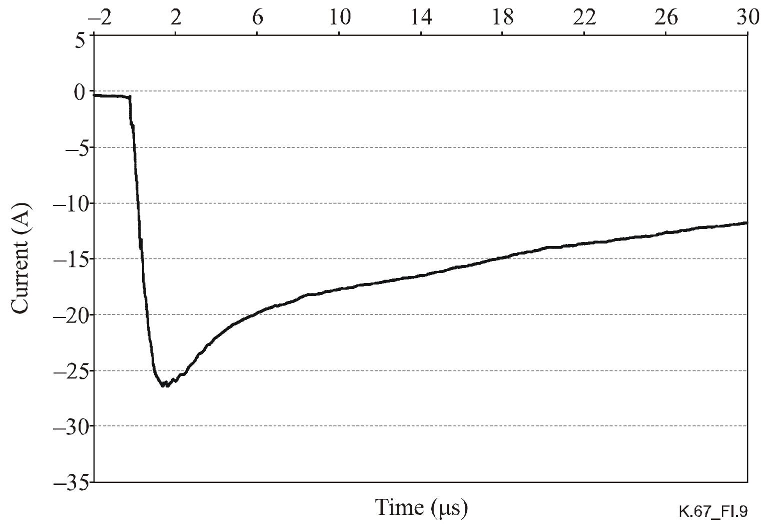


Figure I.9/K.67 – Induced current in the closed loop

The comparison between the waves recorded at the tower top and at the loop shows a very good agreement regarding the wave shape.

The test site data are:

- Distance from the tower axis and the loop: f = 10.7 m;
- Loop height: h = 0.80 m;
- Loop width: e = 1.00 m;
- Loop conductor radius = 0.0075 m.

The mutual inductance between the tower and the loop is given by Equation (I.6) as:

$$L_M = 0.0143\ \mu H$$

The loop self inductance is given by Equation (A.2) as:

$$L_S = 2.89\ \mu H$$

The expected loop current, as given by Equation (I.7), for a lightning current I_a = 7.04 kA is:

$$I_{loop} = 34.8\ A$$

The measured loop current (26.4 A) is somewhat lower (24%) than the expected value because the actual conditions of the test site does not completely fulfil the theoretical assumptions listed in I.2. Among these assumptions, the one that most contributes to this difference is the presence of the electric power line which conducts part of the lightning current away from the station in such a direction that it does not couple with the loop. In order to duplicate the measurement of the lightning current, these factors have been compensated for in the system gain informed to the measuring software.

In conclusion, as experimentally shown, the waveform of lightning induced current into a closed loop is identical to the waveform of the lightning current itself and the relation between their peak values can be assessed by the ratio between the mutual and the self inductances, as given by Equation (I.7).

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Printed in Switzerland
Geneva, 2006